Individual differences in simultaneous color constancy are related to working memory

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Few studies have investigated the possible role of higher-level cognitive mechanisms in color constancy. Following up on previous work with successive color constancy [J. Exper. Psychol. Learn. Mem. Cogn. **37**, 1014 (2011)], the current study examined the relation between simultaneous color constancy and working memory—the ability to maintain a desired representation while suppressing irrelevant information. Higher working memory was associated with poorer simultaneous color constancy of a chromatically complex stimulus. Ways in which the executive attention mechanism of working memory may account for this are discussed. This finding supports a role for higher-level cognitive mechanisms in color constancy and is the first to demonstrate a relation between simultaneous color constancy and a complex cognitive ability.

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1. INTRODUCTION

When the light that is illuminating a surface changes, so does the light that reaches the eye from the surface. Despite this *physical* change in the light reaching the eye, we tend not to experience a corresponding *perceptual* change in the color appearance of the surface. This is the phenomenon of color constancy: the colors of surfaces tend to appear stable across changes in illumination [1]. Color constancy is a fundamental aspect of human vision, playing a crucial role in object identification; if the color of an object appears to change whenever the illumination changes, color is not a reliable cue for detecting and recognizing objects.

In the natural world, illumination can change across both time and space; the types of color constancy responsible for compensating for these illumination changes are called *successive* and *simultaneous*, respectively. For example, successive color constancy compensates for the gradual change in the spectral power distribution of sunlight over the course of the day, while simultaneous color constancy compensates for the difference in illumination between a part of a surface that is in direct sunlight and another part that is in shadow.

Both successive and simultaneous color constancy are thought to rely on creating an (approximately) illuminant-independent representation of the surface [1]. This can be achieved by estimating and then discounting the contribution that the illuminant makes to the light reaching the eye from the surface, a complex computational process that takes advantage of contextual illuminant cues such as specular highlights [2], shadows [3], and the spectral distribution of light from other colored surfaces in the scene [4]. Color constancy, which is never perfect, is best when a scene is rich in such contextual cues, and typically is poorer when few cues are available (e.g., [5]).

A great deal of research focuses on what types of illuminant cues the visual system uses and which cues make the greatest contributions to color-constancy performance (for a review, see [6]). Little research, however, focuses on factors that may contribute to color constancy *other than* illuminant cues. In particular, only a few studies consider the role that higher-level cognitive mechanisms may play in achieving color constancy. One classic study manipulated the instructions given to observers before each session of a simultaneous color-constancy task [7]. Observers adjusted a test patch embedded in a chromatically complex Mondrian background presented under one (simulated) illuminant to match the appearance of a reference patch embedded in a Mondrian background presented under a different (simulated) illuminant. Crucially, in one session, observers were told to match the test patch to the reference patch in hue and saturation (hue–saturation match); in another session the same observers were told to make the two patches look as if they were cut from the same piece of paper (paper match). Color constancy was significantly better in the latter case than in the former, which the authors interpreted as a clear indication of a role for higher-level cognitive mechanisms in color constancy. A similar experiment revealed that different instructions may lead observers to adopt different viewing strategies [8]. In this experiment, observers spent more time scanning the Mondrian backgrounds surrounding the test and reference patches in the paper-match condition than in the hue–saturation-match condition; this may produce more adaptation to the illuminant. Thus, different instructions may lead observers to adopt different strategies when performing a color-constancy task, which in turn causes them to adapt differently to the illuminant. Importantly, however, some observers showed an instructional effect that was larger than could be accounted for by a change in viewing strategies [8].

Recently, higher-level cognitive mechanisms were investigated in a successive color-constancy experiment [9]. Successive color constancy implicitly involves memory: in order to judge whether the color appearance of a surface changes across a temporal interval that includes an illumination change, one needs a remembered representation of the surface under the first illuminant to compare with the appearance of the surface later under the second illuminant [10,11]. Because of the role of memory in successive color constancy, it was hypothesized that an observer's working memory (WM)—their ability to maintain a desired representation in the face of distraction—would be related to their successive color constancy. In the experiment, observers who had been pretested on WM viewed displays containing a central patch surrounded by a background with little chromatic context (uniform-background condition) or a greater amount of chromatic context (complex-background condition). Observers were instructed to memorize the color of the central patch in a display presented under one (simulated) illuminant, and after a 1 min memory retention interval, set the color of a central test patch in a display presented under a different (simulated) illuminant to look like the previously presented patch. The observers' WM and their successive color constancy were significantly related in the uniform-background condition, with few contextual cues available to aid color constancy. Specifically, higher-WM (HighWM) individuals had better color constancy than lower-WM (LowWM) individuals in this condition.

One possible explanation for this result is that the LowWM observers were simply unable to maintain an illuminant-independent representation across the memory retention interval (or at least not as well as the HighWM observers could). However, when observers were tested on "simple" color memory (where the task was identical to the one testing successive color constancy, except no illumination change took place), there was no significant difference in performance between the LowWM and HighWM observers. Thus, an explanation that is based *solely* on a difference in the ability to maintain a representation across a memory retention interval is unlikely. Instead, additional mechanisms operating during the encoding and/or recall of an illuminant-independent representation were posited to cause the relation with WM capacity.

A growing body of evidence suggests that individual differences in WM mainly reflect a domain-general executive attention mechanism, which is deployed to actively maintain a desired representation while inhibiting interference from irrelevant information [12]. Thus, WM "capacity" is less about the number of items one can hold in memory and more about the capacity to use executive attention to resist distraction while maintaining these items. Individual differences in WM may reflect a myriad of factors related to the executive attention mechanism, such as the ability to control the accessibility of a stimulus representation [13], the ability to parse irrelevant from relevant information at encoding [14], and even the strategy used to complete a task [15].

Given the multiple ways in which executive attention can potentially affect performance, several intriguing explanations exist for the successive color-constancy results described above. One possibility is that WM is related to the process of estimating and parsing illuminant information from the representation of a surface, and thus it may play a role in establishing an illuminant-independent representation. Another possibility is that WM is required to keep the illuminant-independent representation accessible while performing a color-constancy task. A third possibility is that HighWM and LowWM observers performing a color-constancy task may employ different strategies that may not be equally effective. Importantly, ignoring these possibilities in favor of an explanation based solely on mechanisms that function during a memory retention interval carries with it the implication that any relation to WM should disappear when the retention interval is eliminated—for example, in an experiment testing simultaneous color constancy.

The present study employed a simultaneous color-constancy task to test for a relation with WM, using a paradigm with no memory retention interval. The task was as similar as possible to the successive color-constancy paradigm used previously. A significant difference in performance was again found between LowWM and HighWM observers, though this effect differed qualitatively from the previous results. The current results provide further evidence for a role of higher-level cognitive mechanisms in color constancy and are consistent with the proposition that the relation between color constancy and WM is not solely due to a mechanism that operates during a memory retention interval.

2. METHOD

A. Observers

LowWM and HighWM groups were established from the distribution of scores on the Reading Span (RSPAN) [16], a commonly used measure of WM [17].

In the RSPAN, observers are presented with a series of sentences on a computer (e.g., "The ranger told the hikers to look out for snakes."). Observers indicate whether the sentence makes sense by clicking "TRUE" or "FALSE" on the screen. A letter is then presented for observers to hold in memory. These sentence–letter trials are presented in sets, with three to seven trials per set, for a total of 75 letters in 15 sets. At the end of each set, a screen with 12 letters appears, and observers use the mouse to select the letters they remember in the correct order.

Scores for the RSPAN were calculated using the partial-credit unit scoring method (recommended by [17]). Observers with a score of at least 60 (out of a possible 75) were classified as HighWM; observers with a score of 40 or less were classified as LowWM. The score criteria were identical to those used previously [9].

Twelve HighWM [four male, $M_{\text{age}} = 20.1$, standard deviation (SD) = 1.68] and six LowWM [one male, $M_{\text{age}} = 21.2$, SD = 3.19] observers participated in the study. Unequal group sizes were due to the difficulty of recruiting LowWM observers who were similar in age to the HighWM observers and also were University of Chicago students. The HighWM [LowWM] observers had RSPAN scores ranging from 61–75, $M_{\text{RSPAN}} = 69.5$ [15–36, $M_{\text{RSPAN}} = 27.2$]. All reported normal or corrected-to-normal visual acuity, had normal color vision as determined by Rayleigh matching [18], and were naïve as to the purpose of the experiment.

B. Experimental Setup

Stimuli were generated using a Macintosh computer on a precisely calibrated NEC AccuSync 120 high-resolution CRT color monitor [19]. A color lookup table generated stimuli according to their Judd (1951) tristimulus values [20]. Observers viewed the CRT screen binocularly without head restraint from a distance of about 1 m. The observers controlled the chromaticity (hue and saturation) of a test patch using a Gravis game controller.

The uniform-background stimulus consisted of a circular central patch of 1.2° diameter visual angle within a contiguous, uniform annular surround of outer diameter 5.9° [Fig. 1(a)]. The complex-background stimulus was identical, except eight colored sectors, separated by 0.29°, were embedded within the surround [sector inner/outer diameter of 1.8°/5.4°; Fig. 1(a)]. In all cases, the area beyond the stimulus was dark (luminance of 0.001 cd/m^2).

All stimulus chromaticities were (simulated) papers from the Munsell Book of Color (Munsell Color Corporation, Baltimore Maryland) under CIE standard illuminant A or illuminant C. To simulate a color paper under an illuminant, its surface reflectance [21,22] was multiplied, wavelength by wavelength, by the spectral power distribution of the illuminant, giving the spectral power distribution of the light reflected from the paper. From this, the Judd (1951) tristimulus values were calculated, and the computer reproduced these values

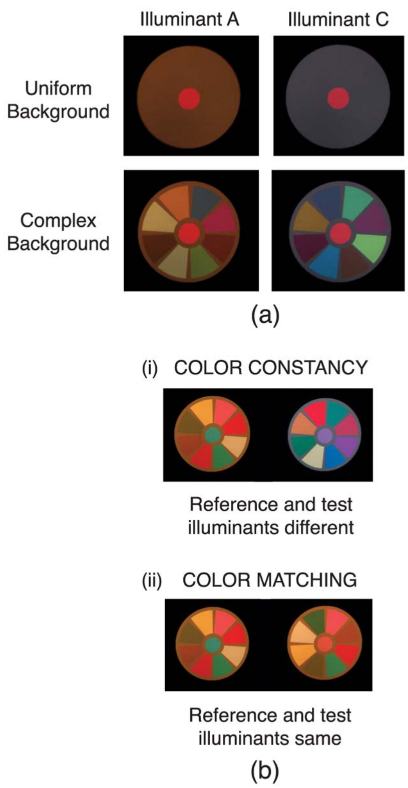


Fig. 1. (Color online) (a) Examples of the four combinations of illuminant and background using the "red" central Reference Color. Note that, in the complex-background condition, the colored sectors embedded within the surround were randomly generated every time a new stimulus was displayed (and thus differ in the left- and right-hand columns of this example). Also note that the color appearance of the stimuli in the figure may be different from their appearance on the fully calibrated computer monitor used in the study. (b) Example of a reference and test display using the complex background, Reference Illuminant A, and "blue" Reference Color. The reference display was always on the left; the test display was always on the right. The central patch in the test display was initially set to a random chromaticity (as pictured here); observers set the chromaticity of this patch to look like the central patch in the reference display. (i) The Test Illuminant is different from the Reference Illuminant; this is a test of simultaneous color constancy. (ii) The Test Illuminant is the same as the Reference Illuminant; this is a test of color-matching ability.

on the CRT (after applying a luminance normalization, see below). Because of the limited color gamut of the CRT, only 165 of 462 possible color papers were used. These colors were divided into ten groups according to the perceptual spacing of the Munsell hue circle [23]: (1) {5R, 10R}, 11 papers; (2) {5YR, 10YR}, 5 papers; (3) {5Y, 10Y}, 5 papers; (4) {5GY, 10GY}, 20 papers; (5) {5G, 10G}, 19 papers; (6) {5BG, 10BG}, 18 papers; (7) {5B, 10B}, 21 papers; (8) {5PB, 10PB}, 27 papers; (9) {5P, 10P}, 23 papers; (10) {5RP, 10RP}, 16 papers.

The Munsell papers used for the central reference patch colors were 5R 4/6 ("red"), 10GY 4/6 ("green"), and 5B 4/6 ("blue"). In the practice session, 10PB 4/8 ("purple") was used as the only reference patch color. The surround was always based on paper N 4/0 ("gray"), which essentially reflected all wavelengths nonselectively.

For the complex-background condition, the central patch color in the reference display was chosen from one of the possible reference patch colors, and then the colors for the sectors embedded within the surround were selected according to a pseudorandom process. First, the Munsell color groups for the sectors were selected randomly from the nine groups that were left after the color group belonging to the test color was removed. From these nine groups, one group was randomly chosen without replacement for each of the eight sectors. Finally, for each sector, one Munsell chip belonging to the chosen group was selected. In the case of the test display, the central patch color was chosen randomly, and then the same procedure was followed to create a complex background. This randomization process took place for each reference and test display that was generated. This prevented any systematic influence of a sector color on the test color (for example, chromatic induction). To avoid strong luminance contrast, the average luminance of the colored sectors in the complex-background condition was scaled to be equal to that of the central patch, which was fixed at 8 cd/m^2.

C. Experimental Procedure

After giving informed consent, observers completed a practice session followed by an experimental session. Observers were instructed to think of the colored patches as papers on a table (see [24]).

Observers completed one practice session of 12 trials, and one experimental session of 24 trials. Prior to a session, observers dark-adapted for 5 min. In each trial, a reference display and a test display (under the same background condition) were presented simultaneously 2.9° apart [Fig. 1(b)]. Trials using the two background conditions and three Reference Colors were counterbalanced and presented in random order. For half of the observers, the reference display always appeared under (simulated) illuminant A; for the other half, the Reference display always appeared under (simulated) illuminant C. All observers saw the test display under (simulated) illuminant A on half of the trials and under (simulated) illuminant C on the other half. This allowed measurement of both color-matching ability (no illuminant difference between the reference and test display) and simultaneous color constancy (different illuminants in the reference and test displays).

On each trial, the central patch within the test display was set to a random chromaticity, and observers used the controls on the game pad to adjust the central test patch to look like the central reference patch. This instruction was as close as possible to the instruction used previously for successive color constancy [9]. Until the observer completed his or her match, a beep was emitted from the computer every 1 s. Observers were instructed to shift their gaze from the reference to the test display (or vice versa) every time they heard the beep, to prevent them from adapting to either the reference or Test Illuminant. Observers had unlimited time to make their match; after a match was made, there was a 10 s break between trials, during which the screen was dark.

In total, each observer made two color matches for each combination of background, Test Illuminant, and Reference Color. All color matches made by observers were recorded as values in the l and s chromaticity coordinate system of MacLeod and Boynton [25]. Results from statistical analyses are reported separately for the l and s measurements.

3. RESULTS

Before any analyses were performed, outliers, defined as measurements falling beyond the "outer fence" [26], were transformed to the value of the nearest outer fence. Nine of 864 measurements were outliers.

A. Simultaneous Color Constancy

The color matches made by observers were submitted to separate $2 \times 3 \times 2 \times 2$ (Test Illuminant [A, C] × Reference Color [red, green, blue] × WM [high, low] × Reference Illuminant [A, C]) analyses of variance (ANOVAs) for the l and s axes, with the last two factors between subjects. Because previous results for successive color constancy suggest that the amount of contextual information in the background may modulate a relation with WM [9], separate planned tests for the two background conditions were conducted. As expected, significant main effects of Test Illuminant, Reference Color, and Reference Illuminant were found in all cases; these are irrelevant to the purpose of this paper so are not discussed further. Reported below are all significant effects that included the WM term.

Simultaneous color constancy reflects the ability to compensate for an illumination change across space. Thus, simultaneous color constancy is measured as the degree to which the Reference Illuminant affects the observer's color match in the test display.

The critical test for a relation between WM and color constancy is a WM × Reference Illuminant interaction, which would indicate that the WM groups show a difference in the degree to which the Reference Illuminant influences their color matches. For the complex background, this interaction was significant for the l axis of MacLeod–Boynton space, $F(1,14) = 4.85$, $p < 0.05$, with a smaller effect of Reference Illuminant (and thus better color constancy) for LowWM observers ($M_{\mathrm{lowWM}} = 0.018l$) than for HighWM observers ($M_{\mathrm{HighWM}} = 0.031l$). This is illustrated in Fig. 2(b) by the larger difference between Reference Illuminants A and C for observers with HighWM (gray bars) than LowWM (white bars). This WM × Reference Illuminant interaction did not reach significance for the uniform background, $F(1,14) = 1.28$, $p > 0.25$; color constancy was very similar across WM groups in this condition [$M_{\mathrm{LowWM}} = 0.027l$; $M_{\mathrm{HighWM}} = 0.028l$; see Fig. 2(a)]. Similar to previous findings, LowWM observers' color constancy improved considerably from the uniform- to the complex-background condition, while HighWM observers' color constancy did not change substantially. Unlike what was found previously for successive color constancy, however, the current work shows that LowWM observers actually showed *better* simultaneous color constancy than HighWM observers in the complex-background condition. Finally, a significant Reference Color × WM × Reference Illuminant interaction, $F(2,28) = 4.00$, $p < 0.05$, reflected greater differences in color constancy among the three Reference Colors for LowWM observers than for HighWM observers in the uniform-background condition.

The WM × Reference Illuminant interaction did not reach significance for the s axis for either the uniform background, $F(1,14) = 1.62$, $p = 0.223$, or the complex background, $F(1,14) = 2.19$, $p = 0.161$ [Figs. 2(c) and 2(d)]. It is important to note that measurements on the s axis exhibit greater variability than measurements on the l axis because a large difference in the s chromaticity coordinate can correspond to a small change in perceived color. This reduces the power to detect a true WM × Reference Illuminant interaction for the s axis, if one exists. Nonetheless, a significant Test Illuminant × WM × Reference Illuminant interaction, $F(1,14) = 8.77$, $p < 0.05$, reflected greater variability in color constancy among the Test Illuminants for LowWM observers than for HighWM observers in the uniform-background condition.

To facilitate comparison with the previous work on successive color constancy, a color-constancy index (CCI) was calculated for these data using the same formula used previously [9]: $1 - (a/b)$, where a is the difference (in chromaticity coordinates) between the average of all of the color matches made by the observers who were assigned Reference Illuminant A and the average of all of the color matches made by the observers who were assigned Reference Illuminant C, and b is the actual difference in chromaticity of the Reference Color under illuminant A and illuminant C. Thus, a CCI value of 0 indicates no color constancy, and a value of 1 indicates perfect color constancy (in that it expresses no influence of the Reference Illuminant). The measurements in Fig. 2 are expressed as CCIs in Fig. 3.

The CCI values on the l axis for LowWM observers were slightly higher than those measured previously for successive color constancy, but values for the HighWM observers were substantially lower in the current experiment than the previous experiment, particularly in the case of the complex background. Table 1 presents these values for comparison. Numbers in the "Difference" columns are positive if the CCI is higher for simultaneous color constancy. Differences in CCI values are relatively large and negative for HighWM observers and relatively small and positive for LowWM observers. These findings will be addressed in Section 4.

B. Color Matching

Color-matching ability was also assessed for the matches made when the Reference and Test Illuminants were the same. Color-matching error was quantified by the absolute value of the difference (in l or s chromaticity) between the observer's color match and the true Reference Color chromaticity (Fig. 4). For each background condition, color-matching errors were submitted to a $3 \times 2 \times 2$ (Reference Color [red, green, blue] × WM [high, low] × Reference/Test Illuminant [A, C]) ANOVA with the last two factors between

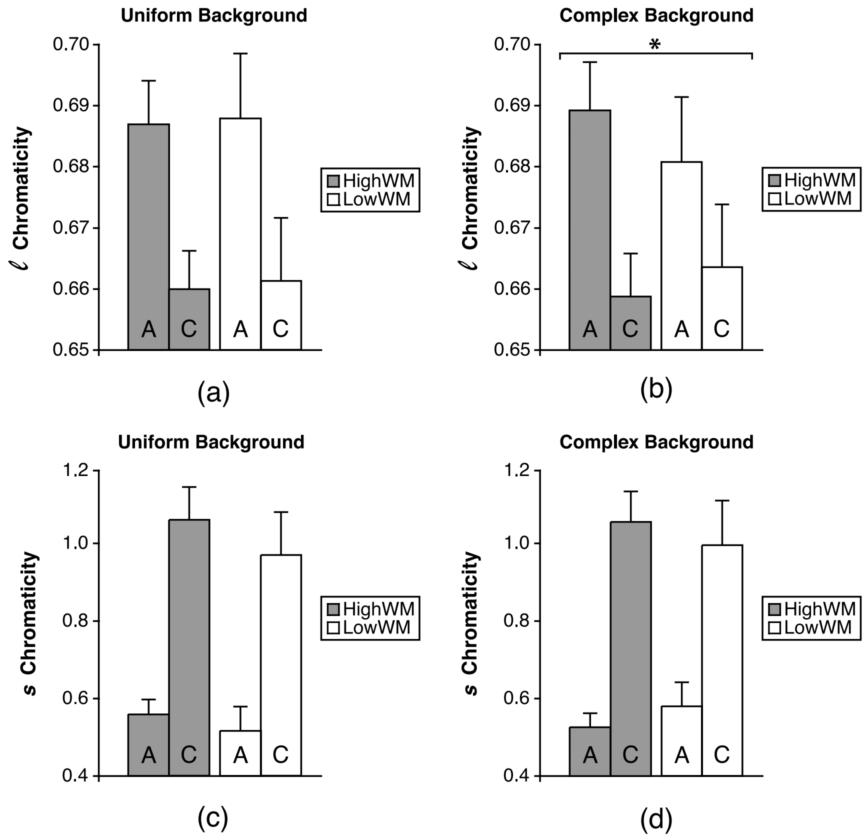


Fig. 2. Observers' color matches averaged across Reference Colors and Test Illuminants for (a), (b) the l axis and (c), (d) the s axis. Results for the uniform [complex] background condition are shown in plots (a) and (c) [(b) and (d)]. Gray [white] bars indicate values for HighWM [LowWM] observers. Bars labeled "A" ["C"] show averaged color matches made by observers who were assigned Reference Illuminant A [C]. The vertical axis indicates the chromaticity of the averaged color match. The difference in height between each pair of same-colored adjacent bars indicates the degree of color constancy; worse color constancy is indicated by a greater difference in height between the bars (as the averaged color match shows a greater change as a function of Reference Illuminant). Error bars indicate standard errors of the mean. An asterisk indicates significance at the $p < 0.05$ level; LowWM observers showed significantly better simultaneous color constancy (that is, a smaller difference between Reference Illuminants A and C) than HighWM observers in the complex-background condition on the l axis.

subjects. The main effect of WM was not significant for the l axis or s axis for either the uniform background, $F(1,14) = 2.61$, $p > 0.12$ [$F(1,14) = 0.0001$, $p = 0.99$], or the complex background, $F(1,14) = 0.177$, $p > 0.65$ [$F(1,14) = 0.080$, $p > 0.75$]. HighWM and LowWM observers did not differ significantly in their ability to accurately make a color match when the illuminant was constant across reference and test displays. No other effects involving the WM term were significant.

Observers had unlimited time to make their color matches, so the total time taken to complete the experimental session differed among observers. HighWM and LowWM observers did not differ significantly in the time taken to complete the experimental session, [$M_{\mathrm{HighWM}} = 30.6$ min, $M_{\mathrm{LowWM}} = 27.5$ min; $t(16) = 0.98$, $p > 0.34$ (two-tailed)].

4. DISCUSSION

LowWM observers showed significantly better simultaneous color constancy than HighWM observers in the complex-background condition, but the two groups did not differ significantly in the uniform-background condition. Importantly, the two groups also did not differ significantly in their color-matching ability under either background condition. Taken together with previous results from successive color constancy [9], the measurements support the conclusion that color constancy is related to a higher-level cognitive ability—in particular, the executive attention mechanism of WM. The two studies are compared below, and some possible factors contributing to the observed relations between WM and color constancy are considered.

Examining the CCI values for the two studies reveals both similarities and differences in performance for simultaneous and successive color constancy (see Table 1). One difference is that HighWM observers have higher CCI values overall in the previous experiment with successive color constancy than in the current experiment, whereas LowWM observers have values more similar across experiments. Why might HighWM observers perform *better* when memory is required than when it is not? One possibility is that HighWM observers perform additional computations on their representation of the central patch during the memory retention interval that results in greater discounting of the illuminant. LowWM observers may not have the resources to perform these additional computations and thus show no benefit from a retention interval. Whether this speculative interpretation is plausible requires further experimentation.

An interesting similarity exists between the current and previous results: in both cases, the CCI values for LowWM observers tend to improve when the contextual information

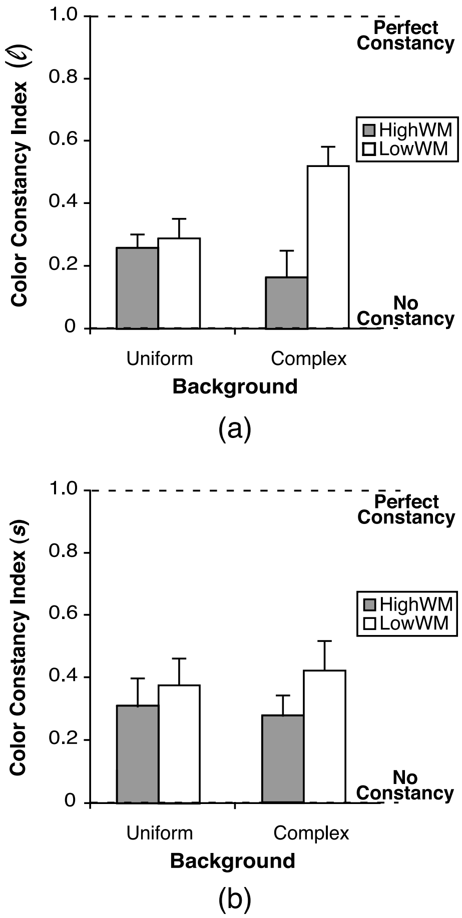


Fig. 3. CCI values averaged across Reference Colors and Test Illuminants for (a) the l axis and (b) the s axis. Results are separated by background condition (uniform and complex). Gray [white] bars indicate values for HighWM [LowWM] observers. The vertical axis indicates the value of the CCI. A larger value indicates better color constancy. "Perfect constancy" refers to a CCI of 1; "no constancy" refers to a CCI of 0 (see text). Error bars indicate standard errors of the mean.

in the background is increased (complex-background condition), while HighWM observers' CCI values are more similar across background conditions (Table 1). As discussed previously [9], one possible reason why LowWM observers tend to show a greater improvement than HighWM observers with an increase in contextual information is that LowWM observers need more cues than HighWM observers to achieve a particular level of color constancy, perhaps because they have greater difficulty discounting the illuminant. This hypothesis is supported by evidence suggesting that WM is related to the ability to parse relevant from irrelevant information at encoding [14] as well as the ability to prevent unwanted information from interfering with the construction and/or maintenance of a desired representation [12]. Though this explanation is consistent with the previous successive color-constancy results (where LowWM observers perform about well as HighWM observers in the complex-background condition only), it appears difficult to reconcile it with the current findings (where LowWM observers actually perform *better* than HighWM observers in this condition). Before discarding this explanation, however, another possibility must be considered: perhaps a real difference in the ability of the two WM groups to discount the illuminant may be masked by a difference in the task demands of the two experiments. In particular, good performance in these two experiments may have required different strategies, strategies that may have been easier for one or the other WM group to implement more effectively.

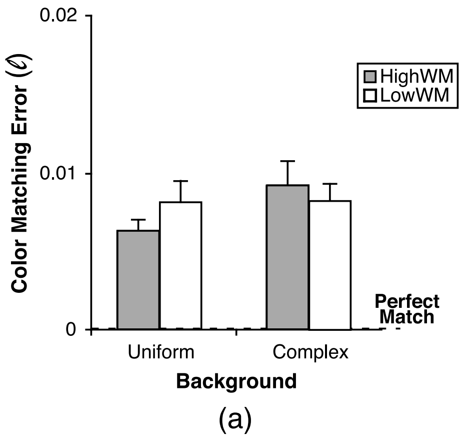
LowWM and HighWM individuals often employ different strategies when performing a task. Moreover, it is not strictly the case that strategies employed by HighWM individuals are more effective than those employed by LowWM individuals [15,27]. Perhaps the structure of the current experiment led the groups to employ different strategies that may not have been equally effective. Since previous research suggests that viewing strategy in particular can affect color constancy [8], a difference in viewing strategy between these two groups is a potential candidate for creating the differences observed here.

In the current experiment, observers heard a beep from the computer every 1 s and were instructed to shift their gaze from the reference to the test display (or vice versa) every time they heard the beep. They were not instructed as to where on the two displays to look; they were told only to shift their gaze from one display to the other while setting the color of the central test patch to look like the central reference patch. Since HighWM individuals sometimes allocate their excess executive attention "resources" to completing the task at hand even when it is not explicitly required of them [15], perhaps they used these resources to maintain attention on the two central patches, shifting their gaze directly from the central reference patch to the central test patch at each beep without allowing their gaze to wander over the background. By contrast, LowWM observers may have been less able to maintain focus on these central patches and thus may have allowed their gaze to wander around the background more often (which has previously been shown to improve color constancy [8]). This could result in the differences in performance observed here: LowWM observers performed better than HighWM observers in the complex-background condition because their viewing strategy allowed them to take in more of the chromatic context in the background.

If this strategy explanation were correct, it could be masking a real difference in the number of cues required by LowWM and HighWM observers for a similar level of color constancy. As was hypothesized to explain the successive color-constancy results, it still may be the case that LowWM

Table 1. Comparison of Values for the CCI for the *l* Axis for Simultaneous Color Constancy ("Simultaneous"), from Observers in the Current Study, and for Successive Color Constancy ("Successive"), from Different Observers Reported by [9], for the Two Background Conditions

	Uniform Background			Complex Background		
	Simultaneous	Successive	Difference	Simultaneous	Successive	Difference
HighWM	0.26	0.47	−0.21	0.17	0.53	−0.36
LowWM	0.28	0.17	0.11	0.52	0.49	0.03



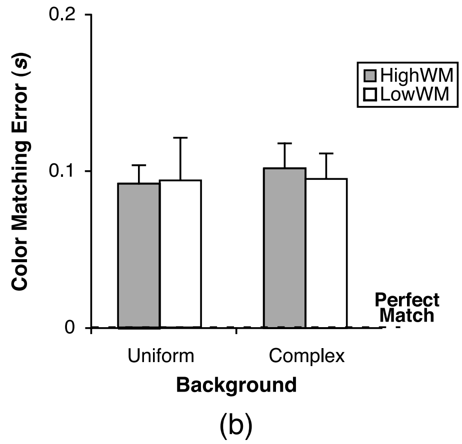


Fig. 4. Color-matching measurements (for trials where the reference and Test Illuminants were the same) averaged across Reference Colors and Illuminants for (a) the l axis and (b) the s axis. Results are separated by background condition (uniform and complex). Gray [white] bars indicate values for HighWM [LowWM] observers. The vertical axis indicates the color-matching error, calculated as the absolute value of the difference between the observer's match and the true Reference Color chromaticity. A smaller value indicates better color-matching ability. "Perfect match" refers to a color-matching error of 0. Error bars indicate standard errors of the mean. No difference between HighWM and LowWM observers was significant.

observers have difficulty inhibiting the irrelevant illuminant information from their representation of the central patch when few cues are available to help them, or they may have difficulty accessing this representation during the task. The difference is that, in this simultaneous color-constancy experiment, the LowWM observers' strategy may be more helpful to their color constancy than the HighWM observers' strategy. Under a different experimental paradigm, LowWM observers may not show the advantage that they do here. Future research could investigate whether instructing observers to allow their gaze to wander over the background would restore the superior color constancy shown by HighWM compared to LowWM observers in the successive color-constancy study.

The results of this study highlight the importance of considering the task demands of a particular paradigm, as well as the instructions given to observers [24], when designing a color-constancy experiment. More importantly, the results of this experiment and the previous work on successive color constancy provide clear evidence that individual differences in high-level cognitive mechanisms are related to individual differences in color perception. These mechanisms include ones other than those that may operate while an illuminant-independent representation is being held in memory, since a relation between WM and color constancy persists even when the memory retention interval is eliminated.

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