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Testing the role of vision spatial processing in color deficiency

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Abstract

In the last 80 years, the role of spatial processing in the visual system has been analyzed and demonstrated from many studies and experiments. From the first studies of Young, Helmholtz and Hering, color vision models have developed, and several biological and physiological research papers proved the importance of spatial processing in color vision. In this paper, we present some studies that have explored the role of spatial processing in studying color vision deficiency. The main scope of this work is to increase the scientific community's awareness on the importance of including spatial processing not only in color vision models, but also in developing color deficiency aids and tests.

Introduction

Human color vision begins in the retina, in particular in photoreceptor cells (cones), which contain different forms of opsin, a light-sensitive group of proteins. The transduction of the light signal operated by the cones initiates the color vision process. Human color vision is trichromatic, and as stated by Young and Helmholtz, trichromacy is a physiological attribute of the eye. After Hering's studies, we also know that color vision has an opponent's behaviour and requires comparisons among the signals acquired and transduced by cones. These color vision theories are based on many color vision assessment tests. Color Vision Deficiency (CVD) is caused by the absence or alteration of one type of cone in the retina, while the complete inability to distinguish colors is called monochromacy or color blindness. Different types of CVD can be distinguished depending on the absent/altered cone type. From this idea, transforming the color matches of the standard observer in a coordinate system like CIExy, it is possible to derive the so-called confusion lines. The possibility to estimate the color confusions by the average dichromats, made possible the design of many diagnosis tests, like Pseudo-Isochromatic Plates (PIP), Anomaloscope, Farnsworth-Munsell Color Vision tests and so many others.

As we stated, retinal signal transduction is the first step in the human visual pathway. Today, so many processes of the visual systems are still unknown, and there are many open questions on the visual signal processing operated by the brain.

The scientific research of the last 80 years demonstrated the role of spatial processing in the visual system and color vision. In 1953, retinal spatial modulation was demonstrated in frogs [6] and in mammals [29]. Later on, in 1987, Dowling accurately described for the first time the retina spatial interactions [16], expanding the work of Hecht et al., and subsequently, the spatial processing has been demonstrated in the visual cortex (De Valois et al., 1980 [13]; Hubel et al., 2004 [25]). Furthermore, thanks to the work of Zecki in 1993, in V4 cortical area have been found cells responsible for color constancy [49]. In addition to biological studies on the role of spatial processing in the visual pathway, in 1964, Land's Retinex color theory began a model of human color vision based on the analysis of complex scenes and Land, and McCann designed many experiments using spatial comparisons and spatial integration across the scene, which have been found successful [30, 33, 32]. The Retinex model is today the base of a widely used family of image enhancement algorithms applied in different application fields. From the presented literature, it is clear that color vision cannot be modeled just at the retinal level. Consequently, the color assessment test should include the spatial processing component of human color vision.

Following the idea of including spatial processing in color vision assessment tests, in this work, we report some studies which have explored the use of different spatial arrangements to study color vision deficiency. The studies and experiments we present in this work approached spatial processing at first modifying some features of existing color vision screening tests, demonstrating that color discrimination can be improved in color deficient observers by changing specific features.

This simple approach has been helpful in demonstrating that color vision is not only point-wise signal transduction, but it is content-dependent, thus, changing the arrangement of the color in the scene color appearance can change. This specific aspect of vision is of particular importance in all the contexts in which color vision tests are used to define the eligibility of candidates to conduct particular jobs (e.g., in aerospace agencies, to drive specific vehicles). In this context, a retinal approach to color vision and a standard test cannot be significant on the concrete ability of a user to distinguish color in real contexts.

The possibility of developing color vision tests which also include a spatial component, could provide a more accurate way to assess the real ability of a user to identify color in real life and provide different thresholds of color deficiencies.

This work aims to provide examples of experiments and scientific literature demonstrating the role of spatial processing in color vision deficiency to promote the development of alternative screening methods and aids. In this work, we report the most recent publications on this topic, discussing the advantages and disadvantages of the reported studies. The considered studies are reported from journal publications and presentations in the leading color conferences.

The common approach to color deficiencies

Color vision is a complex process, which has extensively been studied, but today is still far from being completely understood. The first step of color vision occurs in the *retina*, where the physical color stimuli are transducted into nervous signals and sent to the brain. In general, three types of cones are present in the human retina, which are classified depending on the wavelengths of visible radiation to which they respond. CVD is caused by the absence or alteration of one or more cone types in the retina. The usual terms of CVD types are the *dichromacies* referred to *protanopia*, *deuteranopia* and *tritanopia* and the *anomalous trichromacies*, *protanomalia*, *deuteranomalia* and *tritanomalia* (according to the main cone types involved) [15]. The total lack of ability to distinguish colors is called *monochromacy*. In the field of CIE colorimetry the different types of CDOs (Color Deficient Observers) are described by a transformation of coordinate system [28]. This transformation can be graphically represented by the so-called *confusion lines* in the CIE chromaticity diagram (see Figure 1). Different systems of CVD diagnosis have been designed, among them, the Ishihara test is likely the most common. This test is part of the Pseudo Isochromatic Plates (PIP), a family of tests consisting of figures, numbers or letters embedded in a picture composed of dots of different colors. Here, the colors are aligned on the confusion lines to be visible just to trichromats observers. Following this idea, many different test images can be generated, and today, these tests can be performed on printed papers but also digital versions [44, 45, 2]. Other diffused PIP color vision screening tests are the Waggoner Color Vision Test and the Richmond HRR test (2002). The Ishihara test is widely used in clinics and occupational environments and it can achieve high sensitivity when screening for congenital red–green deficiency [12, 43], as well as the Richmond HRR test (2002). On the other hand, the Waggoner Test allows to diagnose also tritanopia [36, 3] and presents a computerized version, which has been tested and evaluated in clinical studies [36, 3].

Besides the Pseudo Isochromatic Plates tests, the Farnsworth–Munsell 100 Hue Color Vision test [22] is another common method to diagnose not only color deficiency but also to identify the type of CVD. This method has been found to perform less well in diagnosing the anomalous trichromacies [43].

Among the different reference and standard tests to diagnose color deficiency, the Color Assessment Diagnosis (CAD) test has been proposed to overcome some limits of the primary and secondary tests. The standard CAD version shows the observer a moving colored and squared stimulus in a dynamic luminance noise background, and the observer has to define the square movement direction [21]. CAD test is often used in multi-level diagnosis protocols and different studies determined its high reliability (also related to its strong agreement with Nagel's anomaloscope) [44, 43, 5].

The gold standard to diagnose color deficiency is the anomaloscope (or Nagel's anomaloscope) [8]. This instrument is used to determine the Rayleigh match: the amount of a mixture of red and green light to match a yellow light (the primaries' wavelength and intensities are defined according to DIN 6160) [47]. Thanks to this test, it is possible to characterize colour deficiencies and anomalous trichromacies, which form separate distributions outside the CNOs (Color Normal Observers) matching range. Today, the anomaloscope is the only test that distinguishes anomalous trichromacies from dichromacies. Different studies also demonstrated the correlation between anomaloscope matching and the predicted pigment separation from genetic analysis [27, 4]. Thanks to the reliability of the anomaloscope, in diagnosis protocols, it is often performed after a first preliminary diagnosis using PIP or Farnsworth–Munsell tests [9].

On purpose, all these tests carefully avoid any forms of edges on the color target.

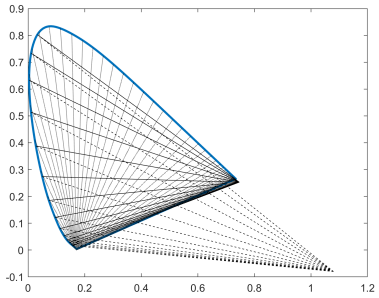


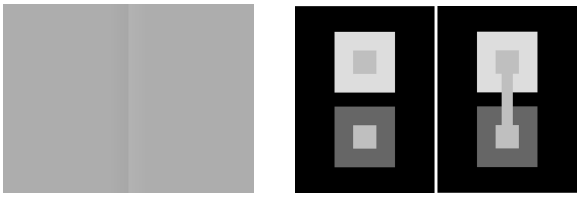
Figure 1: CIE chromaticity diagram, with confusion lines of protanopia (solid lines), deuteranopia (dashed lines) and tritanopia (dotted lines) [28].

The role of spatial processing in color vision

The presence of spatial processing along the whole visual pathway has been studied and demonstrated over the last 80 years of research [32]. From the studies by Hermann von Helmholtz in 1868 and by Hering in 1878, color vision models have been widely studied and developed. Considering the visual pathway, in 1987, Dowling [16] described retina spatial interactions and, subsequently, the operations of spatial comparisons in the retina have been demonstrated in frogs [6] and mammals [29]. Considering the ganglion cells, in 2007, Berson [7] shown spatial modulation from melanopsin photopigment and during the 80s [13] and more recently in 2004 [25], spatial comparison in the visual cortex has been found. Furthermore, in 1993 Zeki [49] found cells responsible for color constancy in the V4 cortical cells.

The role of spatial processing in vision and color vision can also be determined by considering the luminance mechanism. In fact, in several studies of the HVS, it has been confirmed that L and M cones can present very high variability in the retina [48, 23, 24] but, although the luminous efficiency depends directly on these cones, color vision is not affected [11, 37, 10]. This supports the idea that the separation between luma and chroma is likely a spatial higher-level elaboration of the information transducted by the cones. Following this idea, many models and theories have been published aiming at reproducing the behaviour of the HVS, considering spatial processing as the main feature of color vision [30, 14, 35, 1]. Thus, the current state of the art suggests that spatial comparison, carried out along the whole visual pathway, is the underlying mechanism on which colour vision relies [31, 40, 39], and the great importance of the shape in object recognition supports this theory [46, 26, 38].

In this context, visual illusions are a perfect example to visually demonstrate the importance of the spatial configuration of a scene, confirming the idea that color sensation depends not only



(a) Cornsweet illusion (b) Simultaneous contrast

Figure 2: Cornsweet illusion (2a): the gray square on the right appears lighter than the one on the left. In fact, the two grays have the same brightness. This can be proven covering the *edge* between them, using a pen or your finger.
Simultaneous contrast effect (2b): the central squares appears different because of the different backgrounds, unless the edges are removed and a conjunction is made.

on a point-wise stimulus but also on the spatial arrangement of the scene, thus from its edges and gradients. A simple example is given by the Cornsweet illusion [17] (see left Figure 2a, where the edge between two greys generates a difference in their appearance. In the same way, all the effects of simultaneous contrast determine an increase in apparent difference among colors, because of the presence of edges (see right Figure 2b).

Spatial computation in HVS has two main goals that aim at making it robust against widely varying viewing conditions. Using spatial processing, HVS can perform an unsupervised color partial normalization, often referred to as color constancy. In fact, extracting appearance through edges allows HVS to discount glare or slowly vary color casts [35]. At the same time, spatial computation counteracts eye-ball glare. The lens of our eyes is largely prone to glare [34], an unwanted spread of light that causes a severe loss of contrast in the retina. In a test by one of the authors a contrast of about 250'000 : 1 of the cones results in almost 150 : 1 in the retina [34]. This important loss of contrast is partially compensated by spatial comparisons [42]. For these reasons, visual-spatial mechanisms are fundamental for our vision in both CDOs and CNOs.

The role of luminance and spatial processing in CVD

As described in the previous Section, spatial processing has a role in color vision, both in CDOs and CNOs, and should be considered when designing new models or diagnosis systems. The interaction of higher- and lower-level elaboration, in fact, produces many effects on the overall color vision, like local signal amplification, normalization and adaptation. This causes a local variation in color perception depending on the spatial arrangement, which the most diffused CVD tests cannot characterize. The common approach to CVD (see Section) avoids edges and complex spatial arrangements, to modelling CVD under controlled and standard conditions.

The separation of Luma and chroma is easily understood using the common idea of color and lightness. However, a sensor only for luminance is not present in our retina. Luminance and edges are an important influence on color vision. Since luma and chroma separation occurs along the visual pathway, this regards both CDOs and CNOs and is derived from the spatial arrangement. Luminance is a piece of information that CDOs do not *confuse*, and it is constructed from cone information spatial arrangement.

In the literature, few works provide evidence on the role of spatial processing in CVD modelling since this phenomenon still needs to be fully understood in normal color vision. In Section , we report some of the few perceptual tests that preliminary demonstrated the role of edges in improving CDOs color discrimination, e.g., increasing Ishihara-plates-based dots or considering the color discrimination in a complex contest.

Furthermore, for CDOs, visual illusions can be an interesting framework to test the role of spatial processing in color assessment. Thus, a condition of simultaneous contrast can be an essential baseline for testing the possible increase in the correcting rate under the edge condition of color vision deficiencies.

Spatial processing and CVD: literature experiments

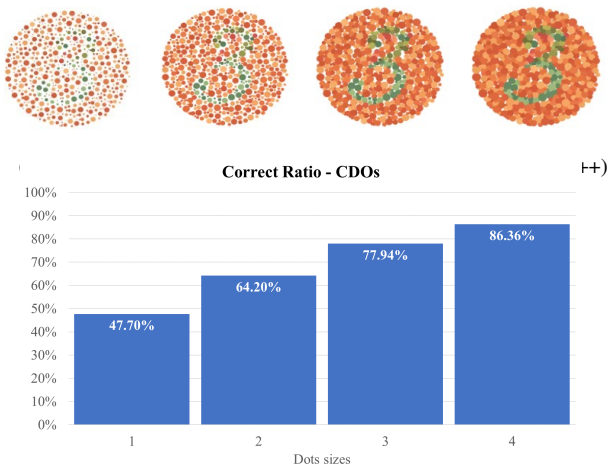
The role of spatial processing in vision and color vision has been widely studied and demonstrated. Nevertheless, few studies in the literature provide evidence of this phenomenon in CVD. It is clear that the spatial processing operated at higher-level of vision involves CNOs as well as CNOs, but since the diagnostic systems are based on punctual or isolated stimuli (avoiding edges), the effect of spatial processing is not included in the analysis of CVD.

Starting from the literature presented in the previous Section, in this Section we report some experiments trying to include the effect of spatial processing in the study and analysis of CDOs.

In 2014, two studies analyzing the role of edges and spatial arrangements in color deficiency were published [18, 41]. In these papers, authors decided to investigate the role of edges since they noticed that in commonly used tests (e.g., PIPs, Farnsworth–Munsell 100 Hue Color test), the contact and interaction among colors is avoided (thus, preventing the creation of edges). Therefore, they decided to set up an Ishihara-based test starting from 9 classic plates and generating 1 variant decreasing the dots' sizes (Mini) and 2 variants increasing the dots' sizes (Plus and PlusPlus) to the point of generating edges among dots (see Figure 3). In this preliminary test, 9 normal trichromats and 9 CDOs were tested. In this first study, just the 17% of CDOs could correctly identify the plates with Mini dot size, the 28% the Normal plates, the 31% the Plus plates and the 37% the PlusPlus plates. Thus, this preliminary test has demonstrated that the presence of edges among colors can enhance the readability of the Ishihara plates for CDOs and provided a first practical confirmation of the role of edges in color vision.

More recently, a similar test has been published in [19]. Also in this case, some pseudo-isochromatic plates' spatial attributes have been changed to test the ability of CDOs to identify numbers in a different spatial context. The main difference between those first two tests is that in the latter one, the charts have been created directly from self-calculated confusion lines based on published copunct locations [28]. This modification has been made to provide a more deterministic explanation of the motivation correlated to improved recognition and increase or readability of the plates. The experiment described in [18, 41] was more like a *proof of concept*, hardly reproducible since it was based on *found* WEB-based charts and morphological operations with no verification of color data.

In this updated second experiment, four versions of the



(e) Results

Figure 3: Example of Ishihara-based plates with mini (3a), Normal (3b), Plus (3c) and PlusPlus (3d) dots sizes, from [18].

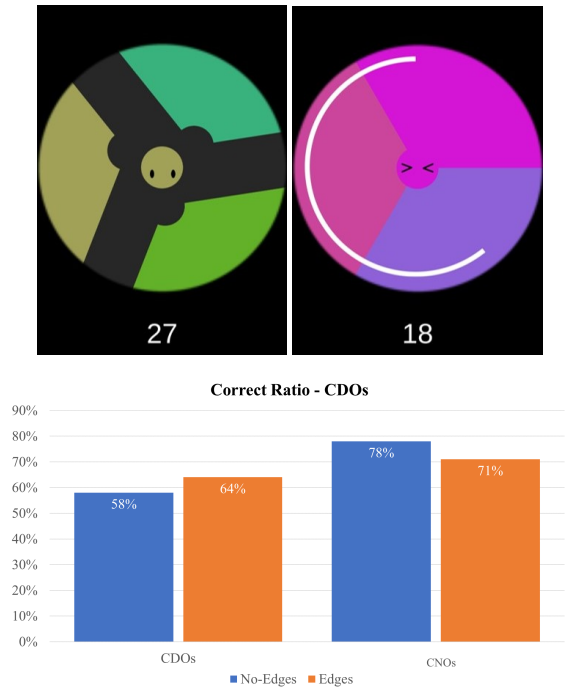
Ishihara-like plates have been computed, increasing the dots' sizes from 1 to 4, where 1 corresponds to the sizes of the normal dots and 4 to the bigger dots sizes. In this test, 485 observations from 10 CDOs have been collected. The results from this study agree with the one presented in [18, 41], they indicated an improvement in number identification for the larger dots (from 47.7% to 86.36%).

The important aspect of these experiments in the context of deficiency aids is the spotlight they shed on the strong scene dependency of a CDO response. In the complex scenes, the CDOs seem to "see" information that, following constant field colorimetric explanations, *they should not be able to see*.

In recent years, another preliminary evaluation of the role of edges in color perception was conducted using a mobile game called *qU - Color Game*, designed explicitly for this purpose[1]. In this game the user has to match a static colored circle with moving color slices, which at the beginning of the game are well separated from the circle (Figure 4a) and after a defined time reach the central circle touching it (i.e., creating a color edge, see Figure 4b). A preliminary analysis of the performance of 13 CDOs and 12 CNOs shows that color deficient subjects had a lower ratio of correct guesses and took longer to answer, improving the answer accuracy when the color slices were closer to the centre color. In fact, considering the ratio of correct guesses given when the color slices are near the center (e.g., Figure 4b), CDOs have a higher rate of correct answers (from 58% to 64%), while an opposite trend has been verified for color normal subjects (from 78% to 71%).

Similarly, Eschbach et al. in 2022 presented another study at the Electronic Imaging conference aimed at studying the color identification variations in PIP charts changing the background [20]. This study was conducted on 6 color deficient people. The correct identification rate in this experiment has been of 52% with black (RGB 0) background, 72% with RGB 64 background, 64% with RGB 128 background, 27% with RGB 192 and 10% with RGB 255 background. Considering that the usual background

[1] http://mercurio.di.unimi.it/mascetti/research/qu/qu.html



(c)

Figure 4: Screenshots of the *qU - Color Game*. In 4a an example of color slices approaching the center circle (starting phase of the game) and in 4b an example of color slices touching the central circle (ending phase of the game). In 4c are reported the test results.

in PIP is usually white, with this preliminary experiment, it has been demonstrated a decrease in background tone can improve PIP identification.

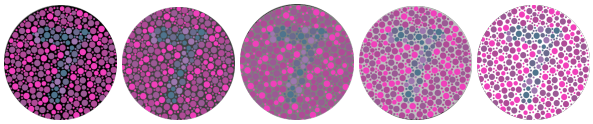
The presented experiments show a strong variation in PIP identification, just changing some features. These trends and variations should be considered when designing color deficiency tests and aids since they allow us to determine the ability to identify colors at a higher level in the visual system.

This work aims at resuming the main experiments and tests published in the literature on the role of spatial processing in color vision deficiency. This work aims to focus on the most recent approaches to color vision deficiency and raise the scientific community's awareness of the need to develop color deficiency aids and tests, including spatial processing behaviours.

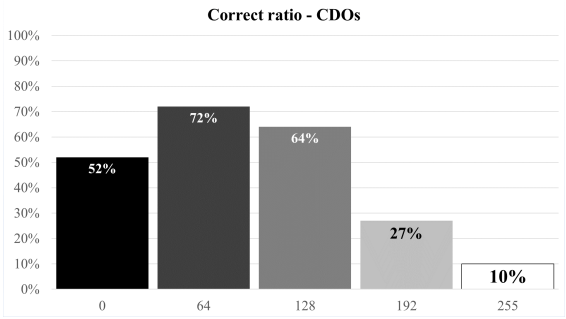
Conclusion

This paper wants to suggest an expanded approach to color deficiencies. The basic idea is that since spatial processing is a fundamental part of explaining color perception in normal viewers, consequently it has to have an important role also for CDOs.

In this work, we have presented a series of experiments that tested the role of spatial processing for CDOs using different approaches. We report two tests that studied the roles of color edges in increasing the dots' sizes in Ishihara-based tests. Here, it has been proven that changes in dots dimension, arrangement and background strongly change the ability of CDOs to perform the required task successfully. These results have also been demonstrated thanks to the mobile game *qU - Color Game*, which con-



(a) 0 (b) 64 (c) 128 (d) 192 (e) 255



(f) Results

Figure 5: Example of Ishihara-based plates with different shades of gray background (0, 64, 128, 192 and 255 in RGB coordinates).

firmed the existence of an influence of the spatial arrangement in the scene, which affects CDOs and CNOs.

In conclusion, this could be the first step in defining a new research direction in CVD studies. New CVD models accounting for spatial distribution will be a quantum leap in understanding CVDs and for the new generation of CDOs aids.

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Alice Plutino obtained a PhD in Computer Science at Università degli Studi di Milano (2021), where now is Research Fellow. Her research interests are Color Science, Colorimetry, Image Enhancement, Image Digitization and Archiving, with a particular interest in Cultural Heritage applications. She is author of the a book and of several journal and conference papers of national and international relevance. She is Adjunct professor at Università degli Studi di Milano and Centro Sperimentale di Cinematografia, teaching digital film restoration and digital media conservation. She is member of the Italian color group (Gruppo del Colore), deputy editor of the Color Culture and Science Journal (CCSJ) and vice-coordinator of Division 1 and Division 8 of NC CIE Italy.
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Roberta Marcucci is Ophthalmologist MD, Italian Air Force Medical Officer at Aerospace Medicine Institute in Rome. Her clinical field of application is aviation medicine and the assessment of medical fitness of military and civilian aviation personnel, according to their special duty status. Her professional background includes medical retina, cornea, refractive surgery.

Alessandro Rizzi is Full Professor at the Department of Computer Science at the University of Milano (Italy), teaching Multimedia, Colorimetry and Film restoration. He is doing research since 1990 in the field of digital imaging with a particular interest on color, visualization, photography, HDR, VR and on the perceptual issues related to digital imaging, interfaces and lighting. He is the head of the MIPS Lab at the Department of Computer Science. He has been one of the founders of the Italian Color Group, Secretary of CIE Division 8, IS&T Fellow and Vice President. In 2015 he received the Davies medal from the Royal Photographic Society. He is co-chair of the IS&T Conference "Color Imaging: Displaying, Processing, Hardcopy and Applications", Topical Editor for "Applied Color Science" of the Journal of Optical Society of America A, Associate Editor of Journal of Electronic Imaging, member of several program committees and author of about 400 scientific works.