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The Effect of Simultaneous Contrast on Color Deficient Observers

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Abstract. *Today, different models and instruments exist to study and model color vision and color vision deficiency. These systems are often modeled at spectral and retinal levels. In this study, we propose a novel approach to set up models and aids for color vision deficiencies, considering the role of spatial color processing in human visual system. In particular, we present the results of a perceptual test to identify the role of the spatial arrangement in color discrimination by Color Deficient Observers (CDOs) and Color Normal Observers (CNOs), using simultaneous contrast effect.*
Keywords: *color vision, human visual system, color, color blindness, color deficiency*

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1. INTRODUCTION

Several standard color vision tests (e.g., pseudo-isochromatic plates, Farnsworth Munsell 100 Hue Test, and Color Blindness Test) assess color deficiencies by employing color arrangements based on confusion lines [1]. These confusion lines are derived from transformations of L, M, and S cone sensitivity curves, which model color blindness at the retinal level only.

Recent studies have highlighted the importance of spatial processing in color vision for both Color Deficient Observers (CDOs) and Color Normal Observers (CNOs). For example, research has shown that CDOs perform better on Ishihara-based charts when larger colored dots are used [2–4] or when the background is varied [5]. These findings underscore the need to incorporate spatial arrangements into color vision testing and modeling, as preliminary experiments [6] have demonstrated the influence of spatial processing on the color perception of CDOs.

Human color vision is mediated by a complex visual pathway, with the retina serving only at the initial stage. After retinal phototransduction, visual signals are transmitted through the optic nerve to the lateral geniculate nucleus and eventually to cortical areas, where final color perception occurs. It is well-established that color perception is not limited to isolated points and that spatial interactions play a fundamental role in the overall color experience (see review in [7]). Thus, color perception is shaped by both retinal signal transduction and spatial processing within the brain [4, 8, 9]. Consequently, modeling color sensation requires a shift from a purely pointwise framework to one that includes spatial processing. Importantly, this complex visual structure largely persists even in color-deficient vision.

Building on these insights, this study investigates the role of spatial processing in the color vision of color-deficient individuals. We developed a perceptual experiment employing a simultaneous contrast configuration—a well-known spatial effect—to further assess and compare color vision in both CDOs and CNOs.

2. EXPERIMENTAL SETUP

Our experimental setup was designed to investigate the color contrast effect for CDOs and comprises two color-matching experiments. These experiments have been developed and implemented as an interactive web application. This web app facilitates extensive data collection and analysis, and by leveraging the accessibility and versatility of a web-based tool [10], we reached a diverse participant pool and enhanced the generalizability of our results.

At the beginning of the test, participants were required to complete a brief survey to gather demographic information, prior experience working with colors, and awareness of having any color deficiency. Following this preliminary step, the main interface presented two small square patches, each surrounded by a larger square forming a different

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background. The patch on the left was displayed against various solid colored backgrounds (*fixed patch*), while the patch on the right (*matching patch*) was consistently shown against a pseudo white noise background (see Figure 1).

Participants were instructed to adjust the color of the *matching patch* on the right to match the color appearance of the *fixed patch* on the left. To facilitate this adjustment, three sliders were provided at the bottom of the screen, corresponding to hue, saturation, and brightness. Users were allowed to modify the color as many times as necessary without any time constraint. Upon achieving a satisfactory color appearance match, participants submitted their responses, and the test proceeded to the next chart. In the current version of the test, each participant was presented with 18 different configurations, derived from 6 color patches, each on two different colored backgrounds and one neutral background, resulting in 12 combinations under test and 6 as a reference.

As an initial study to investigate the effect of spatial context in CDOs using the simultaneous contrast effect, we opted for a straightforward approach by starting with six colors. These colors included the primary colors of both additive (red, green, and blue) and subtractive (cyan, magenta, and yellow) color synthesis. Given that this was an online test conducted in uncontrolled environment, we desaturated the primary colors. This adjustment ensured that the colors fall within a more central region of the device's gamut, avoiding severe gamut mismatch. The primary colors used in this test were selected with the following RGB values:

$$r:\begin{bmatrix}200\\30\\30\end{bmatrix},g:\begin{bmatrix}30\\200\\30\end{bmatrix},b:\begin{bmatrix}30\\30\\200\end{bmatrix},c:\begin{bmatrix}128\\200\\200\end{bmatrix},$$
$$m:\begin{bmatrix}200\\128\\200\end{bmatrix},y:\begin{bmatrix}200\\200\\128\end{bmatrix}$$

To reiterate, each chart was also shown against a pseudo-white-noise background. This solution was been chosen in order to have a configuration without simultaneous contrast effects, which could be produced, on the contrary, by the use of a medium gray or a solid-colored background [11, 12]. Moreover, the use of a white noise background was designed to minimize the effect of the background and reduce any shifts in visual appearance [8, 13].

Given that this test was designed to run on various computers, displays, and browsers, certain constraints had to be imposed on background generation to ensure consistency across different systems. High spatial frequency content is particularly problematic, especially on older displays that use noise-sensitive analog signal formats (e.g., composite), which may cause blurring and shift the uniform distribution characteristic of a white-noise signal towards a Gaussian-shaped distribution centered around the middle grey value. This variability implies that the same stimuli might be rendered differently for each user, complicating the establishment of a common ground truth. To address this issue, we generated a smaller pseudo-white-noise image of 50×50 pixels and upscaled it to a final size of 350×350 pixels using nearest-neighbor interpolation. This resulted in an image composed of 7×7 pixel blocks. Nearest-neighbor interpolation is the simplest method and does not introduce any blurring, thus preventing the distribution from shifting toward a Gaussian shape while ensuring a consistent amount of low-frequency components. The initial 50×50 pixels image was created by assigning a random grey level (between 0 and 255) to each pixel, with the constraint that each of the 256 possible values can only be used a limited number of times. Formally, given a square image with s pixels per side encoded with b bits, 2^b empty bins with a maximum size $d = s^2/2^b$ are created. Each time a pixel value is generated, the corresponding bin is incremented by one. If the bin is not full, the value is assigned to the pixel, and the algorithm moves on to the next one; otherwise, the value is discarded, and a new value is generated. This method reduces "randomness" but ensures that the distribution remains as uniform as possible, as illustrated in Figure 2.

The setup described in this Section has been used for first and the second experiments. For simplicity, we refer to the color combinations as *patch id_background id* as illustrated in Figure 3.

In this work, CIEDE2000 ΔE^* metric [14] was used to quantify the difference between two colors. In our study, it serves to measure the color difference between the fixed patch and the participant's selected matching patch. ΔE^* values represent the magnitude of deviation in color perception, with lower values indicating closer matches and higher values representing greater differences. In general, a ΔE^* value below 2.3 is often considered imperceptible to the average observer, while values above this threshold become increasingly noticeable. In the context of Tables I and II, the ΔE^* values allow us to assess the accuracy of color matching by CDOs and CNOs under simultaneous contrast conditions, providing insight into their comparative performances.

2.1 *Glossary of Terms*

Color Patch: in this study, a "patch" refers to a uniform color area or swatch presented to participants. Each patch is surrounded by a background that influences the perceived color through simultaneous contrast effects.

Fixed Patch: the fixed patch is the colored square on the left side of the test interface, displayed against various solid-colored backgrounds. This serves as the reference color that participants aim to match by adjusting the matching patch on the right.

Matching Patch: the matching patch is the colored square displayed on the right side of the interface, always shown against a pseudo-white noise background. Participants are instructed to adjust this patch to closely match the color of the fixed patch on the left.

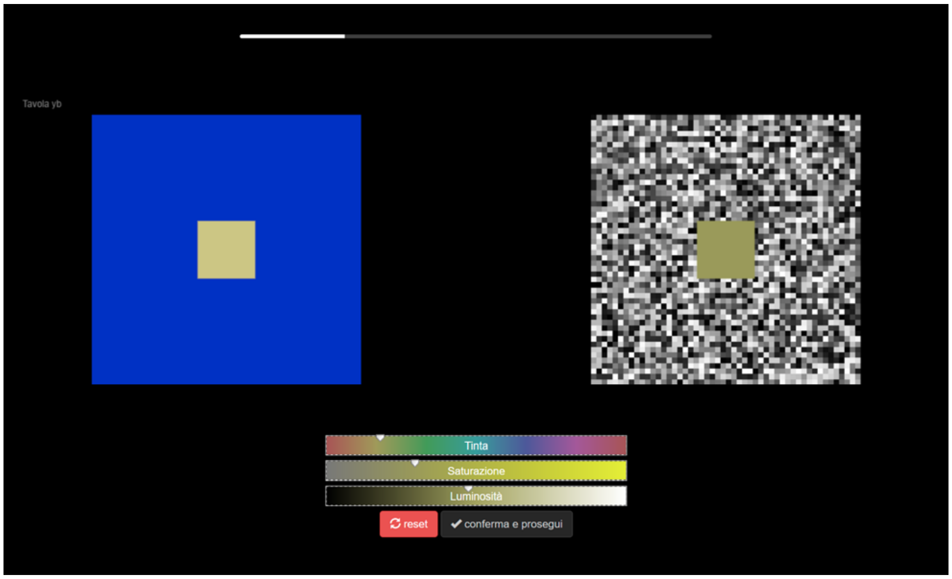


Figure 1. Test setup. The perceptual test was conducted in English and Italian versions. In the Italian version, *Tinta* stands for *Hue*, *Saturazione* for *Saturation*, and *Luminositá* for *Brightness*.

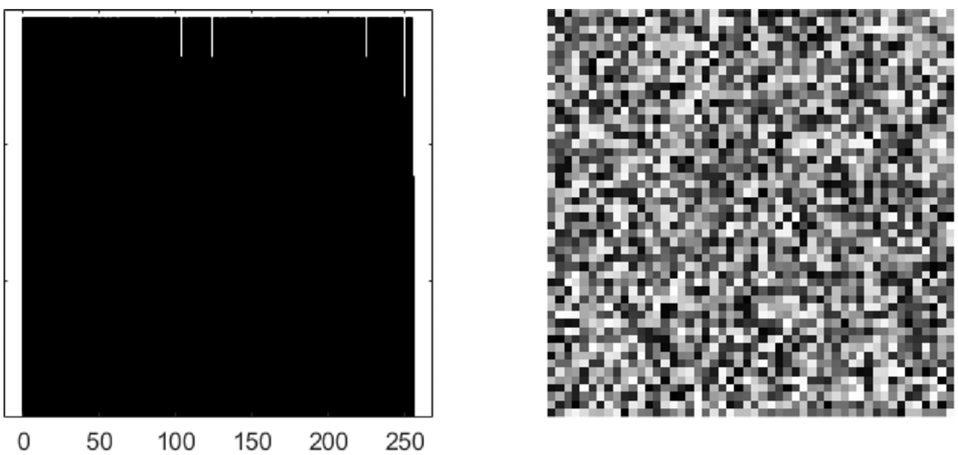


Figure 2. White noise image generated using the binning algorithm described in Section 2. It is evident that the value distribution is almost perfectly uniform, with few missing values due to the image size not being a multiple of 2^8.

Starting Color: the initial color of the matching patch, chosen in the HSV color space. This introduces initial variation that participants must adjust to achieve the visual match.

3. FIRST EXPERIMENT

62 subjects participated in the first experiment. Among them, 37 were CNOs, and 25 were CDOs.

As described in the previous section, in this test, the user had to modify the *matching patch* until it reached the apparent color of the *fixed patch*. The starting color of the *matching patch*, in this first test, was chosen to be a random color in the HSV space with a random distance of $\pm 10°$ in Hue, ± 20 in Saturation and ± 20 in Value from the *fixed patch* HSV coordinates. The constraint was implemented to facilitate the matching process for participants, allowing them to start from a different but manageable color. This setup made the task more intuitive and helped reduce response times, which otherwise would have been considerably longer.

Table I depicts the median ΔE^* computed between the answers given by the users and the *fixed patch* colors.

To better assess the average error made by CDOs and CNOs, in Figure 4 are shown the values of median ΔE^* between the *fixed patch* and the *matching patch* of CDOs (in blue) and CNOs (in yellow), together with the ΔE^* between the *fixed patch* and the starting color (black dotted line). This representation makes it possible to assess whether the observers changed the starting color during the test (i.e., if the median value of the starting color corresponds exactly to the median value of the given answer, we infer that the users did not change the starting color), and second, the amount of error made by CDOs and CNOs.

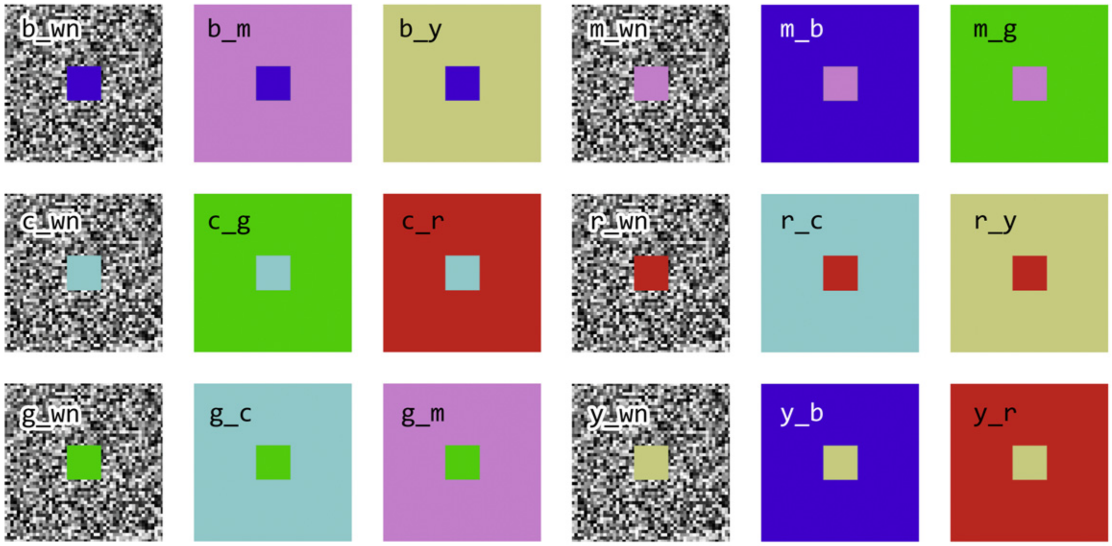


Figure 3. All 18 different configurations derived from 6 color patches, each of them on two different colored backgrounds and one neutral background, with corresponding nomenclature.

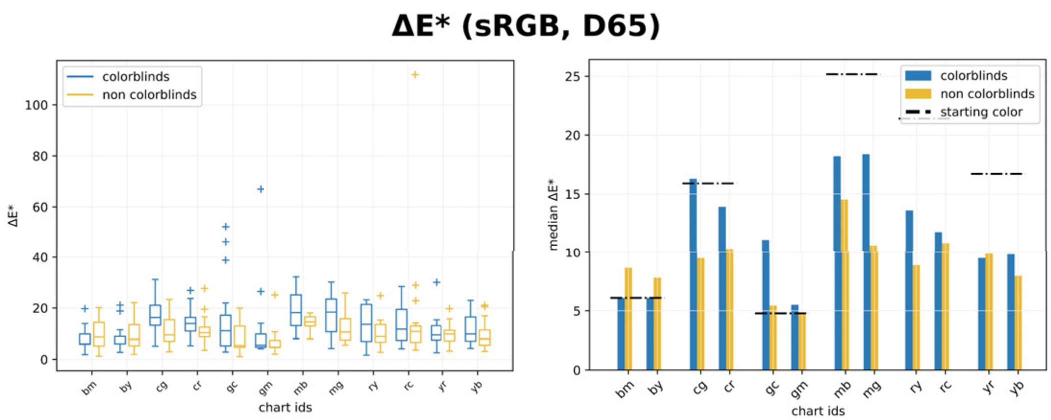


Figure 4. ΔE^* median and variance for each test combination (left) and median ΔE^* among the *fixed patch* and the *matching patch* (right), of CDOs (blue), CNOs (yellow) and the first experiment starting color (black dotted line).

In general, considering the performances of CDOs and CNOs, observers with color deficiency performed worse than normal observers, except in cases where the starting color was very similar to the *matching patch* (e.g., combinations b_m and b_y). In these cases, along with the g_m arrangement, CDOs displayed a lower median error. However, their median response often matched the starting color values closely, suggesting that they perceived the *matching patch* and *fixed patch* as identical to the initial starting patch. This trend, confirmed by the values in Table I, indicates a potential response mismatch. It is assumed that observers may have considered that the matching task was already complete when the starting color closely resembled the target, thus introducing a systematic mismatch in their answers (see Figure 8(a)).

Figure 5 elucidates few examples of matching colors chromaticity distribution in the CIELAB color space, visualized in the function of the fixed color patches (black dot and arrow). It is noteworthy that the answers given by CDOs (blue dots and arrows) present a direction that is (in the majority of the cases) different or even opposite compared to the one given by CNOs (yellow dots and arrows). Furthermore, CDOs tend to give more scattered answers, while the answers of CNOs are more coherent. The answers for the same colors with different setups are also compared.

Nevertheless, few preliminary results on the role of spatial arrangement in color perception can be ascertained; the low difference between the *fixed path* colors and starting color in some arrangements limited the first experiment. Thus, we designed a second test to investigate further.

4. SECOND EXPERIMENT

29 subjects participated in the second experiment. Among them, 16 were CNOs, and 13 were CDOs. The number

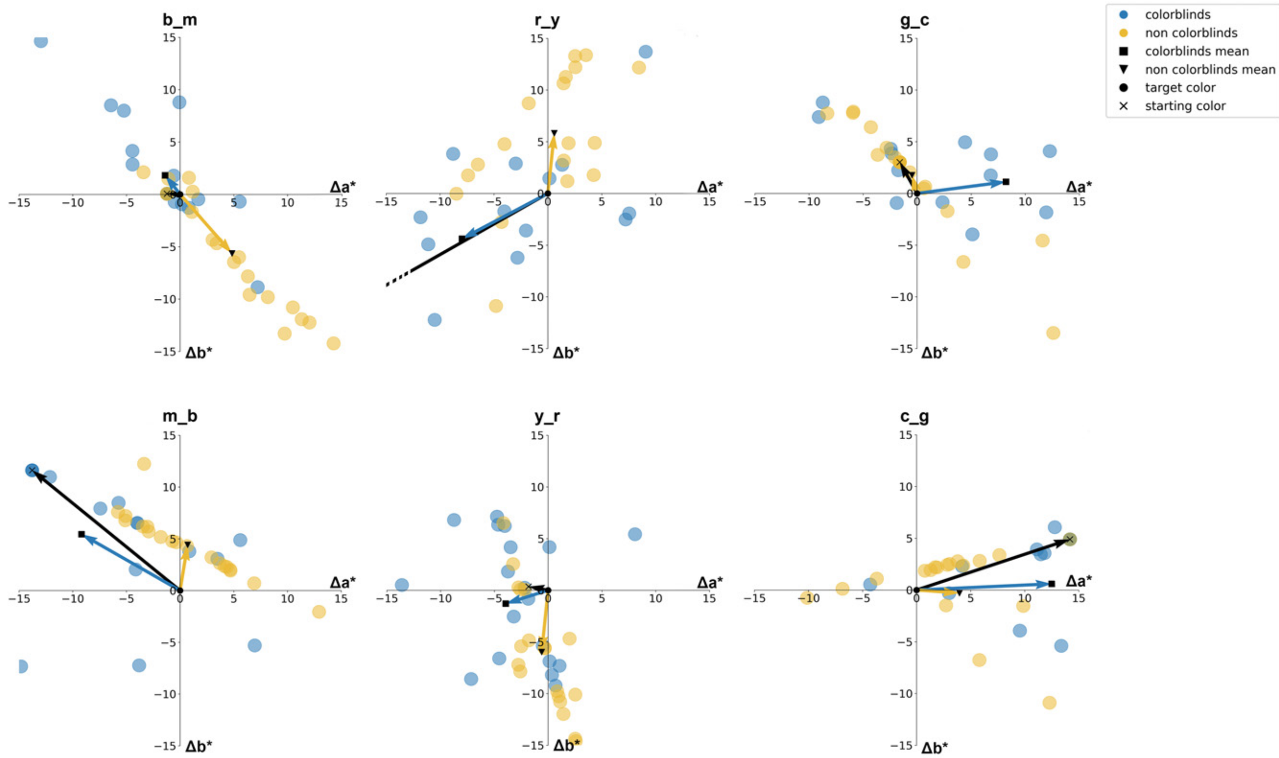


Figure 5. Plot of the CIELAB a^* b^* values of the given answers (in blue from CDOs and in yellow from CNOs). The arrows indicate the direction between the correct color a^* b^* values and the center of the answers distributions of CDOs and CNOs.

Table I. Median ΔE^* for every simultaneous contrast color combination reported in the first experiment. In yellow are evidenced the values ≥ 5 and < 10, in orange the values ≥ 10 and < 15 and in red the values ≥ 15.

Combination	CDOs med ΔE^*	CNOs med ΔE^*
b_m	6.089	8.662
b_y	6.089	7.819
c_g	16.289	9.495
c_r	13.912	10.311
g_c	11.086	5.446
g_m	5.507	4.779
m_b	18.207	14.527
m_g	18.381	10.607
r_y	13.601	8.899
r_c	11.754	10.807
y_r	9.506	9.874
y_b	9.816	7.981

Table II. Median ΔE^* for every simultaneous contrast color combination reported in the second experiment. In yellow are evidenced the values ≥ 5 and < 10, in orange the values ≥ 10 and < 15, in red the values ≥ 15 and < 20 and in violet the values ≥ 20.

Combination	CDOs med ΔE^*	CNOs med ΔE^*
b_m	7.859	9.260
b_y	13.071	8.201
c_g	25.473	10.755
c_r	25.636	9.112
g_c	11.005	7.927
g_m	6.203	5.872
m_b	29.834	12.228
m_g	19.401	10.384
r_y	7.934	6.425
r_c	9.253	8.272
y_r	13.081	7.354
y_b	11.576	6.817

of subjects was lower in this experiment than in the first experiment, which leads to weaker statistical significance; however, the outcomes still highlight a trend similar to that observed in the first experiment, where the number of CDOs was substantially higher. While we acknowledge that a larger sample would enhance statistical robustness, the high proportion of CDOs relative to their prevalence in the general population adds value to our findings. It underscores the relevance of the observed phenomenon.

From the analysis of the results of the first experiment, we identified some critical issues to address in the second experiment. First, we increased the color distance between the *fixed patches* and the starting color of the *matching patches*. The new distance was $\geq 54°$ and $\leq 72°$ in Hue and ≥ 3 and ≤ 4.5 in Saturation from the *fixed patch* (the

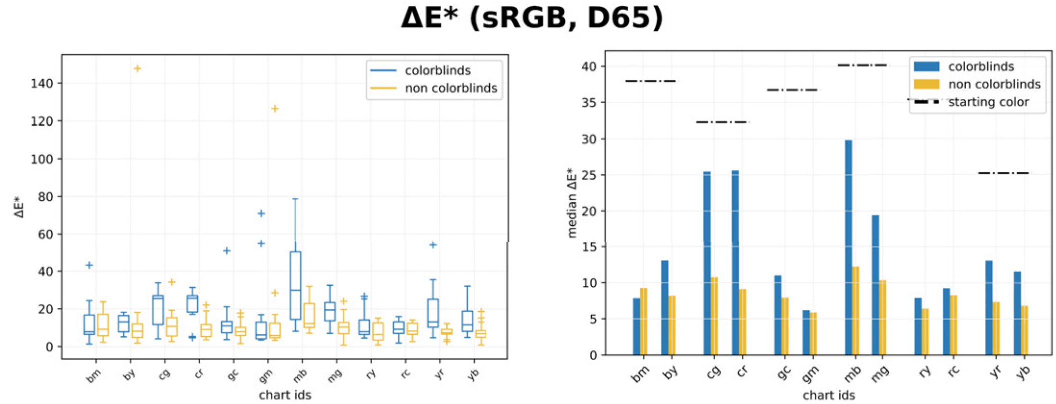


Figure 6. ΔE^* median and variance for each test combination (left) and median ΔE^* among the *fixed patch* and the *matching patch* (right), of CDOs (blue), CNOs (yellow) and the second experiment starting color (black dotted line).

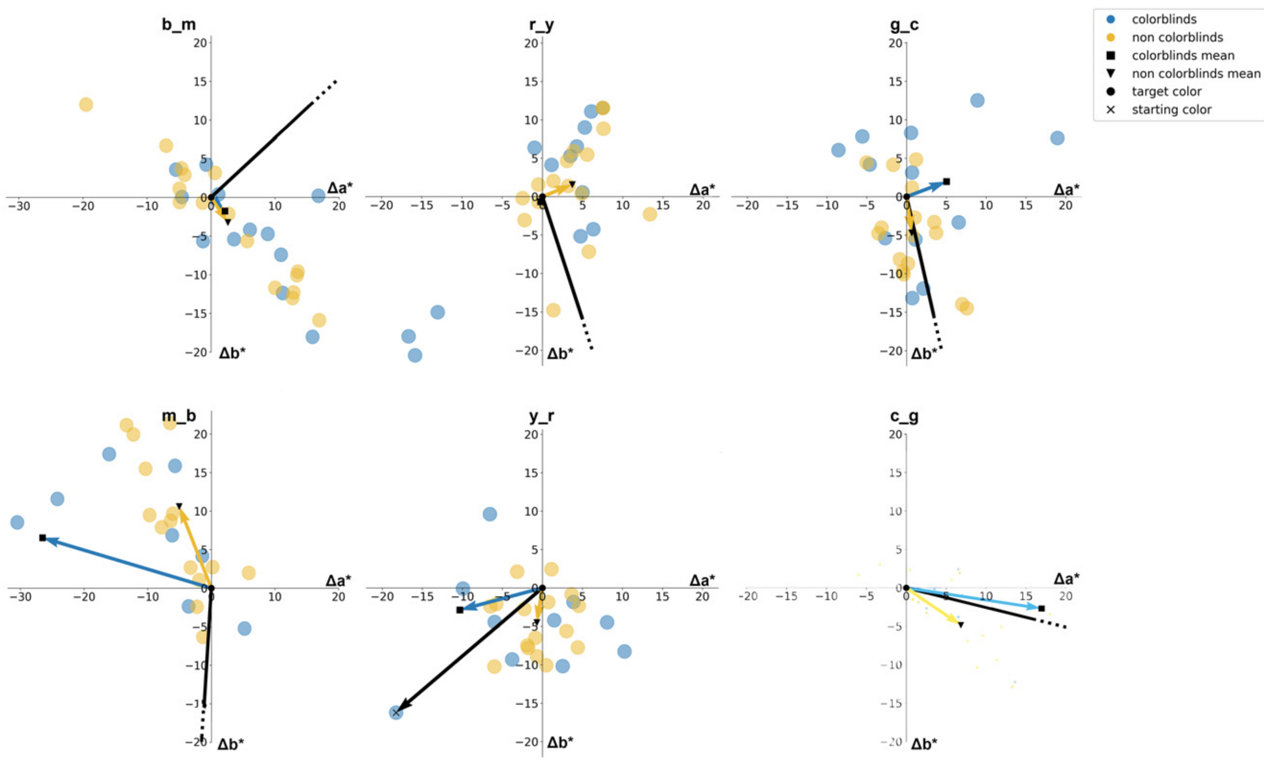
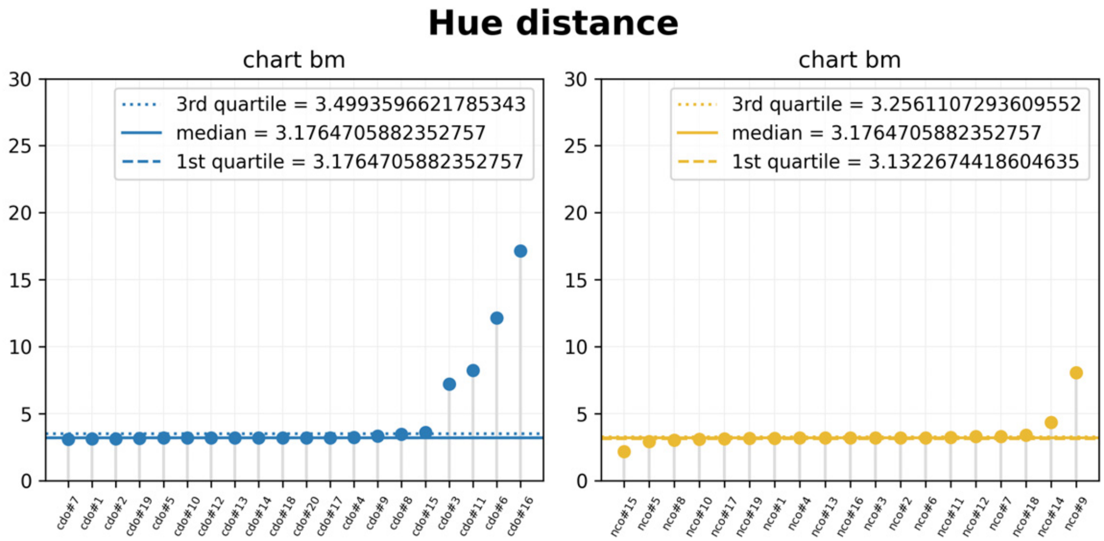


Figure 7. Plot of the CIELAB a^* b^* values of the given answers (in blue from CDOs and in yellow from CNOs). The arrows indicate the direction between the correct color a^* b^* values and the center of the answers distributions of CDOs and CNOs.

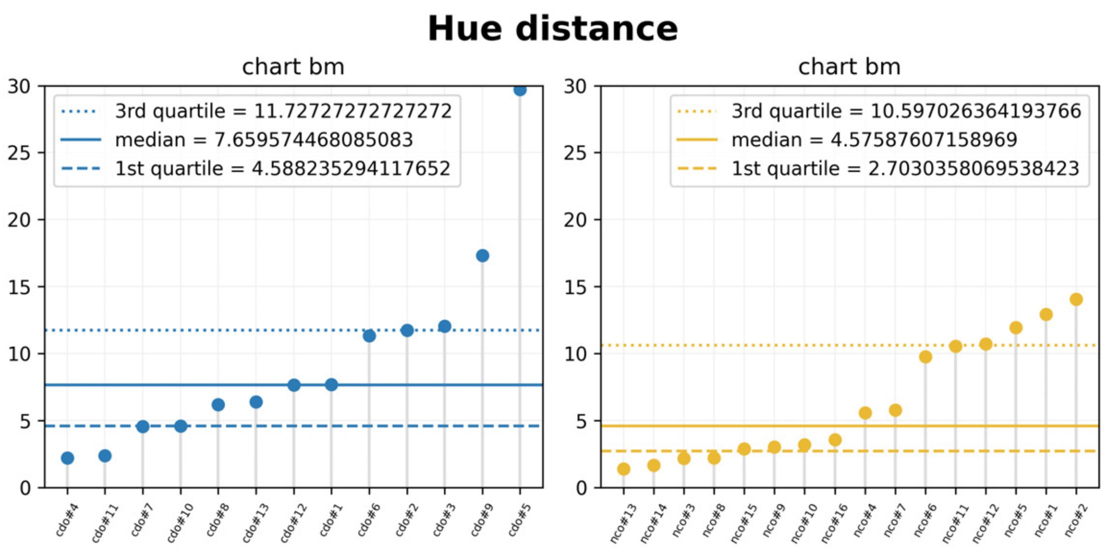
Value is constant). Second, we lintroduced a pause every 15 seconds during which the colored patches were substituted with white patches for 5 seconds. This decision was made to avoid palinopsia and adaptation effects during the test since the duration of first experiment was longer than expected.

Table II shows the median ΔE^* computed from the answers given by the users and the *fixed patch* colors. Considering Figure 7, the chromaticity distribution of the given answers compared to the correct fixed color underlines specific trends. In the case of b_m, the directions of the answers of CDOs and CNOs in a^* b^* chromaticity diagram are very similar and tend to diverge in m_b configuration. This variation is determined by the influence of the background of the color, which is different for CDOs and CNOs. The same trend can also be observed for r_y and g_c in Fig. 7, where the background influenced the color perception in CDOs and CNOs in a different way.

The improvement introduced in the second experiment produced an initial increase in the variance of the matching colors selected by the subjects. This trend can be inferred from the high variability of the data reported in Table II and in the example reported in Fig. 8(b). Comparing Fig. 7



(a)



(b)

Figure 8. Hue Euclidean distance from the answer given by each user (CDOs on the left and CNOs on the right) and the *fixed patch* color. In (a) (top) the results of the first experiment and in (b) (bottom) the results of the second experiment.

with Fig. 8(a), it can be seen that the answer trends in the first and second experiments are different and confirm the overcoming of the first experiment mismatch.

The higher tendency to modify the starting test colors can also be noticed in Figure 6. In fact, in the second experiment, the median given answers from CDOs and CNOs were always different from the starting color (represented by the black dots and lines in Fig. 6).

This second experiment confirmed the trend in the first one, where CNOs performed better than CDOs. Considering the blue and green color patches, which were strongly subject to the answers mismatch in the first experiment, the second one presented a similar trend with a higher error and, in this case, for *g_m*, CDOs and CNOs perform very similarly. Furthermore, *b_m* is the only arrangement where the median CDO error is lower than the median CNO error.

5. CONCLUSIONS

In this study, we aimed to deepen the understanding of spatial processing in color vision, particularly in Color Deficient Observers (CDOs) and Color Normal Observers (CNOs). By employing visual configurations based on simultaneous contrast, we investigated how spatial effects contribute to variations in color perception between these groups. The simultaneous contrast effect, a fundamental and well-documented spatial phenomenon, served as a tool to explore how contextual factors influence color appearance, especially for individuals with color vision deficiencies.

Our findings underscore the necessity of incorporating spatial processing into research on color vision deficiency. Traditional color vision models often rely on point-wise descriptions, where each color is processed independent of its spatial context. However, our results suggest that spatial mechanisms—such as those involved in simultaneous contrast—may also be integral to the color perception of CDOs. It is reasonable to propose that spatial interactions are embedded within the visual pathways of CDOs, impacting their perception in ways not captured by classical models.

The inclusion of spatial mechanisms in the diagnosis, modeling, and simulation of color vision deficiencies could clarify several instances where CDOs' performances diverge from predictions made by traditional, point-wise approaches [15]. For example, scenarios where CDOs respond unexpectedly to color stimuli may be better understood through a model that accounts for spatial interactions. Furthermore, this perspective opens pathways for developing new, spatially informed methods to enhance inclusivity for CDOs. Rather than relying solely on basic color palette adjustments, tools that integrate spatial processing may provide more robust support, allowing CDOs to interact with visual content in a way that aligns more closely with their unique perceptual experiences.

We recognize that color vision deficiencies have been effectively modeled for many decades using point-wise approaches, which have yielded significant insights and practical applications. However, we propose that a broader framework, one that integrates spatial processing, could offer fresh insights into the complexities of color vision in CDOs. By embracing a model that goes beyond traditional methods, we aim to reveal new aspects of color perception that highlight the fundamental role of spatial interactions, ultimately advancing our understanding of CDOs' visual capabilities and informing the design of future color vision solutions.

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