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Research Article

Daltonization Enhances Working Memory Performance in Color Vision-deficient Observers

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ABSTRACT

Daltonization methods are image adaptation techniques that adjust screen colors to aid people with color vision deficiency (CVD). Though their effectiveness in boosting the hue's dissimilarity has been documented, it was not entirely clear to what extent they improve color processing. The purpose of our study was to measure the direct contribution of daltonization to color working memory.

Two different types of daltonization methods were tested: severity–based (SB) enhancing red-green contrast, and type-based (TB) enhancing blue-yellow contrast. We used simple behavioral tasks while measuring speed and accuracy. Participants in our experiments were asked to find the target color among the two presented choices (2AFC task). The colors were either presented simultaneously (perception task) or sequentially (memory task).

Both daltonization methods significantly improved CVD participants' performance on both tasks and with both measures, with stronger effects found in the memory task. The effects of the TB method were robust across tasks, while the effects of the SB method were smaller and dependent on the level of enhanced red-green contrast when colors needed to be remembered.

We confirmed the previously reported effects of daltonization and demonstrated that these effects extend to the level of short-term retention of color information. Based on the differences in the effects of the two daltonization methods under varying cognitive demands, we identified the specific conditions under which each method supports cognitive functions. Consequently, our findings enable precise application decisions: using daltonization for promoting fast discrimination vs. enhancing memory during material learning.

Keywords: Color Vision, Color Vision Deficiency, Working memory, Daltonization, Color correction

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Introduction

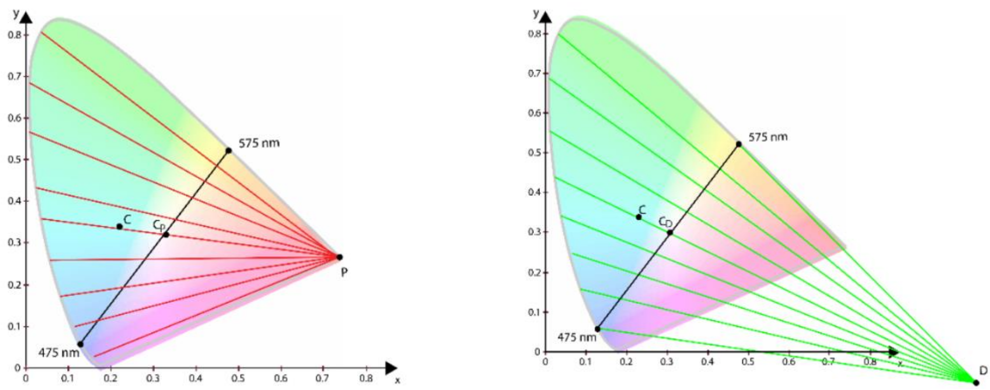
Color is a fundamental cue for interpreting the visual environment, enabling efficient segmentation of the visual scene but also shaping our mental representations of the world. It plays an essential role in encoding, storing, and retrieving information, and aids in recognizing and categorizing important objects, such as identifying ripe food (Witzel & Gegenfurtner, 2018). However, approximately 8% of European males and 0.4% of females (Birch, 2012) experience some degree of color vision deficiency (CVD) – a condition that results in the reduced or lost ability to discriminate certain colors. Complex gene mutations prevent the functional expression of one or more photopigments in the retinal cones of CVD observers (Neitz & Neitz, 2011); thereby compromising the initial stages of color processing.

Almost 98% of CVD observers exhibit a deficit or dysfunction in M or L pigments, leading to reduced discrimination of greenish and reddish hues (Neitz & Neitz, 2011). The most severe reduction happens in the case of *dichromacy* when one type of cone pigment gene is absent – in *deuteranopia*, the cones that would normally express M opsin express L opsin instead, and vice versa in the case of *protanopia* (Davidoff, 2015). The milder and the most common form of CVD is called *anomalous trichromacy*, in which three cone types are present, but two of them are from the same class – S, and two M cone types in *protanomaly* and S and two L cone types in *deuteranomaly* (Davidoff, 2015). The peak spectral sensitivities of the two M or L cone types are closer together than usual, lowering the threshold contrast for color differences in the respective spectral regions. The proximity of these peak spectral sensitivities may vary among anomalous trichromats and can affect the extent to which their color discrimination ability is reduced (Boehm et al., 2014). Anomalous trichromacy is considered a mild to moderate deficiency, within which individuals have a reduced color gamut compared to individuals without color deficiency but can still retain some degree of red-green discrimination.

The hues whose discrimination is impossible or reduced for CVD observers (i.e., *confusion hues*) are located along specific lines within the CIE 1931 space known as confusion or pseudo-isochromatic lines (Figure 1). These lines connect the edge of the diagram to the confusion points specific to the CVD type. For instance, for the protanopes, the confusion point (P) is the light that maximally stimulates the affected L cones (Figure 1a). Confusion hues are perceived as achromatic or as more/less saturated *residual hues*, i.e., hues that are distinguishable for CVD observers. In deuteranopia and protanopia, those hues are bluish and yellowish (for details, see Pridmore, 2014). They are represented in Figure 1 by a line connecting the white point and fixed monochromatic stimuli, which should correspond to the unique blue (475nm) and unique yellow (575nm) for whose perception the red-green color channel is irrelevant (Brettel et al., 1997). The confusion lines are slightly different for protanopes and deuteranopes due to the differences in the spectral sensitivities of M and L cones (Figure 1).

Figure 1

CIE 1931 Chromaticity Diagrams



(a) (b)

Note. CIE 1931 chromaticity diagrams showing confusion lines in red for protanopes (**a**) and in green for deuteranopes (**b;** Milić, 2016). The black line represents chromaticities that protanopes and deuteranopes easily discriminate. All colors along a confusion line are perceived as the same color, corresponding to the intersection of the confusion line and the chromatic line. For example, color C will be perceived as color C_D by deuteranopes and color C_P by protanopes.

In recent decades, humans have started to spend significantly more time not looking directly at natural objects but at their representations on various screens. For individuals with CVD, this represents a unique opportunity to overcome their deficit as screen colors could be corrected. As a result, different methods of image adaptation, known as *daltonization methods*, have been developed (Kotera, 2012; Machado et al., 2009; Ribeiro & Gomes, 2019). To compensate for the reduced chromatic input, these methods usually enhance chromatic and/or lightness contrast between confusion hues (Commission Internationale de l'Eclairage, 2020). The success of these methods has been predominantly tested with computer simulations (Commission Internationale de l'Eclairage, 2020; Shen et al., 2021; Zhu et al., 2021). When human participants are involved, the tests primarily focus on simple color discrimination (Bonanomi et al., 2017) or the observers are asked to subjectively evaluate differences between the original and corrected images or the corrected images themselves (Chen et al., 2024; Shen et al., 2021; Zhou et al., 2024; Zhu et al., 2019). However, current findings are insufficient to conclusively determine the effectiveness of these methods for color information processing in CVD observers since this process involves more than simply discriminating between incoming hues. Knowing what the red color is, or recognizing all the red objects in the scene, requires that the incoming signal be related to previous knowledge stored as a mental representation. Given the complex mechanism of color processing, we can ask to what extent daltonization methods can facilitate this process beyond basic visual discrimination.

In this study, we focused on the color working memory (CWM) of individuals with CVD, which previous studies have not directly addressed. CWM temporarily retains and manipulates information for the ongoing task/behavior (Baddeley & Hitch, 1974) and serves as a critical interface between perception and long-term memory, where color knowledge is stored. The ability to maintain color information in CWM is fundamental for various everyday activities, such as performing targeted visual searches (e.g., identifying a red apple among green ones) or navigating effectively (e.g., locating a specific metro line while disregarding others). Here, we specifically aimed to investigate, in terms of accuracy and reaction times (RTs) in a cognitive task, the extent to which daltonization methods can improve short-term retention of color information for individuals with CVD. From a scientific perspective, understanding the cognitive benefits of on-screen color adaptation provides insights into the cognitive processing mechanisms of individuals with chronically reduced visual input and probes their mental representation in comparison to the control group. From a practical standpoint, the obtained results could offer valuable insights into the efficacy of daltonization in supporting individuals with CVD.

According to the CATMET model (Bae et al., 2015), the retention of color information relies on both the continuous representation of a specific hue and its categorical classification, e.g., red or blue. In CVD individuals, reduced visual input obstructs the retention of continuous color information but also contributes to the shaping of distinctive mental representations of colors and unique patterns of color categorization (Bonnardel, 2006; Nagy et al., 2014; Uchikawa, 2014). In this study, we singled out the visual component of the CWM and examined how two recently proposed daltonization methods (Keresteš et al., 2023), which differ in their approach to enhancing discriminability, affect the memory of confusion hues for CVD observers. The **type-based (TB) method** enhances the blue-yellow axis by moving colors perpendicular to the confusion lines. By altering the chromatic content in this orthogonal direction, **TB** adaptation creates distinct color differences that all CVD individuals readily perceive. In contrast, in the **severity-based (SB) method**, colors are shifted along the confusion lines in the opposite direction of the simulated CVD projection, thereby boosting red-green contrast. This approach is conceptually straightforward—improving discriminability precisely where CVD individuals struggle the most and has proven especially beneficial for the most common group of milder CVDs.

We tested these methods in a task where participants were required to briefly retain a single color, rather than complex images, to minimize reliance on compensatory strategies commonly employed by CVD participants in more complex tasks (Gegenfurtner et al., 1996; Shepard & Cooper, 1992). To gain insights into the specific effects of daltonization on different levels of cognitive processing, we directly compared the performance in a memory task to the performance in a simple perceptual discrimination task. The novelty of our study lies not only in confirming that daltonization enhances discrimination along confusion lines—a finding that could be expected even when we add a memory component to the task — but also in conducting behavioral tests to evaluate the magnitude of these effects for two distinct daltonization methods and, for the first time, directly comparing the effects in tasks with and without memory load.

The practical goal of our study was to behaviorally evaluate the **SB** and **TB** daltonization methods, both of which have shown promising outcomes in previous assessments (Keresteš et al., 2023). The **SB** method preserves the overall naturalness of a scene, which is critical for user acceptance, particularly with natural imagery, and milder CVDs. In contrast, the TB method has proven to be beneficial for artificial images, where naturalness is less of a priority (Keresteš et al., 2023). Although both methods have been shown to yield user-preferred outcomes under certain conditions, practical implementations must consider not just subjective preference and immediate perceptual gains, but also whether improved chromatic contrast translates into measurable cognitive benefits. Therefore, the results of our study could guide the selection of daltonization strategies tailored to the task — e.g., promoting speedy and accurate recognition of color-coded signals versus facilitating learning or memorization of color-labeled content, thereby providing a foundation for task-specific optimization of color accessibility solutions for CVD observers.

The idea that daltonization methods can be behaviorally evaluated through implicit measures in cognitive tasks is supported by a few prior studies with promising results. Flatla and Gutwin (2012) showed that their SSMR recolor method significantly increased accuracy and reduced RTs for CVD participants in a perceptual task. Simon-Liedtke and colleagues (2015) proposed a visual search task (VisDem) in which observers answered whether the presented image (with or without correction) matched the previously presented statement about the colors in the picture. The authors demonstrated that some of the available daltonization methods have the potential to improve participants' accuracy in this task but not their RTs (Simon-Liedtke & Farup, 2016). The VisDem task is relevant to our research as it incorporates a memory component. However, in this task, participants were not asked to memorize colors themselves but rather a text associated with images. Nevertheless, these studies provide a broader framework for comparing the effectiveness of the SB and TB methods with those previously tested in behavioral tasks.

In line with the practical goal of our study, our methodological decision was to achieve a high degree of ecological validity. We decided to conduct the testing under conditions typical for our participants – on the screens of the devices they regularly use (without any pre-configured software color corrections) rather than in laboratory settings. This approach allowed us to determine whether the selected methods can genuinely assist individuals with CVD in their everyday use of color content on screens.

Method

Participants

Participants were volunteers gathered through social networks. We estimated the number of participants using the G*Power 3.1 software (Faul et al., 2007). Due to the lack of prior studies with a comparable design, to determine the sample size for the within-between interaction, we used a medium effect size (f = 0.25; Cohen, 1988), an α = 0.05, and a power = 0.95. The power analysis indicated a total sample size of 20. However, considering our decision to conduct the whole process in a natural environment for our participants, we opted for a larger sample than suggested and the one used in previous studies with CVD observers conducted in laboratory conditions (Flatla & Gutwin, 2012; Simon-Liedtke & Farup, 2016). We recruited 23 participants with CVD (M_{age} = 37.7; 1 female) and 23 matched participants with typical color vision (M_{age} = 37.3; 1 female) for the control group.

Participants were selected based on their results on the online color vision test which uses cone isolation to test the sensitivity of each type of cone (enchroma.co.uk). In the CVD group, 17 participants were classified as deutans, while 6 were classified as protans, which is consistent with the prevalence of the two types of red-green color vision deficiency (Neitz & Neitz, 2000).

Participants signed the informed consent before taking part in the study. The study was approved by the ethical committee of the Psychology Department at the University of Novi Sad and was conducted according to the ethical norms of the Helsinki Declaration.

Stimuli

We selected two sets of color pairs from pseudo-isochromatic lines (in further text: PL1 and PL2) in CIELab space, separately for protan and deutan conditions. Each line was derived by ensuring a controlled shift in hue, with a constant Euclidean distance along the b-axis (Δb=0.4). This approach was taken to maintain a consistent step in color appearance while holding lightness constant (L=0.5), as standardized luminance levels are crucial in isolating hue differences (Fairchild, 2013; Wyszecki & Stiles, 2000). By doing so, we minimized the influence of lightness cues and ensured that any difficulty in discrimination arose primarily from chromatic differences.

The precise values for the protan and deutan projections were calculated via rotation in a polar coordinate system with angles θ_{p} = -11.48° and θd = -8.11 (Kuhn et al., 2008). These angles correspond to known confusion axes for the respective types of CVD, allowing us to place stimuli precisely along and around lines where hue discrimination is known to be diminished for these observers. Color pairs were then selected from opposite sides of the dichromatic gamut plane such that their color difference (ΔE) measured 0.2 in CIELab space. For observers with typical vision, this ΔE ensures that colors are easily distinguishable. However, for dichromats—who map both colors onto the same confusion point—the effective difference (ΔEd) is zero, making them indistinguishable. For anomalous trichromats, the apparent color difference (ΔEat) lies between 0 and 20, depending on severity. Table 1 provides CIELab coordinates of the protan and deutan stimuli.

Table 1

CIELab Coordinates of Color Stimuli Pairs Selected From the Two Deutan and Protan Pseudo-Isochromatic Lines (PL1 and PL2)

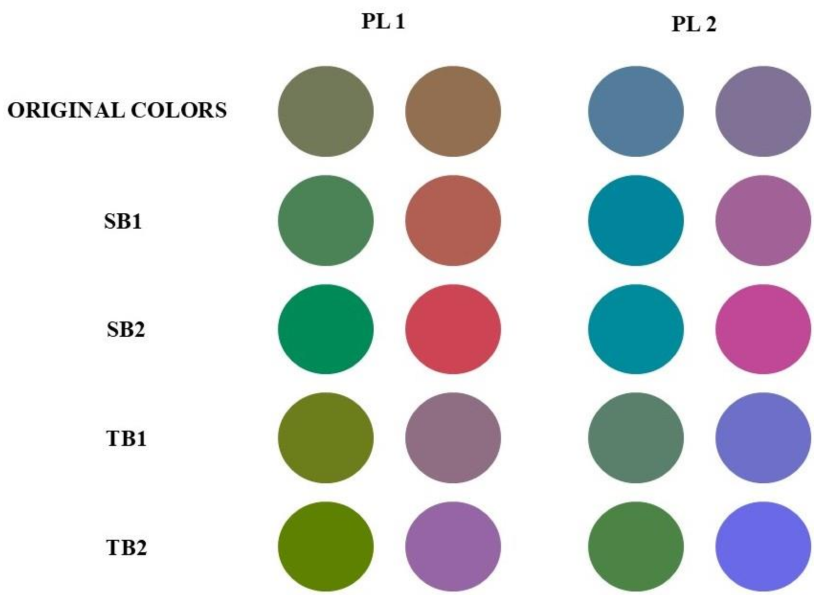
PL	Deutan						Protan					
	Color 1			Color 2			Color 1			Color 2		
	L	a	b	L	a	b	L	a	b	L	a	b
1	0.5	-0.09	0.19	0.5	0.11	0.21	0.5	-0.08	0.18	0.5	0.12	0.22
2	0.5	-0.09	-0.21	0.5	0.11	-0.19	0.5	-0.08	-0.22	0.5	0.12	-0.18

After selecting the original colors, we applied two daltonization strategies to increase their discriminability for CVD participants. In the SB method, colors were shifted along their original confusion lines, effectively increasing red-green contrast, while in the TB method, colors were moved perpendicularly to those lines to enhance blue-yellow contrasts. Both methods were applied at two levels to represent mild and more pronounced adjustments, with level 1 involving a moderate color shift (ΔE_{76} = 0.6) and level 2 a slightly larger shift (ΔE_{76} = 1.0).

Figure 2 illustrates an example of how the protan colors appear before and after daltonization at both levels. The CIELab coordinates of colors after daltonization are given in the Supplementary Materials.

Figure 2

Illustration of Color Pairs From the Protan Pseudo-Isochromatic Lines (PL1 and PL2) Before Daltonization (Original Colors), After SB Method (Levels 1 and 2), and After TB Method (Levels 1 and 2)



Procedure

The study was conducted online and hosted on a protected personal website. We used custom JavaScript code written for this purpose. The participants accessed the study via a computer (desktop or laptop). Access to the experiment was not available through other mobile devices. In the first step of the procedure, participants were directed to the EnChroma website and asked to take an online CVD test. After that, they were required to check the box with their results provided on the first page of the study.

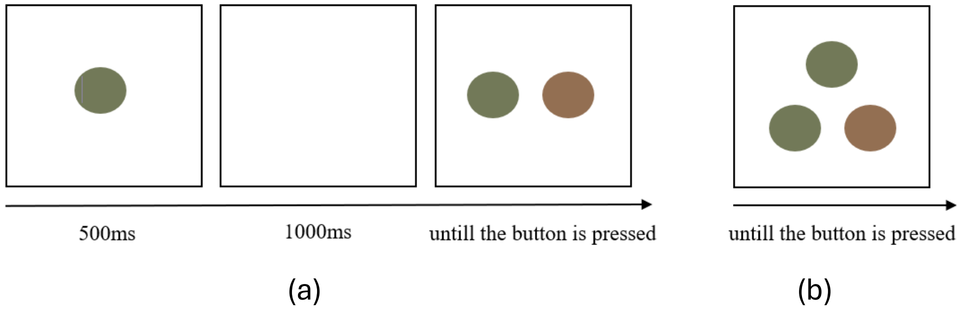
According to their results, participants were assigned either to one of the experimental groups (deutan or protan) or to the control group (from which they were randomly assigned to the deutan or protan condition). The conditions differed only in the colors used as stimuli. At the beginning of the study, participants provided demographic information (gender, age, occupation, and, in the experimental group, their personal experience with color vision deficiency).

In the experimental part of the study, participants performed four blocks of 2AFC tasks. In the first and third blocks, they performed a delayed 2AFC, which required retention of the target color in the working memory, i.e., a memory task (Figure 3a). A single target color was presented at the center of the white screen for 500ms, followed by the blank screen for 1000ms. After that, two colors would appear left and right from the screen center and participants had to indicate which of the colors matched the previously presented target by pressing the keyboard keys (S for left and L for right). The test colors stayed on the screen until the response was made. Before each target, a white noise screen was presented for 500ms to avoid the aftereffect of previously displayed color stimuli.

In the second and fourth blocks, stimuli were presented simultaneously, meaning that participants had to discriminate displayed colors perceptually. In this type of 2AFC task, the target color was presented centrally on the upper part of the screen, while the two test colors were presented below, left and right from the center of the screen (Figure 3b). Again, participants pressed S or L on the keyboard to indicate which test stimuli matched the target in color. They had no time limit for the answer. In this task, there was a white noise screen between the trials shown for 1000ms to prevent color aftereffects.

Figure 3

Procedure for (a) Memory (Delayed) and (b) Perceptual (Simultaneous) 2AFC Task



Each block consisted of 40 trials. There were 10 color pairs: color pairs from PL1 and PL2 were shown in each of the five conditions – original colors, SB daltonization level 1 (SB1), SB daltonization level 2 (SB2), TB daltonization level 1 (TB1), and TB daltonization level 2 (TB2). Each color pair was shown four times so that both colors could become the targets, and that the correct answer could be once on the left and once on the right side of the screen. Within each block, trials were shown randomly for each participant. The whole procedure took about 30 minutes.

Results

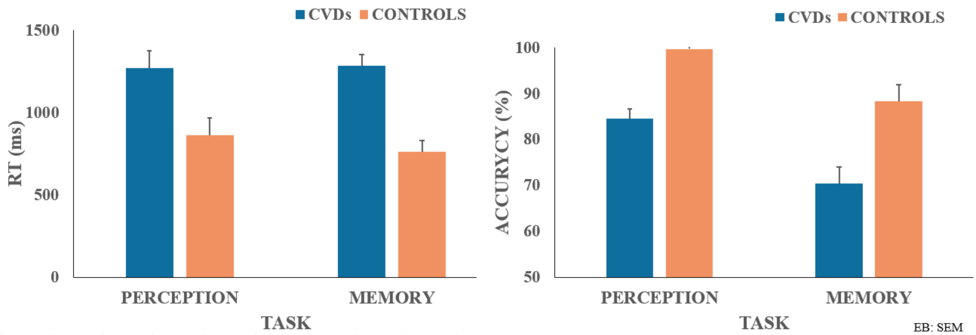
Participants' groups and tasks

The first analysis examined the performance of the experimental versus the control group across the two tasks (perception and memory) with the originally selected colors, before the corrections were made. This analysis was crucial for assessing whether implicit measures in the cognitive task accurately reflected the anticipated differences between the groups, given their color discrimination abilities. We conducted two mixed ANOVAs with the participants’ group as a between-subjects factor and task as a within-subjects factor using two dependent variables: RTs (obtained only on the correct answers) and accuracy.

RTs. The analysis showed a significant main effect of the participants' group - CVD observers were significantly slower than controls in both tasks (F(1,44) = 20.41; p = .00; η_p^2 = .32). As shown in Figure 4, the differences in RTs between the two groups were pronounced, with the memory task showing up to 500ms advantage for the control group. There was no significant interaction between the group and task (F(1,44) = .64; p = .42; η_p^2 = .01).

Figure 4

RTs and Accuracy in Perception and Memory Task for CVD and Control Participants



Accuracy. The accuracy analysis also showed a significant main effect of the group; the CVD group was significantly less accurate in both tasks (F(1,44) = 22.9; p = .00; η_p^2 = .34). While accuracy in the perception task was nearly perfect for the control group, it dropped to 84% for the CVD group (Figure 4). We also observed a significant main effect of the task: as expected, both groups were more accurate in the easier perception task (F(1,44) = 28.2; p = .00; η_p^2 = .39). There was no significant interaction between group and task (F(1,44) = .31; p = .57; η_p^2 = .01) indicating that both groups performed comparably on the two tasks, albeit with notable differences in their levels of success.

Daltonization

Our main analysis focused on the effects of the two types of daltonization methods on participants' performance in both tasks. We conducted two mixed ANOVAs with the participants' group (CVD/controls) as a between-subjects factor and two within-subjects factors: task (perception/memory) and daltonization (original/SB1/SB2/TB1/TB2) using two dependent variables – RTs (obtained only on the correct answers) and the percentage of correct answers.

RTs. A significant main effect of the group was observed in the expected direction (F (1,44) =4.21; p=.04; η_p^2=.09), with the control group producing faster responses. We found a strong main effect of daltonization (F(4,176) = 89.23; p = .00; η_p^2 = .67) – in both tasks, all participants showed a significant performance enhancement after colors were corrected. This result was anticipated, given that daltonization increases the perceptual distance between colors. The main effect of the task did not reach statistical significance (F(1,44) = 3.43; p = .07; η_p^2 = .07). We also observed significant interactions between daltonization and the other two factors, which provided valuable insight into the specific effects of this method on participants' performance in cognitive tasks and which will be discussed in the following text.

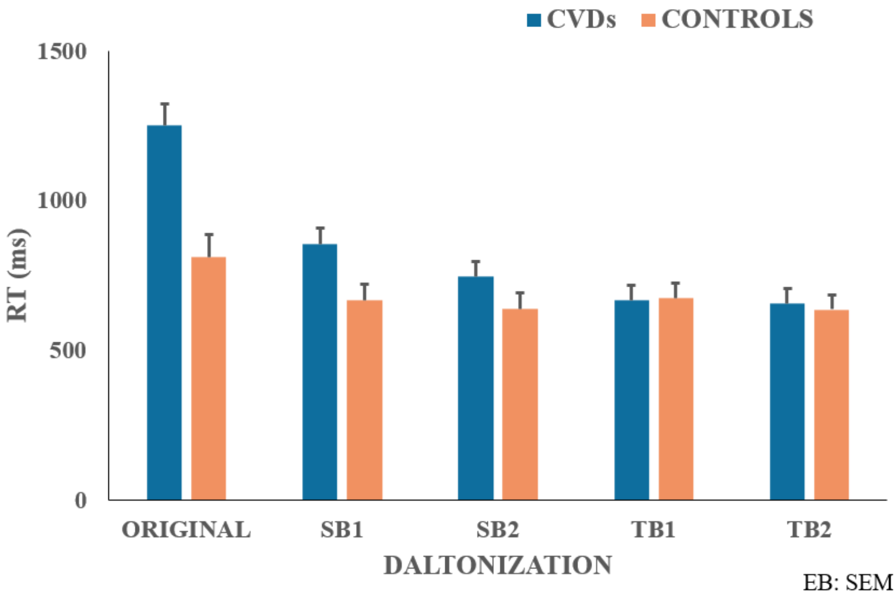
First, a significant interaction between daltonization and participants' group was observed: when colors were daltonized, RTs for CVD participants decreased to the level of RTs for control participants discriminating the original colors (F(4,176) = 28.79; p = .00; η_p^2 = .39; Figure 5). This was confirmed by an LSD post-hoc test, which showed no significant differences between the original color condition in the control group and all daltonization conditions in the experimental group.

For the CVD group, daltonization significantly reduced the task-solving time – TB method at both levels reduced RTs by as much as 600ms with no significant differences between the two levels (p = .74; Figure 5). On the other hand, the effect of the SB method depended on its level, favoring level 2 (p = .00). Moreover, even level 2 of the SB method showed a smaller effect than both levels of the TB method (both p = .01).

For the control group, the recorded acceleration due to daltonization was noticeably smaller – the greatest speed-up compared to the time required for original colors occurred with the TB2 method, amounting to about 180ms (Figure 5). This is possibly a ceiling effect; the initial RTs were already low, and there was not much room for improvement.

Figure 5

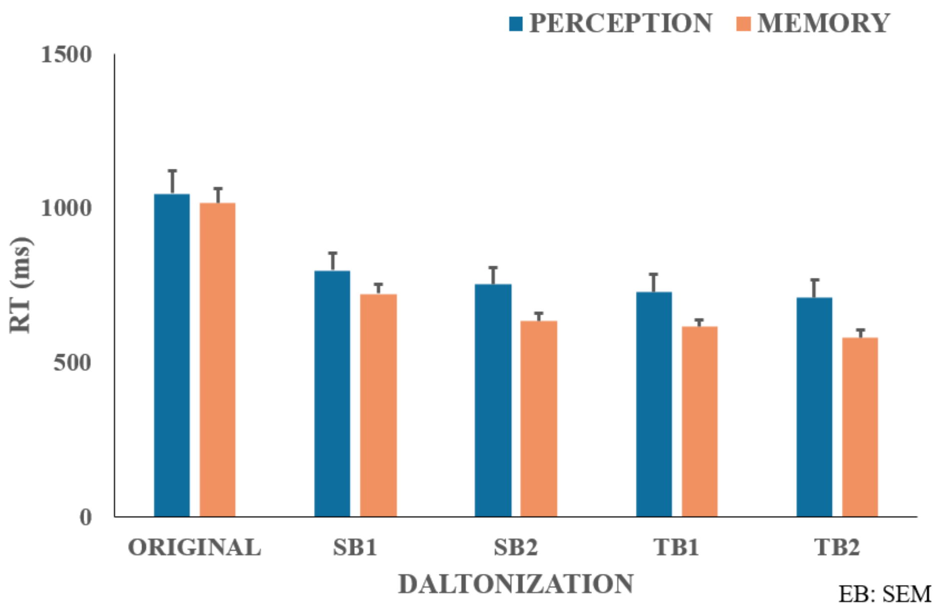
RTs for CVD and Control Participants With Original and Daltonized Colors



Daltonization also significantly interacted with the task – for both groups of participants, the RT enhancement after daltonization was more pronounced in the memory than in the perception task ($F(4,176) = 2.61$; $p = .04$; $\eta_p^2 = .06$; Figure 6).

Figure 6

RTs in Perception and Memory Tasks for Both Groups and With Original and Daltonized Colors



The LSD post-hoc test revealed that, on average, participants required the same amount of time for the perception and memory tasks with the original colors (p = .22) as the difference in task-solving speed between CVD participants and controls was similar in both tasks (see Figure 4). However, this interaction demonstrated a specific effect of color correction on the memory task, applicable to both levels of both types of daltonization (Figure 6).

Again, for the TB method, there was no difference in RTs regarding its level both in perception (p = .52) and the memory task (p = .18). For the SB method, participants were significantly faster with level 2 in the memory task (p = .00), while the difference in the perception task was not significant (p = .06).

The interaction between the participants' group and the task was not statistically significant (F(1,44) = 3.43; p = .02; η_p^2 = .04), nor was the three-way interaction between the participants' group, task, and daltonization ($F(4,176) = .02$; $p = .99$; $\eta_p^2 = .00$).

Accuracy. We recorded all three main effects in the expected direction – the accuracy was lower in the CVD group ($F(1,44) = 8.8$; $p = .00$; $\eta_p^2 = .17$), the accuracy increased in each daltonization condition ($F(4,176) = 30.14$; $p = .00$; $\eta_p^2 = .41$), and participants were more accurate when performing the perceptual task ($F(1,44) = 23.41$; $p = .00$; $\eta_p^2 = .34$). Then again, the complex impact of daltonization methods on participants' performance becomes apparent only when considering the interactions observed between the factors.

As in the RT analysis, we recorded a two-way interaction between daltonization and participants group ($F(4,176) = 17.1$; $p = .00$; $\eta_p^2 = .41$) as well as a two-way interaction between daltonization and task ($F(4,176) = 14.29$; $p = .00$; $\eta_p^2 = .25$). These results confirmed our previous findings regarding the stronger effects of daltonization for CVD participants, especially in the task that required color memory. As in the RT analysis, the interaction between the participants' group and the task was not statistically significant ($F(1,44) = 0.13$; $p = .72$; $\eta_p^2 = .00$).

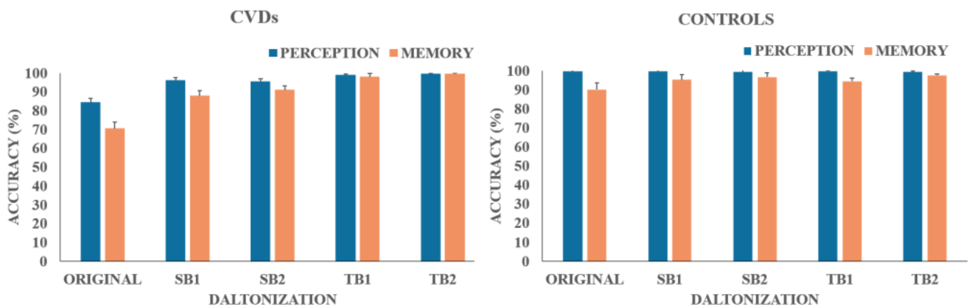
Finally, a significant three-way interaction between group, daltonization, and task was also recorded ($F(4,176) = 2.79$; $p = .03$; $\eta_p^2 = .06$). Figure 7 illustrates the different effects of daltonization on the performance of the two groups depending on whether the colors needed to be remembered or just perceptually discriminated.

For the control group, we observed a ceiling effect for accuracy regardless of the type and level of daltonization. Still, in the memory task, level 2 of the TB method increased accuracy to 98% compared to 90% recorded for the original colors (Figure 7).

For the CVD group, we observed a significant increase in accuracy after applying daltonization in both tasks. Examining the effects of the two types of daltonization, we can see similar patterns observed in the RT analyses. Namely, for the SB method, there was no difference between level 1 and level 2 in the perception task ($p = .6$), but a stronger effect was recorded for level 2 in the memory task ($p = .00$). The TB method once again demonstrated a robust effect which remained consistent across two levels in both perception ($p = .72$) and the memory task ($p = .39$). Most importantly, Figure 7 depicts how TB daltonization implemented at either level across both tasks elevates the performance of the CVD group to match that of the control group achieving almost perfect accuracy of 100%.

Figure 7

Three-Way Interaction Between Participants Group, Daltonization, and Task on Accuracy



Discussion

This study examined the impact of screen color correction (i.e., daltonization methods) on color processing in CVD observers, aiming to extend our understanding of this issue beyond basic visual discrimination. We questioned to what extent daltonization could enhance CVD performance in tasks engaging CWM, a critical cognitive component that bridges visual perception and mental representations. We tested two types of daltonization methods: severity–based (SB), enhancing red-green contrast, and type-based (TB), enhancing blue-yellow contrast, focusing on implicit measures of speed and accuracy in simple cognitive tasks with single color targets. To assess the practical efficacy of these methods, we conducted research in non-laboratory conditions, focusing on the ecological validity of the obtained results.

Our initial analysis with non-corrected colors showed the expected lower performance of CVD participants compared to the control group in both accuracy and response time in the memory task. This observed trend mirrored the trend present in the perceptual discrimination task. Based on the absence of a significant interaction between the participants' group and task type, we can conclude that CVD participants in our study performed the memory task comparably to the control group, with performance differences attributable to CVD-related deficits, just like those observed at the level of perceptual discrimination. Notably, CVD participants achieved relatively high accuracy, with approximately 84% in the perception task and 70% in the memory task. These results align with the performance of CVD observers in previous studies (Flatla & Gutwin, 2012; Simon-Liedtke & Farup, 2016), indicating that most of our participants have mild to moderate deficiencies. Thus, our conclusions primarily concern this group of CVD observers.

Our main findings revealed strong effects of both daltonization methods on CVD participants' performance in the memory task – when colors were adjusted to accommodate their deficits, participants exhibited significantly faster response times and higher accuracy. The applied color corrections, contingent upon the type and level of application, accelerated CVD participants by 423ms to 645ms and increased their accuracy by 17 to 28 percent, thereby clearly demonstrating their effectiveness in tasks that require brief maintenance of color information. Moreover, in the TB condition, CVD participants reached performance levels comparable to those of non-CVD participants. Similar effects were recorded for the perceptual task – both levels of daltonization methods significantly accelerated CVD participants and increased their response accuracy. Given that daltonization increased the perceptual distance between the colors, it enhanced the performance of the control participants as well; however, the effect was considerably less pronounced, as they already performed near the accuracy ceiling with non-corrected colors.

Our findings suggest that adapting visual input significantly facilitates cognitive processing following perceptual discrimination, in an expected manner. Moreover, we found even stronger effects in the memory task, compared to the perceptual task. These findings are highly significant for future studies on CWM, especially in the context of CVD, as prior studies did not directly compare the effects of daltonization across tasks involving different cognitive processes. Within the CATMET model of CWM (Bae et al., 2015), this could mean that the color correction brought stimuli closer to category prototypes, making them easier to categorize and label. As a result, both the continuous and categorical channels of CWM could benefit from daltonization, leading to a more pronounced effect in the memory task. This hypothesis is particularly supported by the finding that CVD participants experienced a significant memory benefit from the TB method. This method shifts colors away from the confusion line, aligning them more closely with color categories that are identifiable for these observers.

Our results indicated important differences between the effects of the two daltonization methods. The TB method showed robust effects, independent of its level, demonstrating excellent performance across both tasks. This method reduced participants' RTs by as much as 645ms, effectively halving them, compared to the results obtained with original colors. Moreover, it brought the performance of CVD observers to the level of the control group. The absence of significant differences between the two levels of application of this method shows that even a moderate color shift within this approach (in our study, a shift of ΔE_{76} = 0.6) was sufficient to produce such an effect. In terms of accuracy, this method elevated the performance of CVD participants to nearly 100%. In the memory task, this represented an improvement of approximately 30%. We did expect that the enhancement of the blue-yellow contrast would particularly improve performance, especially with artificial stimuli like single colors. However, here we show precisely how much it was enhanced both in terms of time and accuracy. On the other hand, the SB method exhibited slightly lower efficacy: level 1 accelerated CVD participants by 400ms across both tasks, which is 200ms less than the improvement observed with level 1 of the TB method. Regarding accuracy, after level 1 of the SB method, accuracy in the perceptual task increased by 10% and in the memory task by slightly less than 20%. Importantly, the SB method also showed a dependence on both the daltonization level and the type of task—the level of daltonization significantly influenced both speed and accuracy in the memory task.

Our findings support existing attempts to evaluate daltonization methods behaviourally rather than solely through subjective user assessments. Like Flatla and Gutwin (2012), we found improvements in performance among CVD participants following color correction in the perceptual task on both measures, with the improvements being comparable. However, it is particularly noteworthy to compare our findings with those of the study employing the VisDem task (Simon-Liedtke & Farup, 2016), where the most effective correction improved CVD accuracy by 15%, whereas we observed a nearly 30% improvement with the TB2 method. More importantly, while these authors found no effects of color correction on participants' RTs, our participants exhibited significant acceleration up to 650ms. Furthermore, we showed even stronger effects in the memory task compared to the perceptual task. The discrepancies between the two studies' results could stem from differences in daltonization methods, stimuli, or task demands. As noted earlier, VisDem required participants to remember the text, i.e., verbal content, while our task required participants to remember the color itself. Our task involved a visual component of the WM, potentially making the effect of daltonization more pronounced in participants' performance. These insights provide important guidelines for future studies on daltonization and color memory, highlighting the significance of the task-specific demands.

The observed differences between the SB and TB methods provide practical insights into optimizing color adjustments for CVD users, surpassing subjective preferences and mere perceptual improvements. Prior research indicates that CVD observers prefer the SB method for naturalistic imagery due to its red-green contrast enhancement which preserves global visual coherence (Keresteš et al., 2023). In these contexts, the TB method may distort object recognition and perceptual naturalness, making it less suitable. Conversely, in scenarios involving artificial color-coded materials—such as maps and charts, the TB method is often favored for its strong, orthogonal enhancement of blue-yellow contrasts. Our findings build upon these preferences by demonstrating that the choice of daltonization method should consider not only image type but also the cognitive demands of the task at hand.

For tasks centered on straightforward perceptual discrimination, especially where maintaining the natural appearance of an image is essential (e.g., viewing photographs or realistic scenes), the SB method may provide adequate improvements. However, the present results show that for more cognitively demanding tasks—such as those requiring the retention of color information—the TB method offers a distinct advantage. Although further research is needed to clarify the underlying cognitive mechanisms, our findings already offer a preliminary guideline: when memory or learning from color-coded information is paramount, the TB method should be carefully considered.

The practical implications of our findings are further reinforced by our methodological decision to allow participants to complete the entire process in their natural environment using their personal computers. This approach also has limitations. Specifically, we did not conduct clinical testing to determine the CVD severity, nor did we have strictly controlled conditions, calibrated screens, and computers with known response times and accuracies. From a scientific standpoint, this indicates that our results represent a preliminary step in understanding the cognitive functioning of individuals with CVD and provide a foundation for further investigations under laboratory conditions. However, regarding the practical contributions of this study, the chosen methodology enabled us to assess the effectiveness of daltonization methods in real-world settings and conditions and across the widest possible population of individuals who experience any kind of CVD to make better generalization from results to everyday conditions. Most participants in our study, who benefited from the applied color corrections, had never undergone clinical testing for CVD and were unaware of their precise diagnosis, despite experiencing difficulties with hue discrimination. Thus, by showing the robust effects of TB and SB methods, we conclude that both methods are effective and hold substantial potential for commercial application without requiring a controlled environment. Future research should extend our work by testing the effectiveness of these methods under more complex conditions. This includes examining their impact on images containing multiple hues presented simultaneously and assessing how well observers recall color-coded information embedded in real-world scenes. By incorporating more natural viewing conditions and additional device types, future studies can refine the practical guidelines derived from this work.

To conclude, our study demonstrated that enhancing visual input improves not only perception but also the subsequent cognitive processing of color information in individuals with CVD, specifically in terms of memory. Despite their extensive experience with reduced visual input, under certain conditions of color correction, CVD participants' performance can match that of control participants in both reaction time and accuracy, which are crucial indicators of cognitive processing. These findings have significant theoretical and practical implications. Theoretically, these findings suggest that, despite impaired visual input, individuals with CVD possess the necessary mechanisms for working memory function that are comparable to those of the control group. This could imply that the visual component of working memory in CVD participants remains intact, such that improvements in visual input led to enhanced visual working memory performance. However, the complete mechanism of CWM in CVD individuals is yet to be explored, particularly in terms of examining whether category-based naming tasks can further clarify how memory benefits arise. Consequently, an important direction for future research is to control for color naming in experiments, both within the control group and among CVD individuals. The primary practical implication of this study is that, regardless of the underlying WM mechanism, appropriate image correction can be highly beneficial for the cognitive processing of CVD individuals in real-world settings.

Conflict of interest

We have no conflicts of interest to disclose.

Data availability statement

Data files are available upon a reasonable request.

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Supplementary Materials

Table A

CIELab Coordinates of PL1 Color Stimuli Pairs After SB1, SB2, TB1 and TB2 Daltonization

Dalton.	Deutan						Protan					
	Color 1			Color 2			Color 1			Color 2		
	L	a	b	L	a	b	L	a	b	L	a	b
SB1	0.5	-0.28	0.19	0.5	0.32	0.21	0.5	-0.27	0.18	0.5	0.33	0.22
SB2	0.5	-0.47	0.18	0.5	0.53	0.22	0.5	-0.45	0.17	0.5	0.55	0.23
TB1	0.5	-0.16	0.45	0.5	0.16	-0.05	0.5	-0.17	0.47	0.5	0.17	-0.07
TB2	0.5	-0.25	0.62	0.5	0.27	-0.24	0.5	-0.27	0.65	0.5	0.29	-0.27

Table B

CIELab Coordinates of PL2 Color Stimuli Pairs After SB1, SB2, TB1 and TB2 Daltonization

Dalton.	Deutan						Protan					
	Color 1			Color 2			Color 1			Color 2		
	L	a	b	L	a	b	L	a	b	L	a	b
SB1	0.5	-0.28	-0.21	0.5	0.32	-0.19	0.5	-0.27	-0.22	0.5	0.33	-0.18
SB2	0.5	-0.47	-0.22	0.5	0.53	-0.18	0.5	-0.45	-0.23	0.5	0.55	-0.17
TB1	0.5	-0.16	0.05	0.5	0.16	-0.45	0.5	-0.17	0.07	0.5	0.17	-0.47
TB2	0.5	-0.27	0.24	0.5	0.25	-0.62	0.5	-0.29	0.27	0.5	0.27	-0.65