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On the need for spatial component in describing colour vision deficiency

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Abstract

Colour vision deficiency (CVD) is traditionally described using colorimetric models that treat colour perception as a pointwise phenomenon. While this approach has been essential for defining diagnostic methods and colour vision simulators, it does not account for the spatial mechanisms through which the visual system interprets colour. These mechanisms, acting mainly at cortical levels, play a central role in how colours are perceived. However, studies investigating their role in colour-deficient observers are still limited and fragmented. This paper reviews and discusses research that introduces spatial processing into the study of CVD. The results consistently show that small contextual variations can significantly affect colour discrimination in colour-deficient observers. We argue that colour vision, both normal and deficient, cannot be fully described through pointwise colorimetric principles alone. To achieve a realistic understanding of colour perception, diagnostic tools and simulators must include the spatial mechanism of vision.

Keywords: colour deficiency, colour blindness, colour in context, spatial processing in vision



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Introduction

Colour vision deficiency (CVD) is a visual condition in which colour perception differs from that of colour-normal observers. According to Hunt and Carvalho,¹ it affects about 8.5% of men and 0.5% of women in the Caucasian population. One of the three types of cone photoreceptors in the retina is usually absent or malfunctioning in CVD, which alters the normal balance of spectral sensitivities of the eye and causes a reduced ability to discriminate certain chromatic differences.

Historically, CVD has been described using the principles of classical colorimetry that describe colour perception as a pointwise phenomenon, based only on the spectral composition of light and its chromatic coordinates. Diagnostic tools and colour vision deficiency simulators have therefore been developed based on the idea that colour discrimination can be fully represented by pixel-by-pixel transformations in colour space. This approach has been useful for defining and standardizing the study of colour vision, but it does not account for an important aspect of human perception: the influence of spatial context and visual interactions in how colours are actually seen. Human vision is not only based on retinal sensitivity

¹ David M. Hunt and Livia S. Carvalho, “The Genetics of Color Vision and Congenital Color Deficiencies,” in *Human Color Vision*, ed. Jan Kremers, Rigmor C. Baraas, and N. Justin Marshall (Springer International Publishing, 2016), 1-32. https://doi.org/10.1007/978-3-319-44978-4_1.

but also depends on cortical processing, where spatial mechanisms compare information across different areas of the visual field, detect edges, and combine chromatic and luminance signals to form a coherent perception of colour. Ignoring these spatial factors gives only a limited and simplified view of colour perception and, consequently, of colour vision deficiency. In this work, spatial mechanisms are intended as post-retinal processes based on spatial comparison, edge integration, and contextual relationships that shape the final colour sensation. This concept refers to the general post-retinal spatial elaboration that contributes to how colour is perceived, even when chromatic signals are measured under controlled conditions.

While colour assessment tests are designed to measure chromatic sensitivity under controlled conditions, the sensation of colour is the result of post-retinal processing that includes spatial interactions. The aim of this paper is to raise awareness in the scientific community that colour vision, both normal and deficient, cannot be fully described with a pointwise approach. The study and modelling of colour vision deficiency should include the spatial dimension of vision and consider the interactions that take place across retinal and cortical levels, and we hope to encourage further research in this direction. The need for further study of spatial mechanisms does not diminish the importance of the extensive literature on cone sensitivity thresholds but addresses a complementary level of visual processing.

Classical Descriptions of Colour Vision Deficiency

In normal vision, also known as trichromacy, colour perception arises from the combined activity of the three classes of cone photoreceptors responding to different portions of the visible spectrum: long- (L), medium- (M), and short-wavelength (S) sensitive cones. When one of these cone types is altered or absent, distinct forms of colour vision deficiency occur.

When one of these cone types is completely nonfunctional or absent, the condition is classified as dichromacy. Protanopia results from the absence of L-cones and deuteranopia from the absence of M-cones; both conditions lead to a reduced ability to distinguish colours along the red–green axis, and since they are X-linked recessive genetic disorders they occur predominantly in males. In contrast, tritanopia,

which involves the loss of S-cones, affects colour discrimination along the blue–yellow axis. It is a rare genetic disorder linked to chromosome 7 and therefore affects males and females equally.

Less severe variants of these conditions are known as anomalous trichromacies, in which all three cone types are present but one exhibits a shifted spectral sensitivity rather than a complete loss of function. The corresponding anomalous forms of protanopia, deuteranopia, and tritanopia are known respectively as protanomaly, deuteranomaly, and tritanomaly.

A complete loss of function of all three cone types results in achromatopsia, an extremely rare condition in which colour discrimination is entirely absent, leading to a monochromatic visual experience.

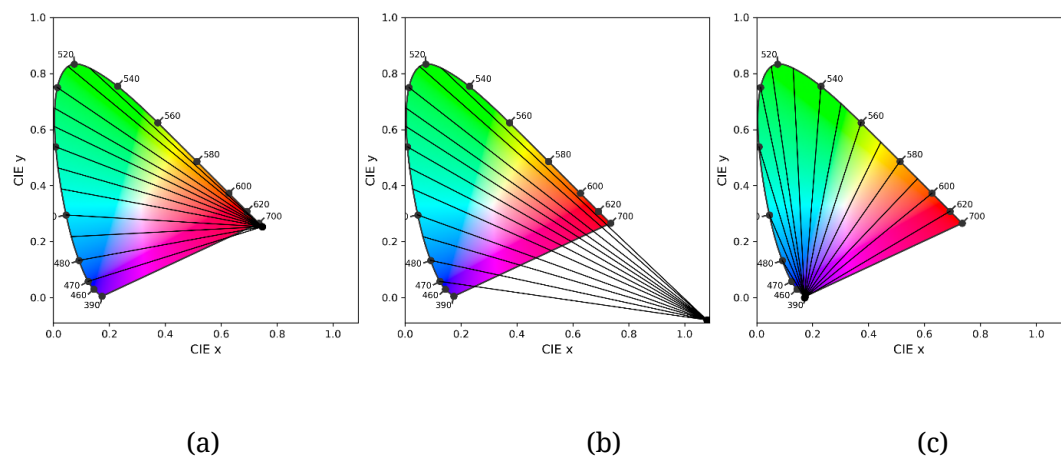


Figure 1. CIE 1931 chromaticity diagram with confusion lines of protanopia (a), deuteranopia (b) and tritanopia (c).

The classical description of colour vision deficiency is based on the principles of colorimetry, the science that provides an objective way to measure colour and standardize colour perception. In this context, colours are represented within defined colour spaces. One of the most commonly used colour space is the CIE 1931 xyY space, where each colour is described by its chromaticity coordinates (x , y) and its luminance value (Y). When these coordinates are plotted on the CIE chromaticity diagram, the visible colours form a characteristic horseshoe-shaped area that represents the range of chromaticities perceived by a normal trichromatic observer. In this space, the perception of colour-deficient observers can be described through *confusion lines* (Fig. 1). According to this model, individuals

with a specific type of colour vision deficiency (such as protanopia, deuteranopia, or tritanopia) perceive all colours lying along a given confusion line as identical. These lines radiate from distinct *copunctal points*, each corresponding to the missing or malfunctioning cone type.

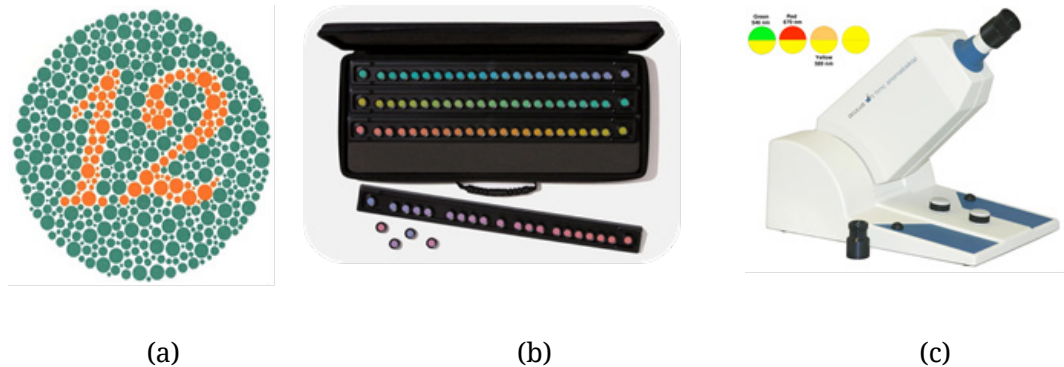


Figure 2. Ishihara plate (a), Farnsworth–Munsell 100 Hue Colour Vision test (b), and Nagel’s anomaloscope (c).

The principles described above have guided the development of diagnostic tools for colour vision deficiency. These instruments use controlled colour differences and predicted confusion patterns to assess the type and severity of the deficiency. The most common tools are the *Pseudo-Isochromatic Plate (PIP) tests*, the *Anomaloscope*, and the *Farnsworth–Munsell Colour Vision tests*.

The PIP is a family of tests that uses figures, numbers, or letters embedded in images composed of coloured dots. In these images, the chosen colours align along confusion lines, making them distinguishable only to trichromatic observers. The great success of the paper and digital versions of these tests relies on their easy applicability, since using a few tables it is possible to assess the presence of colour deficiency and perform a preliminary screening to determine the type of defect. Among them, the Ishihara test (one of its 38 plates is represented in Fig. 2a) is the most common and is widely used in clinics. It has a high sensitivity in screening red and green deficiencies (protanopia/protanomaly and deuteranopia/deuteranomaly), but it is proven to be unsuitable for screening tritanopia/tritanomaly.¹ Other widely used PIP-based tests include the 2002 Richmond HRR

¹ Marisa Rodriguez-Carmona et al., “Color vision assessment-2: Color assessment outcomes using single and multi-test protocols,” *Color Research and Application* 46, no. 1 (2021), <https://doi.org/10.1002/col.22598>.

test, which achieves similar sensitivity to the Ishihara test,² and the Waggoner Colour Vision test, that can also diagnose tritanopia.³

The Farnsworth–Munsell 100 Hue Colour Vision test⁴ (Fig. 2b) is another commonly used method. The purpose of the test is to measure hue discrimination in a curve of constant value and chroma. It allows not only for diagnosing colour deficiency, but also for identifying the type of CVD. However, it is known to be less effective in diagnosing anomalous trichromacies.⁵

Among the various reference and standard tests for diagnosing colour deficiency, the Colour Assessment Diagnosis (CAD) test has been introduced to address some of the limitations of the aforementioned tests. The CAD test⁶ requires the observer to identify the movement direction of a coloured square stimulus displayed against a dynamic luminance noise background.⁷ This test is frequently used in multi-level diagnostic protocols since it has proven to have a high reliability and strong agreement with the anomaloscope.⁸

The gold standard for diagnosing colour deficiency remains the anomaloscope, represented in Fig. 2c. Different types of anomaloscope exist, depending on the chromatic axis being tested. The Rayleigh match, used to assess red–green deficiencies, involves

² Barry L. Cole et al., “The new Richmond HRR pseudoisochromatic test for colour vision is better than the Ishihara test,” *Clinical and Experimental Optometry* 89, no. 2 (2006), <https://doi.org/10.1111/j.1444-0938.2006.00015.x>.

³ Jason S. Ng et al., “Evaluation of the Waggoner Computerized Color Vision Test,” *Optometry and Vision Science* 92, no. 4 (2015), <https://doi.org/10.1097/OPX.0000000000000551>.

⁴ Dean Farnsworth, “The Farnsworth-Munsell 100-Hue and Dichotomous Tests for Color Vision,” *Journal of the Optical Society of America* 33, no. 10 (1943), <https://doi.org/10.1364/JOSA.33.000568>.

⁵ Rodriguez-Carmona et al., “Color vision assessment-2.”

⁶ Jayasree Seshadri et al., “Evaluation of the New Web-Based ‘Colour Assessment and Diagnosis’ Test,” *Optometry and Vision Science* 82, no. 10 (2005), <https://doi.org/10.1097/01.opx.0000182211.48498.4e>.

⁷ Benjamin E. W. Evans et al., “Color vision assessment-1: Visual signals that affect the results of the Farnsworth D-15 test,” *Color Research and Application* 46, no. 1 (2021), <https://doi.org/10.1002/col.22596>.

⁸ John L. Barbur et al., “Color vision assessment-3. An efficient, two-step, color assessment protocol,” *Color Research and Application* 46, no. 1 (2021), <https://doi.org/10.1002/col.22599>; Rodriguez-Carmona et al., “Color vision assessment-2.”

adjusting a mixture of red and green light to match a yellow light, with primary wavelengths and intensities defined according to DIN 6160 standards.⁹ The Moreland match is used for the diagnosis of defects along the blue–yellow axis instead. Through the anomaloscope, colour deficiencies and anomalous trichromacies can be diagnosed since they form distinct distributions outside the matching range of a colour normal observer. The anomaloscope remains the only test that can distinguish between anomalous trichromacies and dichromacies. Different studies have also demonstrated a correlation between the anomaloscope matches and the predicted pigment separations from genetic analysis,¹⁰ underscoring its diagnostic reliability.

To ensure accuracy, all the tests mentioned so far intentionally avoid any form of edges on the colour targets. So despite being effective for classifying colour vision deficiencies, this choice makes them purely pointwise and also shows their main limitation: they exclude the spatial mechanisms that are fundamental to human vision, as borders could introduce spatial information that changes colour appearance.

Concerning colour deficiency simulation, many different daltonization methods exist, such as Françoise Viénot et al.,¹¹

⁹ Peter B. M. Thomas and John D. Mollon, “Modelling the Rayleigh match,” *Visual Neuroscience* 21, no. 3 (2004), <https://doi.org/10.1017/S095252380421344X>.

¹⁰ John L. Barbur et al., “A study of unusual Rayleigh matches in deutan deficiency,” *Visual Neuroscience* 25, no. 3 (2008), <https://doi.org/10.1017/S0952523808080619>; Wolfgang Jagla et al., “Hybrid Pigment Genes, Dichromacy, and Anomalous Trichromacy,” *Normal and Defective Colour Vision* (2003), <https://doi.org/10.1093/acprof:oso/9780198525301.003.0032>.

¹¹ Françoise Viénot et al., “Digital video colourmaps for checking the legibility of displays by dichromats,” *Color Research and Application* 24, no. 4 (1999), [https://doi.org/10.1002/\(SICI\)1520-6378\(199908\)24:4<243::AID-COL5>3.0.CO;2-3](https://doi.org/10.1002/(SICI)1520-6378(199908)24:4<243::AID-COL5>3.0.CO;2-3).

Vischeck,¹² Coblis V1,¹³ Coblis V2,¹⁴ Gustavo M. Machado et al.¹⁵ These simulators accept RGB images as input and map them to the colour space corresponding to the dichromatic vision of interest using a suitable transformation matrix. This matrix can be obtained with different methods and can be dependent on several factors such as the spectral sensitivity functions used, the normalization factors and the spectral power distribution of the RGB primaries of the chosen colour space. The variability of these factors results in significant differences across simulators: the different principles and experimental data they are based on lead to inconsistent results as illustrated in Fig. 3. In this example, the original colour checker image (Fig. 3a) is compared with its simulated appearance for a protanopic observer obtained using different daltonization algorithms (Fig. 3b–f). Although these simulators all aim to reproduce the same type of colour vision deficiency, the resulting images show noticeable differences in the rendering of the colour patches. For instance, the orange patch is rendered as a light yellow in some simulations, while in others it appears as a darker, brownish yellow. Similarly, the purple patch is mapped to different shades of blue depending on the adopted model, and other variations can be observed across the remaining patches. These variations highlight how current pixel-wise simulation methods can lead to perceptually different results.

¹² Vischeck is a software tool that implements the colour vision deficiency simulation algorithm described in Hans Brettel et al., “Computerized simulation of color appearance for dichromats,” *Journal of the Optical Society of America A*, 14, no. 10 (1997), <https://doi.org/10.1364/JOSAA.14.002647>.

¹³ Coblis V1 – Coblis is an acronym for “Color Blindness Simulator” (Colblindor, 2008), available at <https://www.color-blindness.com/coblis1-color-blindness-simulator/>. This version (V1) relies on an outdated method, also known as “ColorMatrix,” that relies on a very simplified and inaccurate matrix, <https://web.archive.org/web/20081014161121/http://www.colorjack.com/labs/colormatrix/>.

¹⁴ Coblis V2 – Coblis is an acronym for “Color Blindness Simulator” (Colblindor, 2016), available at <https://www.color-blindness.com/coblis-color-blindness-simulator/>. This version (V2) applies the Color Blind Simulation function by Matthew Wickline and the Human-Computer Interaction Resource Network (HCIRN), https://web.archive.org/web/20090318054431/http://www.nofunc.com/Color_Blindness_Library

¹⁵ Gustavo M. Machado et al., “A Physiologically-based Model for Simulation of Color Vision Deficiency,” *IEEE Transactions on Visualization and Computer Graphics* 15, no. 6 (2009), <https://doi.org/10.1109/TVCG.2009.113>.

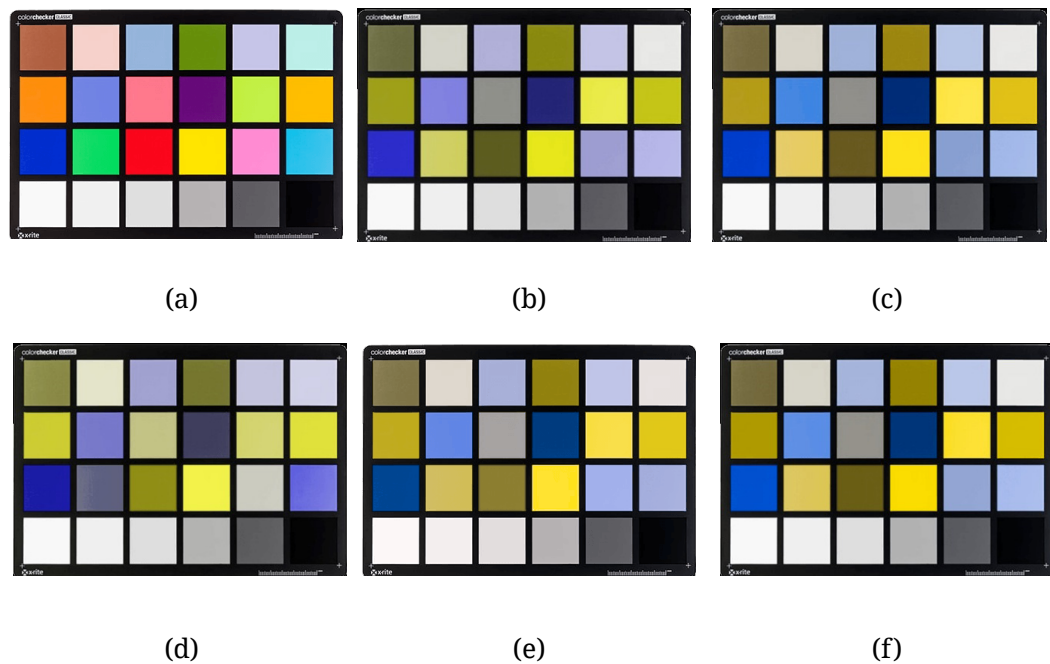


Figure 3. Original colour checker image (a) and comparison of results of a few daltonizers: (b) Viénot (Viénot et al. 1999), (c) Vischeck (Brettel et al. 1997), (d) Coblis V1 (2008), (e) Coblis V2 (2016), (f) Machado (Machado et al. 2009). The results were obtained from the DaltonLens website, available at <https://daltonlens.org/colorblindness-simulator>.

In addition, all of these simulators compute a pixel-wise transformation. However, as we will discuss in the next section, the colour perception in humans has a strong spatial component. For this reason, besides their wide differences in the results, simulators can only offer a partial solution to the problem of simulating and understanding colour perception in colour-deficient individuals.¹⁶

The Spatial Mechanism in Colour Perception

Colour vision begins with the signal that reaches the retina, where light is captured by the cone photoreceptors. However, visual processing does not stop there: the signal is transmitted to the brain, where it is

¹⁶ Russell L. De Valois and Karen K. De Valois, “A multi-stage color model,” *Vision Research*, 33, no. 8 (1993), [https://doi.org/10.1016/0042-6989\(93\)90240-W](https://doi.org/10.1016/0042-6989(93)90240-W); Paul DeMarco et al., “Full-spectrum cone sensitivity functions for X-chromosome-linked anomalous trichromats,” *Journal of the Optical Society of America A* 9, no. 9 (1992), <https://doi.org/10.1364/JOSAA.9.001465>.

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transformed and interpreted through several processing mechanisms that shape our final perception of colour.

Current research supports the idea that spatial comparison throughout the visual pathway is fundamental for colour perception,¹⁷ and shape recognition appears to reinforce this spatial mechanism through edge detection and gradients' compensation. Spatial computation in the human visual system serves two main purposes: it promotes colour constancy making vision robust against widely varying viewing conditions, and it compensates for the effect of glare. The lens of the eye is in fact highly affected by glare,¹⁸ an unwanted spread of light that causes a severe loss of contrast in the retina, that is then partially compensated by the neural spatial processes.¹⁹

Each point in the visual field is interpreted in relation to its neighbours rather than in isolation. This process, often described as local contrast or spatial comparison, allows the observer to distinguish subtle differences in colour and brightness across a scene.²⁰

At the neural level, edge detection plays a key role in defining colour boundaries. The visual system enhances changes at edges and reduces uniform regions or gradients, emphasizing spatial transitions that convey meaningful information. These edge-based signals are essential for object recognition and maintaining colour constancy under different lighting conditions.²¹

¹⁷ Alessandro Rizzi, "Colour after colorimetry," *Coloration Technology* 137, no. 1 (2021), <https://doi.org/10.1111/cote.12496>.

¹⁸ John J. McCann and Alessandro Rizzi, "Retinal HDR images: Intraocular glare and object size," *Journal of the Society for Information Display* 17, no. 11 (2009), <https://doi.org/10.1889/JSID17.11.913>.

¹⁹ Alessandro Rizzi and John J. McCann, "Glare-limited appearances in HDR images," *Journal of the Society for Information Display* 17, no. 1 (2009), <https://doi.org/10.1889/JSID17.1.3>.

²⁰ John J. McCann, "Retinex at 50: Color theory and spatial algorithms, a review," *Journal of Electronic Imaging* 26, no. 3 (2017), <https://doi.org/10.1117/1.JEI.26.3.031204>.

²¹ John J. McCann et al., "Edges and gradients in lightness illusions: Role of optical veiling glare," *Frontiers in Psychology* 13 (2022), <https://doi.org/10.3389/fpsyg.2022.958787>.

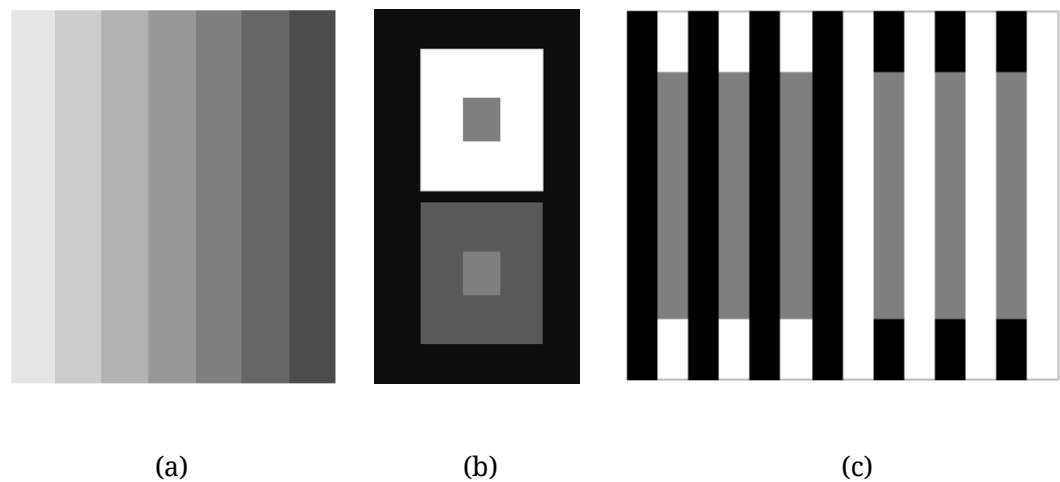


Figure 4. Mach band (a), simultaneous contrast (b), and assimilation effect (c).

Visual illusions can effectively demonstrate how colour perception relies not only on point-wise stimuli but also on the spatial arrangement within a scene. In the Mach bands (see Fig. 4a) and Cornsweet illusion, the edges between the different grey stripes create the illusion of a gradient: despite being uniform, the strips are perceived as darker on their left boundaries and lighter on their right boundaries. The simultaneous contrast (represented in Fig. 4b) further demonstrates how edges and surroundings influence perception. In this case, the central patch appears to have different brightness depending on its background: the darker the background the lighter the centre will appear and vice versa, even though the central colour remains unchanged. The assimilation effect (shown in Fig. 4c) operates in the opposite way to simultaneous contrast. In this case, the grey patch on the right, surrounded by white, appears lighter than the identical grey patch on the left, which is surrounded by black.

These examples show that colour perception emerges from the spatial relationships between different areas of an image. Colour perception is not determined by single pixel values, but by how colours interact and compare with each other across space. Colour sensation at a given point is not determined by isolated local stimuli, but by how colours interact and are compared across space. Retinal encoding and cortical processing cannot be separated in the perception of colour: the signal captured by the photoreceptors is further shaped by spatial

mechanisms in the visual pathway, which play a fundamental role in the final percept.

The Spatial Mechanism in Colour Vision Deficiency

Even though the role of spatial processing in vision has been widely demonstrated, only a few studies provide evidence of this phenomenon in colour vision deficiency. Research on colour vision deficiency is largely focused on retinal mechanisms, and post-retinal processing is usually assumed to be identical to that of colour-normal observers. However, this assumption lacks direct experimental confirmation, as only a few studies have explicitly investigated post-retinal spatial processing in colour-deficient individuals. These studies demonstrate how small changes in spatial or contextual features can significantly impact the performance of colour-deficient observers.

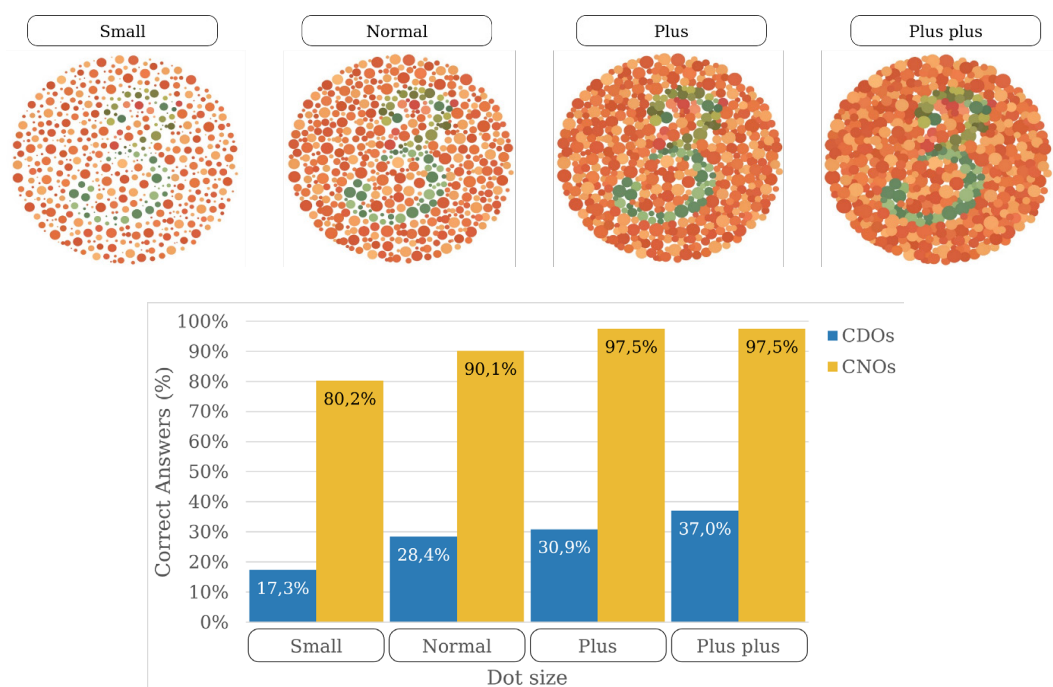


Figure 5. Example of Ishihara-based plates showing different dot sizes (small, normal, plus, and plus plus) and the respective perceptual outcomes for colour-deficient and colour-normal observers.

Source: Adapted from (Rizzi et al. 2014).

Studies reported in the papers by Eschbach and Nussbaum²² and Rizzi et al.²³ explored the role of edges and spatial arrangements in colour vision deficiency tests. These studies highlighted that standard tests avoid contact between colours, preventing in this way the formation of edges. To address this issue, variants of the Ishihara plates were created by modifying the size of the dots to create edges between them.

In the 2014 study, represented in Fig. 5, the test was conducted on 9 Colour Normal (CNOs) and 9 Colour Deficient Observers (CDOs) using a mobile application that recorded both accuracy and response time. Each plate was presented in four variants with different dot sizes: Small, Normal, Plus, and Plus Plus. Results showed a clear improvement in recognition for colour-deficient observers alongside the increasing size of the dots: correct responses increased from 17.3% with smaller dots to 37.0% with larger ones. Colour-normal observers also performed slightly better, improving from 80.2% to 97.5% accuracy.

Building on these findings, in the 2021 study, the experiment was redefined by varying the size of the dots, ranging from normal to larger diameter and using confusion lines derived from published copunctal points. The study involved 10 CDOs and generated three enlarged versions of each plate to increase edge content. The scaling factors applied to the dot diameters were approximately +5 %, +13 %, and +30 % for large, medium, and small dots, respectively. The results confirmed that edges improve readability for colour-deficient observers: recognition rates rose from about 47.8% with standard plates to 86.4% with the enhanced-edge versions, while the average response time for correct answers decreased from 3.33 seconds to 2.52 seconds.

These results provide further evidence that spatial processing, and especially the use of edge information, plays an important role in colour perception for individuals with colour vision deficiency.

²² Reiner Eschbach and Peter Nussbaum, "Examining Spatial Attributes for Color Deficient Observers," *Electronic Imaging* 33 (2021), <https://doi.org/10.2352/ISSN.2470-1173.2021.16.COLOR-308>.

²³ Alessandro Rizzi et al., "Modified Ishihara test to study the role of edges in color discrimination," *Italian Journal of Aerospace Medicine* 11 (2014), <https://hdl.handle.net/2434/266235>.

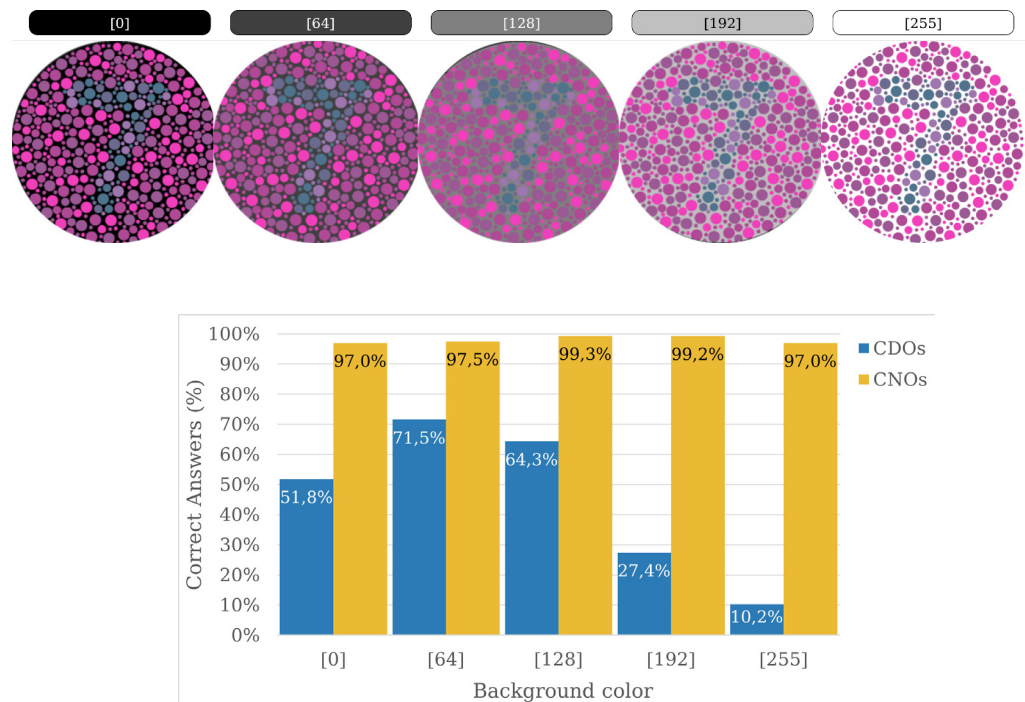


Figure 6. Example of Ishihara-based plates showing different background colour (black, shades of grey, and white) and the respective perceptual outcomes for colour-deficient observers (CDOs) and colour-normal observers (CNOs).

Source: Adapted from (Eschbach et al. 2022; Eschbach and Nussbaum 2022).

In 2022, two complementary studies²⁴ extended this line of research by investigating how changes in background colour affect colour identification in pseudo-isochromatic plates. In both experiments, the standard white background (RGB [255, 255, 255]) of the plates was replaced with three grey backgrounds at different luminance levels (RGB = [196, 196, 196]; [128, 128, 128]; and [64, 64, 64]) and one black background (RGB = [0, 0, 0]).

The first experiment²⁵ was conducted with 6 CDOs, while the second experiment²⁶ involved 11 CNOs. The respective results are reported in Fig. 6.

²⁴ Reiner Eschbach et al., “The gray side of Ishihara bubbles,” *Color and Colorimetry. Multidisciplinary Contributions*, vol. XVII A (2022), <https://doi.org/10.23738/RCASB.006>; Reiner Eschbach and Peter Nussbaum, “Initial findings on changing the background in pseudo-isochromatic charts,” *Electronic Imaging 34* (2022), <https://doi.org/10.2352/EL.2022.34.15.COLOR-363>.

²⁵ Eschbach and Nussbaum, “Initial findings.”

²⁶ Eschbach et al., “The gray side.”

For CNOs, recognition improved slightly for mid-grey backgrounds (up to 99.3 %) and decreased for the darkest and brightest conditions. Response times were also shorter for intermediate grey levels (around 1.6 seconds) compared to the white background (2.4 seconds).

For CDOs, this trend is even more evident, with correct responses increasing from 10.2 % with a white background to 71.5 % with a mid-grey background (RGB = [64, 64, 64]).

These experiments show that even small contextual changes, such as background luminance, can strongly influence colour perception. They provide further evidence that both colour-deficient and colour-normal observers rely on spatial mechanisms when interpreting colour information.

More recently, the study by Armellin et al.²⁷ investigated the influence of simultaneous contrast on colour perception in colour-deficient observers. The study aimed to assess how the chromatic context surrounding a stimulus affects perceived colour differences between targets.

The experimental setup, illustrated in Fig. 7, consisted of two coloured patches presented side by side. On the left, a fixed patch was displayed over uniform backgrounds of different colours (6 different colour backgrounds were tested), while on the right a matching patch appeared over a pseudo-white-noise background. Participants adjusted the hue, saturation, and brightness of the matching patch until it visually matched the fixed patch. The experiment involved 13 CDOs and 16 CNOs.

The results, summarized in Fig. 7, show the median CIEDE2000 (ΔE_{00}) values between the adjusted and target colours.

For CNOs, the median colour difference exceeds $\Delta E_{00} = 5$. This means that, although the paired colours are perceived as identical, they are not colorimetrically the same colour, a result that reflects the influence of spatial processing in human vision.

Overall, CNOs exhibited lower median ΔE_{00} values than CDOs under most background conditions, indicating higher colour-matching accuracy. In contrast, CDOs showed greater variability, although

²⁷ Luca Armellin et al., “The Effect of Simultaneous Contrast on Color Deficient Observers,” *Journal of Imaging Science and Technology* 68, no. 6 (2024), <https://doi.org/10.2352/J.ImagingSci.Technol.2024.68.6.060403>.

they consistently adjusted the test patch away from its initial colour, demonstrating an effective perception of chromatic differences. Even in the presence of altered chromatic sensitivity, spatial mechanisms still play a key role in colour perception.

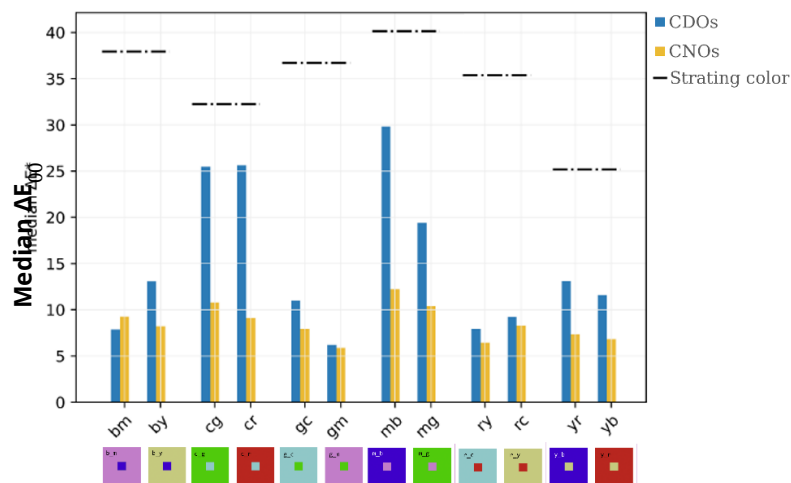
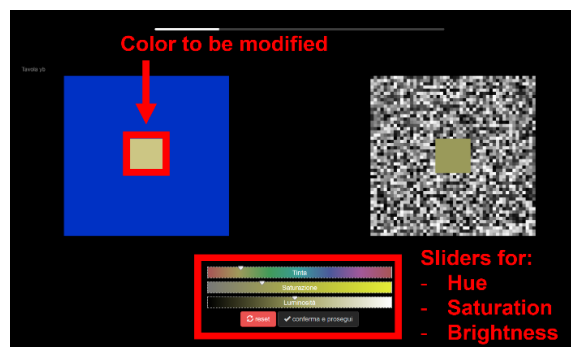


Figure 7. Test setup and median ΔE_{00} between the fixed patch and the matching patch (right), of CDOs, CNOs, and the second experiment's starting colour (black dotted line).

Source: Adapted from (Armellin et al. 2024).

Although the studies discussed here provide clear evidence that spatial factors influence colour perception in both colour-normal and colour-deficient observers, research in this field is still limited and unsystematic. Each study explores a specific aspect of spatial processing; yet there is still no unified framework that connects these results into a consistent understanding of colour vision in colour-deficient observers.

Although many of these spatial effects have been known in vision science for decades, as discussed in Section 3 they have rarely been explicitly explored in the context of colour vision deficiency. Even

more importantly, they have not yet been systematically incorporated into the design of diagnostic tests and simulation models for CVD. While the origin of colour vision deficiency lies in altered cone photoreceptor mechanisms at the retinal level, post-retinal processing largely contributes to shaping the final perceptual experience. So far, colour vision deficiency has been described on a pointwise basis. However, considering that the role of spatial processing in human vision has been widely proven and established, the description of colour vision deficiency must be extended to the high-level functions that generate post-retinal information. Colour vision is not based on point-wise signal processing but highly depends on the context. This has important implications for real-world applications. A pure retinal approach to colour vision might not well capture our real ability of visual perception in realistic settings and thus highlights the need for the development of spatially aware testing methodologies.

A deeper understanding of the spatial mechanisms involved in colour vision deficiency may also prove useful for the development of visual accessibility strategies in the future. From this broader perspective, the CIE 240:2020 Technical Report²⁸ summarizes current image enhancement approaches for colour-deficient observers, but also underlines the need for the development of new enhancement techniques and evaluation methods. This further highlights the need for perceptually grounded models to support future assessment methodologies.

We encourage the scientific community to continue in this direction and develop new diagnostic tools and simulation models that better reflect how colour-deficient individuals perceive their visual environment. Including the spatial dimension in the study of colour vision will allow for a more complete and realistic understanding of human perception.

Conclusions

Current models of colour vision deficiency and most diagnostic tests are still based mainly on pointwise colorimetric principles and do not account for the spatial processing carried out by the brain.

²⁸ International Commission on Illumination (CIE). Enhancement of Images for Colour-Deficient Observers. CIE 240:2020. <https://doi.org/10.25039/TR.240.2020>.

Although these mechanisms are well known, only a few studies have investigated them in the context of colour vision deficiency. The studies reviewed here in this work show that colour perception cannot be separated from spatial processing. Mechanisms such as edge detection, local contrast, and comparison of the surrounding information play a key role in how both colour-normal and colour-deficient observers perceive visual scenes.

We intend for this study to raise awareness in the scientific community about the need for a comprehensive view of colour perception in colour vision deficiency. Future research should include spatial mechanisms in both theoretical and experimental approaches. This will lead to a more accurate and realistic description of how colour-deficient individuals perceive colour.

References

- Armellin, Luca, Alice Plutino, Andrea Mazzoni, and Alessandro Rizzi. “The Effect of Simultaneous Contrast on Color Deficient Observers.” *Journal of Imaging Science and Technology* 68, no. 6 (2024): 1–8. <https://doi.org/10.2352/J.ImagingSci.Technol.2024.68.6.060403>.
- Barbur, John L., Marisa Rodriguez-Carmona, and Benjamin E. W. Evans. “Color vision assessment-3. An efficient, two-step, color assessment protocol.” *Color Research and Application* 46, no. 1 (2021): 33–45. <https://doi.org/10.1002/col.22599>.
- Barbur, John L., Marisa Rodriguez-Carmona, J. A. Harlow, Katherine Mancuso, Jay Neitz, and Maureen Neitz. “A study of unusual Rayleigh matches in deutan deficiency.” *Visual Neuroscience* 25, no. 3 (2008): 507–516. <https://doi.org/10.1017/S0952523808080619>.
- Brettel, Hans, Françoise Viénot, and John D. Mollon. “Computerized simulation of color appearance for dichromats.” *Journal of the Optical Society of America A*, 14, no. 10 (1997): 2647–2655. <https://doi.org/10.1364/JOSAA.14.002647>.
- “Coblis.v1 – Color Blindness Simulator.” Colblindor. 2008. <https://www.color-blindness.com/coblis1-color-blindness-simulator/>.
- “Coblis – Color Blindness Simulator.” Colblindor. 2016. <https://www.color-blindness.com/coblis-color-blindness-simulator/>.
- Cole, Barry L., Ka-yee Lian, and Carol Lakkis. “The new Richmond HRR pseudoisochromatic test for colour vision is better than the Ishihara test.” *Clinical and Experimental Optometry* 89, no. 2 (2006): 73–80. <https://doi.org/10.1111/j.1444-0938.2006.00015.x>.

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- De Valois, Russell L., and Karen K. De Valois. "A multi-stage color model." *Vision Research*, 33, no. 8 (1993): 1053–1065. [https://doi.org/10.1016/0042-6989\(93\)90240-W](https://doi.org/10.1016/0042-6989(93)90240-W).
- DeMarco, Paul, Joel Pokorny, and Vivianne C. Smith. "Full-spectrum cone sensitivity functions for X-chromosome-linked anomalous trichromats." *Journal of the Optical Society of America A* 9, no. 9 (1992): 1465–1476. <https://doi.org/10.1364/JOSAA.9.001465>.
- Eschbach, Reiner, and Peter Nussbaum. "Examining Spatial Attributes for Color Deficient Observers." *Electronic Imaging* 33 (2021): 1–10. <https://doi.org/10.2352/ISSN.2470-1173.2021.16.COLOR-308>.
- Eschbach, Reiner, and Peter Nussbaum. "Initial findings on changing the background in pseudo-isochromatic charts." *Electronic Imaging* 34 (2022): 1–2. <https://doi.org/10.2352/EI.2022.34.15.COLOR-363>.
- Eschbach, Reiner, Alice Plutino, Luca Armellin, and Alessandro Rizzi. "The gray side of Ishihara bubbles." *Color and Colorimetry. Multidisciplinary Contributions*, vol. XVII A (2022): 71–75. <https://doi.org/10.23738/RCASB.006>.
- Evans, Benjamin E. W., Marisa Rodriguez-Carmona, and John L. Barbur. "Color vision assessment-1: Visual signals that affect the results of the Farnsworth D-15 test." *Color Research and Application* 46, no. 1 (2021): 7–20. <https://doi.org/10.1002/col.22596>.
- Farnsworth, Dean. "The Farnsworth-Munsell 100-Hue and Dichotomous Tests for Color Vision." *Journal of the Optical Society of America* 33, no. 10 (1943): 568–578. <https://doi.org/10.1364/JOSA.33.000568>.
- Hunt, David M., and Livia S. Carvalho. "The Genetics of Color Vision and Congenital Color Deficiencies." In *Human Color Vision*, edited by Jan Kremers, Rigmor C. Baraas, and N. Justin Marshall, 1–32. Springer International Publishing, 2016. https://doi.org/10.1007/978-3-319-44978-4_1.
- International Commission on Illumination (CIE). *Enhancement of Images for Colour-Deficient Observers*. CIE 240:2020. <https://doi.org/10.25039/TR.240.2020>.
- Jagla, Wolfgang, Tanja Breitsprecher, Itala Kucsera, Gyula Kovacs, Bernd Wissinger, Samir S. Deeb, and Lindsay T. Sharpe. "Hybrid Pigment Genes, Dichromacy, and Anomalous Trichromacy." *Normal and Defective Colour Vision* (2003): 307–317. <https://doi.org/10.1093/acprof:oso/9780198525301.003.0032>.
- Machado, Gustavo M., Manuel M. Oliveira, and Leandro A. F. Fernandes. "A Physiologically-based Model for Simulation of Color Vision Deficiency." *IEEE Transactions on Visualization and Computer Graphics* 15, no. 6 (2009): 1291–1298. <https://doi.org/10.1109/TVCG.2009.113>.
- McCann, John J. "Retinex at 50: Color theory and spatial algorithms, a review." *Journal of Electronic Imaging* 26, no. 3 (2017): 031204. <https://doi.org/10.1117/1.JEI.26.3.031204>.
- McCann, John J., and Alessandro Rizzi. "Retinal HDR images: Intraocular glare and object size." *Journal of the Society for Information Display* 17, no. 11 (2009): 913–920. <https://doi.org/10.1889/JSID17.11.913>.

- McCann, John J., Vassilios Vonikakis, and Alessandro Rizzi. “Edges and gradients in lightness illusions: Role of optical veiling glare.” *Frontiers in Psychology* 13 (2022): 958787. <https://doi.org/10.3389/fpsyg.2022.958787>.
- Ng, Jason S., Eriko Self, John E. Vanston, Andrew L. Nguyen, and Michael A. Crognale. “Evaluation of the Waggoner Computerized Color Vision Test.” *Optometry and Vision Science* 92, no. 4 (2015): 480–486. <https://doi.org/10.1097/OPX.0000000000000551>.
- Rizzi, Alessandro. “Colour after colorimetry.” *Coloration Technology* 137, no. 1 (2021): 22–28. <https://doi.org/10.1111/cote.12496>.
- Rizzi, Alessandro, and John J. McCann. “Glare-limited appearances in HDR images.” *Journal of the Society for Information Display* 17, no. 1 (2009): 3–12. <https://doi.org/10.1889/JSID17.1.3>.
- Rizzi, Alessandro, Reiner Eschbach, Angelo Quaranta, and Cristian Bonanomi. “Modified Ishihara test to study the role of edges in color discrimination.” *Italian Journal of Aerospace Medicine* 11 (2014): 20–25. <https://hdl.handle.net/2434/266235>.
- Rodriguez-Carmona, Marisa, Benjamin E. W. Evans, and John L. Barbur. “Color vision assessment-2: Color assessment outcomes using single and multi-test protocols.” *Color Research and Application* 46, no. 1 (2021): 21–32. <https://doi.org/10.1002/col.22598>.
- Seshadri, Jayasree, Jerry Christensen, Vasudevan Lakshminarayanan, and Carl J. Bassi. “Evaluation of the New Web-Based ‘Colour Assessment and Diagnosis’ Test.” *Optometry and Vision Science* 82, no. 10 (2005): 882–885. <https://doi.org/10.1097/01.opx.0000182211.48498.4e>.
- Thomas, Peter B. M., and John D. Mollon. “Modelling the Rayleigh match.” *Visual Neuroscience* 21, no. 3 (2004): 477–482. <https://doi.org/10.1017/S095252380421344X>.
- Viénot, Françoise, Hans Brettel, and John D. Mollon. “Digital video colourmaps for checking the legibility of displays by dichromats.” *Color Research and Application* 24, no. 4 (1999): 243–252. [https://doi.org/10.1002/\(SICI\)1520-6378\(199908\)24:4<243::AID-COL5>3.0.CO;2-3](https://doi.org/10.1002/(SICI)1520-6378(199908)24:4<243::AID-COL5>3.0.CO;2-3).

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