

A simulation-based analysis of tritanopia colour perception for inclusive colour design

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This study examines colour perception under simulated tritanopia (blue-yellow colour vision deficiencies) conditions to support inclusive colour design within the built environment. While inclusive colour design principles have gained significant attention, academic research has predominantly focused on accommodating red-green colour vision deficiencies, leaving tritanopia relatively under-addressed. To address this gap, a simulation-based analysis was conducted using the Munsell Color System as a standardised framework for evaluating colour perception. Ten Munsell hue charts were analysed under normal colour vision and simulated tritanopia conditions using the Coblis colour vision deficiency simulator. A systematic comparative analysis was performed to identify changes in hue and chroma across the colour samples. Based on the observed perceptual transformations, inclusive colour scheme design guidelines were developed through the integration of colour harmony theories and the functional roles of colour in the built environment. The findings reveal distinct hue shifts and diminished saturation in specific colour regions, which can impair visual discrimination and information recognition. By translating these perceptual characteristics into practical colour scheme recommendations, this study provides a framework for designers seeking to enhance accessibility, legibility, and visual effectiveness for users with diverse colour vision capabilities.

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Introduction

Designing the built environment to address the varied physiological and psychological requirements of all people is a cornerstone of contemporary practice and is closely aligned with the principles of Inclusive Design. As a key architectural component, colour significantly influences wayfinding, safety, and the overall aesthetic quality of spaces. Consequently, inclusive colour design has paid increasing attention to the needs of users with colour vision deficiency (CVD). However, a critical review of existing literature shows that red-green colour vision deficiencies (protanopia and deuteranopia) have historically received disproportionate attention, while blue-yellow colour vision deficiencies (tritanopia) remain comparatively underexplored in both scholarly and professional contexts.

To fully support the goals of inclusive design, it is essential to consider the entire range of colour vision deficiencies. While tritanopia occurs less frequently than other types of colour vision loss, it can significantly hinder a person's capacity to understand visual information in the built environment. Inclusive design aims to ensure that spaces are accessible, understandable, and usable for everyone, regardless of age, body size, or sensory capabilities. Consequently, broadening inclusive colour design research to explicitly encompass tritanopia is not only for expanding scholarly understanding but also for improving accessibility and visual communication in the built environment.

The present study aims to address the limited understanding of tritanopia within inclusive colour design research by systematically examining perceptual colour transformations under simulated tritanopia conditions. Specifically, the study pursues two objectives: 1) to analyse changes in hue and chroma across standardised Munsell colour charts under simulated tritanopia relative to normal colour vision, and 2) to develop inclusive colour scheme design strategies informed by the observed perceptual transformations, colour harmony theories, and functional applications of colour within the built environment. In doing so, the study seeks to offer practical support for people with tritanopia while also informing design practitioners about the intricacies of inclusive colour use, thereby contributing to more accessible and functionally effective visual environments.

Colour vision deficiency (CVD) and tritanopia

Colour perception under normal visual conditions is mediated by three types of cone photoreceptors in the retina, which are sensitive to long (red), medium (green), and short (blue) wavelengths of light. Alterations in the function, presence, or photopigment composition of these cone cells can result in impairments in colour discrimination. These difficulties are collectively referred to as colour vision deficiency (CVD), commonly known as colour blindness. CVD is defined as a visual disorder involving a diminished or modified capacity to perceive and differentiate colours, usually arising from anomalies in retinal cone photoreceptors or in the neural pathways that process chromatic information [1-2].

CVD exists along a spectrum and does not generally involve a total absence of colour perception. Most individuals maintain some degree of colour vision but experience difficulty distinguishing specific colour ranges, most commonly red and green or blue and yellow differences [2]. The condition can be broadly categorised into congenital and acquired forms. Congenital CVD is typically inherited and often associated with X-linked genetic mutations affecting photopigments, resulting in a higher prevalence among males. In contrast, acquired CVD may arise from ocular diseases, neurological disorders, aging, or exposure to certain medications [3].

Within the broader classification of CVD, both empirical research and applied methodologies have predominantly concentrated on red-green deficiencies, specifically protanopia and deuteranopia. This focus is largely attributable to their high global prevalence, collectively accounting for approximately 95% of all documented CVD cases [4-5]. In comparison, blue-yellow deficiency (tritanopia) remains relatively underexplored, despite its distinct perceptual implications. Tritanopia is a rare form of CVD, representing less than 1% of cases, and is associated with deficiencies in short-wavelength-sensitive cones [6-7].

Despite increasing scholarly attention to the role of colour in environmental accessibility and design, the relative paucity of empirical research on blue-yellow colour vision deficiency indicates a significant gap in the current literature. Systematically addressing this gap is crucial for the development of more inclusive and evidence-based design strategies that explicitly account for the full range of colour vision impairments.

Colour order system and colour harmony theory

The Munsell Color System serves as a foundational framework in contemporary colour science, characterising colour within a three-dimensional space defined by three independent attributes: Hue (H), Value (V), and Chroma (C). This framework is conceptually structured as a colour sphere and a colour tree, and it enables the precise specification of any colour using the notation H V/C. Munsell's primary objective was to develop a colour atlas characterised by equal visual spacing between samples, serving as a physical colour order system for both pedagogical specification and professional application [8]. The rigour of the system was significantly enhanced through extensive experiments conducted by the Optical Society of America. These studies, involving over three million observations, improved the visual uniformity of the system and established the modern H V/C notation [9]. The Munsell system represents a sophisticated scientific compromise that bridges artistic practice with emerging colour science, maintaining its position as one of the most widely used colour order systems in colour research.

Colour harmony theory		Description
Munsell	Principle of balance	Harmonious colour composition, when mixed as on a spinning disk, should result in a neutral grey. This "balance at the centre" is the mathematical proof of visual comfort.
	Three-dimensional order	Harmony is achieved by selecting colours that have a clear, measurable relationship in terms of Hue, Value, and Chroma.
	Path to harmony	Moving along paths within the colour solid, such as moving vertically through values or horizontally through chromas, creates a rhythmic, predictable, and therefore harmonious experience.
	Law of areas	Strong, high chroma colours should be used in small areas, while weak, low chroma colours should be used in large areas to maintain visual equilibrium.
	Equal interval relationships	Harmony is established when colours are chosen at regular, stepping-stone intervals. Whether it is a change in Value or a change in Hue, the regularity of the interval itself creates the sense of order.
	Balanced opposites	Harmony is achieved by balancing opposing hues through an inverse relationship between chroma and spatial area; specifically, higher chroma elements must occupy proportionally smaller areas to maintain visual equilibrium.
	Spatial chroma attenuation	Harmony in large volumes is achieved through diminished chroma. This principle dictates that as surface area expands, saturation must decrease to preserve a comfortable perceptual equilibrium.
Basic	Monochromatic	Monochromatic harmony utilises a single hue with variations in value and chroma to establish maximum visual unity. This approach is particularly effective in interior environments where subtle tonal progressions and spatial stability are required.
	Analogous	Harmony is achieved by selecting adjacent hues on the colour wheel to create a cohesive yet dynamic composition. This strategy promotes natural transitions and minimises visual tension, resulting in a comfortable and fluid environment.
	Complementary	Complementary harmony pairs hues situated directly opposite each other to generate high visual contrast and chromatic intensity. To prevent overstimulation, this vibrant approach requires precise modulation of value and chroma to maintain equilibrium.
	Split complementary	Split-complementary harmony combines a base hue with the two colours adjacent to its direct complement. This method retains the dynamic appeal of complementary contrast while offering a more balanced and versatile chromatic complexity.

Table 1: Colour harmony theory [10-11].

Grounded in Munsell's Color System, this theory of colour harmony emphasises perceptual organisation and systematic relationships among hue, value, and chroma. It posits that harmony emerges when colours are arranged according to clearly defined intervals and structurally coherent

patterns within the colour space, rather than through arbitrary selection [10]. Colour harmony is thereby conceptualised as the deliberate structuring of interrelationships among the three dimensions within a three-dimensional colour space (Table 1). In addition to Munsell's harmony theory, widely used colour harmony schemes such as monochromatic, analogous, complementary, and split-complementary schemes are widely derived from traditional colour wheel relationships and have been systematised in design education, particularly through the work of Itten [11]. The present study applied these theoretical models of colour harmony as foundational principles for the development of inclusive colour scheme design guidelines.

Colour function in built environment

Colour serves as a multifaceted instrument within the built environment, performing various critical functions that have been extensively documented in design literature. Portillo and Dohr [12] proposed a comprehensive framework that categorises the role of colour into five distinct functions, thereby providing a foundational model for understanding the operation of colour in architectural and interior contexts.

First, compositional functions allow designers to use colour as a structural element to create visual unity or emphasis. Through the strategic deployment of colour, designers can modulate spatial perception and formal legibility, such as adjusting the perceived scale of an interior or highlighting specific architectural features. Second, symbolic functions involve the use of colour to express design concepts and convey specific associations or meanings. In this capacity, colour serves as a medium that conveys design concepts, brand identities, cultural values, or abstract narratives aligned with the overarching intent of a project. These symbolic associations may be grounded in cultural conventions, psychological responses, or institutional codes. Third, behavioural functions focus on how colour supports the functional needs of occupants and shapes their movement through space. This includes facilitating wayfinding, structuring spatial orientation, supporting concentration and task performance, and promoting rest or relaxation. Through these mechanisms, colour directly affects how individuals experience, navigate, and cognitively map their environments. Fourth, preferential functions address the subjective nature of colour, reflecting the individual tastes of both designers and clients while also responding to broader market trends and stylistic cycles. These functions reflect the interaction between personal taste, socio-cultural context, and commercial forces in determining colour choices. Finally, pragmatic functions involve the practical considerations of colour planning. This includes issues of maintenance, durability, lighting conditions, material properties, and existing environmental constraints. From this perspective, colour planning is evaluated not only in aesthetic or symbolic terms but also in relation to long-term performance, cost-effectiveness, and sustainability within the built environment.

Building upon these concepts, Kim et al. [13] proposed a correlation model identifying principal functional roles of colour within the built environment (Figure 1). First, the safety function is critical for signaling danger and alerting individuals to potential physical hazards. By utilising high contrast in hue, brightness, or saturation, colour supports safety diagnosis, classification, and maintenance. Second, the identification function enables the highlighting and differentiation of specific objects and informational elements, a role that is particularly critical for the legibility of cartographic materials and wayfinding systems. Third, the aesthetic function focuses on evoking emotional responses, where colour is used to create either positive or negative visual impressions, shaping the overall beauty and atmospheric quality of an environment. Fourth, the symbolic function enables colour to convey deeper meanings and

cultural associations, serving as a medium for institutional or functional symbolism in art, design, and architecture. Furthermore, the model addresses the human-centric aspects of colour through three interrelated categories: physical functions, which concern visibility, legibility, and interaction between light and colour; physiological-psychological functions, which affect users' arousal levels, comfort, and emotional states; and therapeutic functions, in which supportive chromatic environments are intentionally designed to promote health and overall well-being. Finally, the camouflage function involves the use of subdued or blended chromatic schemes to visually downplay or conceal specific elements.

Practical guidelines for inclusive colour design were derived by synthesising these functional dimensions of colour with principles of colour harmony, with the aim of achieving both functional legibility and aesthetic coherence.

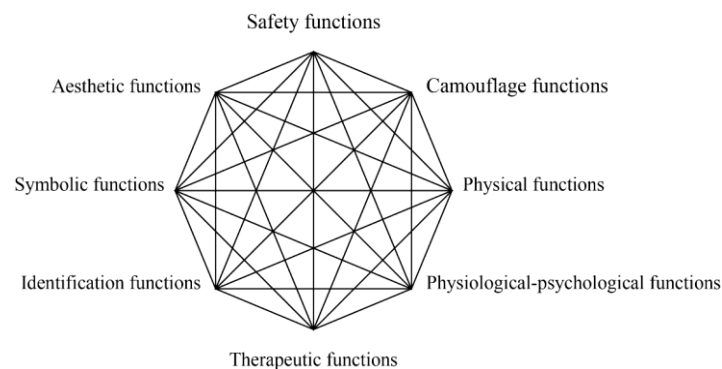


Figure 1: Colour function [13].

Methodology

Research design

This study employed a simulation-based analytical framework to investigate perceptual colour transformations associated with tritanopia and to develop inclusive colour scheme design strategies. The research process consisted of three phases:

1. Assessment of Simulated Tritanopia Perception: Examination and comparison of original Munsell colour charts against their tritanopia-simulated counterparts to identify recurring patterns of hue shifts and chromatic compression.
2. Development of Inclusive Colour Schemes: Formulation of accessible colour scheme recommendations by synthesising the observed perceptual transformations with established theories of colour harmony and the functional roles of colour within the built environment.
3. Validation through Quantitative Colour Difference Analysis: Verification of the proposed colour schemes' efficacy and inclusivity through CIELAB colour difference (ΔE^*_{ab}) calculations, ensuring robust empirical grounding for the design strategies.

Colour simulation and comparative analysis

A computerised colour vision deficiency (CVD) simulation was employed to examine perceptual colour transformations associated with tritanopia. Simulated tritanopia representations of each chart were generated using the Coblis (Color Blindness Simulator) platform. Coblis employs a colour vision

deficiency simulation algorithm derived from the HCIRN Color Blind Simulation model developed by Wickline [14], which has been used for visualising colour perception associated with different forms of colour vision deficiency. Although such simulations cannot fully reproduce the subjective experience of all observers with colour vision deficiency, they provide a practical and systematic framework for comparative colour perception analysis.

Ten standardised Munsell hue charts (5R, 5YR, 5Y, 5GY, 5G, 5BG, 5B, 5PB, 5P, and 5RP) were selected as reference stimuli (Figure 2). The simulation process was conducted to enable direct comparison between the original Munsell colour charts and their corresponding tritanopia-simulated versions. Comparative analysis focused on identifying changes in the primary chromatic attributes of the Munsell Color System, specifically hue and chroma. Particular attention was given to hue shifts, chroma reductions, and the convergence of colour categories that were distinguishable under normal vision. Each of the ten Munsell hue charts was examined individually and compared with its simulated counterpart to identify consistent patterns of perceptual change. Observations were recorded and synthesised to establish recurring trends across the colour spectrum and to determine their potential implications for visual communication, identification, and safety-related colour applications.

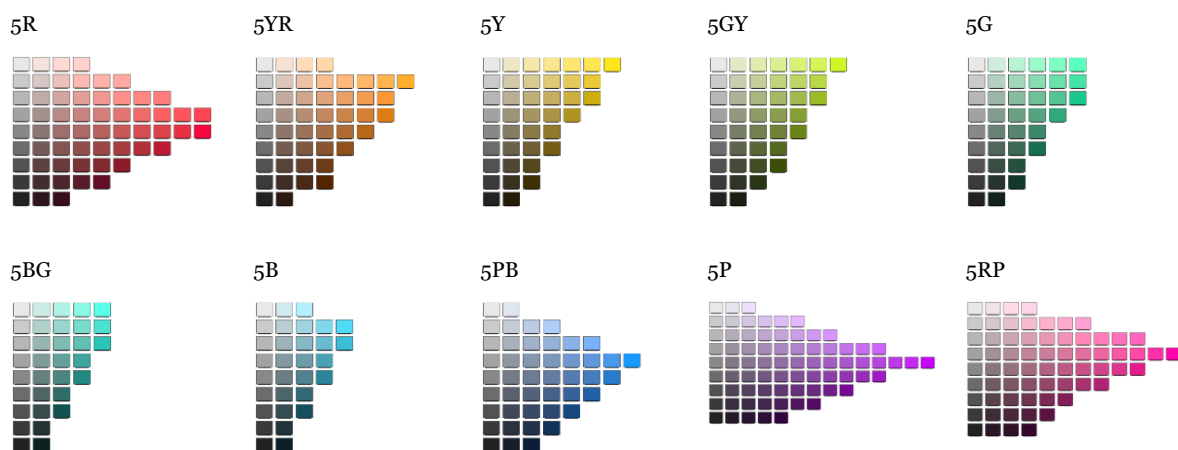


Figure 2: Munsell Color Chart (from left to right: 5R, 5YR, 5Y, 5GY, 5G, 5BG, 5B, 5PB, 5P, 5RP).

Inclusive colour scheme design

The development of inclusive colour scheme guidelines was conducted through a structured synthesis of the comparative colour perception analysis, colour harmony theories, and established functional roles of colour within the built environment. Following the identification of perceptual transformations under simulated tritanopia conditions, colour combinations were evaluated according to their ability to maintain visual differentiation, support information recognition, and preserve overall aesthetic coherence.

Particular emphasis was placed on the identification and safety functions of colour, as difficulties in distinguishing visually similar hues may lead to misinterpretation of information and reduced effectiveness of visual communication systems. Based on the comparative analysis of the Munsell Color Charts, hue categories demonstrating substantial perceptual convergence or chromatic attenuation under simulated tritanopia were identified as potentially problematic for applications requiring clear visual distinction. Conversely, colour combinations that retained perceptual differentiation under simulated tritanopia conditions were selected as the basis for inclusive colour scheme development.

To translate these perceptual findings into practical design strategies, three complementary approaches derived from established colour harmony theories were employed. First, complementary

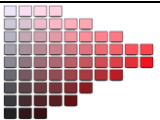
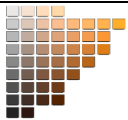
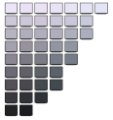
colour relationships were combined with Munsell's Law of Areas to maximise perceptual contrast while maintaining visual balance through the proportional distribution of colours according to their value and chroma characteristics. Second, split-complementary relationships were integrated with Munsell's Balanced Opposites principle to provide strong visual differentiation while reducing the potential visual tension often associated with direct complementary contrasts. Third, Munsell's Path of Harmony was combined with Balanced Opposites to create colour schemes characterised by harmonious value progression and controlled focal emphasis through strategically placed accent colours.

These theoretical frameworks were subsequently applied to generate inclusive colour schemes using hue families that demonstrated favorable perceptual performance under simulated tritanopia conditions. The resulting guidelines prioritise colour combinations that maintain perceptual distinguishability between functional elements while simultaneously supporting visual hierarchy, information communication, and aesthetic coherence.

Results

Comparative analysis of colour perception

The comparative analysis identified consistent patterns of hue shift and chroma reduction across the Munsell hue charts (Table 2). The data indicates that the observers' perceptual colour space is markedly displaced along the blue-red and blue-green axes, while the yellow and purple sectors exhibit pronounced reductions in chroma, consistent with substantial perceptual desaturation in these regions.

	Perspective		Comparative Analysis	
	Normal	Tritanopia	Hue	Chroma
5R			Consistent with target hue; characterised by a subtle blue undertone.	Stable
5YR			Shifted toward red; perceived as desaturated reds.	Diminished
5Y			Perceived as muted reds with significant chromatic attenuation.	Critically Low
5GY			Perceived as achromatic or dull grey.	Critically Low
5G			Shifted toward blue-green; addition of blue tones to green stimuli.	Slightly Low
5BG			Pronounced blue-green shift with dominant blue undertones.	Slightly Low

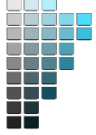
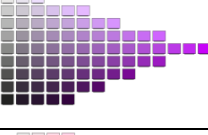
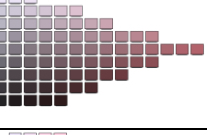
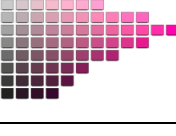
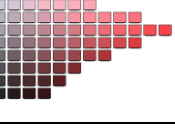
5B			Consistent with target hue; characterised by a subtle green undertone.	Stable
5PB			Significant chromatic shift; perceived as blue-green; green tone added to PB.	Slightly Low
5P			Shifted toward red; characterised by low chromatic intensity.	Low
5RP			Perceived as consistent reds.	Stable

Table 2: Comparison of colour perception between normal colour vision and tritanopia.

Guidelines for inclusive colour scheme design

Drawing on the simulation-based analysis of tritanopia colour perception, a set of guidelines for the design of inclusive colour schemes has been formulated. To preserve visual clarity and informational fidelity under simulated tritanopia conditions, several precautionary principles must be applied when selecting and combining colours. These recommendations are derived from observed instances of chromatic convergence, in which perceptually distinct hues within the standard visible spectrum become indistinguishable under the simulation model (Table 3).

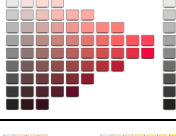
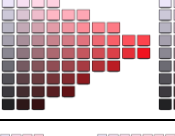
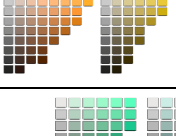
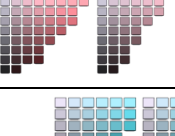
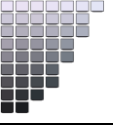
	Perspective		
	Normal	Tritanopia	
5R, 5RP			Avoid the simultaneous application of red and red-violet within a single colour scheme.
5YR, 5Y, 5P			Refrain from using orange, yellow, and purple together due to potential chromatic convergence.
5G, 5BG, 5B, 5PB			Avoid pairing green, blue-green, blue, and blue-violet to ensure sufficient categorical contrast.
5GY			Avoid utilising yellow-green as a primary accent or highlight colour.

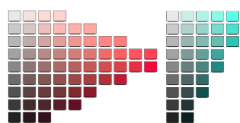
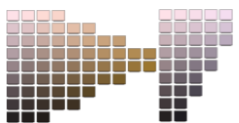
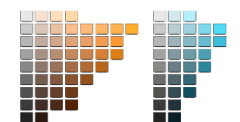
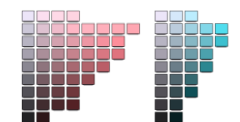
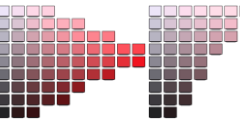
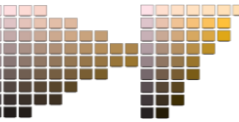
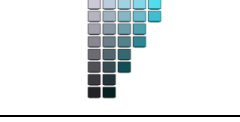
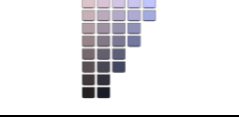
Table 3: Restricted colour combinations for tritanopia accessibility.

In chromatic schemes employing 5R and 5RP, the concurrent use of red and red-violet should be avoided. Due to the perceptual tendency of red-violet hues to shift toward a primary red, these colour categories do not provide sufficient chromatic contrast to function as clearly distinguishable elements within a unified design system. Substantial ambiguity also arises within the 5YR, 5Y, and 5P sectors. For designs intended to be accessible to individuals with tritanopia, orange, yellow, and purple should not be deployed within the same hierarchical colour structure. Under tritanopia conditions, reductions in saturation within these regions cause these nominally distinct hues to converge into a similarly desaturated, red-shifted appearance, thereby undermining their utility for categorical differentiation.

The most critical region of concern encompasses the 5G, 5BG, 5B, and 5PB ranges. Owing to the presence of blue and green components across these hue charts, observers with tritanopia tend to perceive these intervals as a continuous blue-green band. Accordingly, green, blue-green, blue, and blue-violet should not be used in combination within a single palette, as the diminished perceived hue variation leads to substantial loss of informational clarity.

Finally, the 5GY sector requires particular attention. This hue is perceived as a muted or near-achromatic grey under tritanopia vision. Consequently, yellow-green should not be employed as an accent or highlight colour. Its inherently low perceived chromatic intensity prevents it from providing the level of visual salience necessary for critical interface elements, alerts, or navigational cues.

In addition to addressing fundamental constraints associated with incompatible colour combinations, principles of colour harmony were incorporated to derive recommended colour pairings for inclusive colour schemes (Table 4).

		Normal	Tritanopia	Red-Green Blindness
Complementary	5R 5BG			
	5YR 5B			
	5Y 5PB			
Split-complementary	5R 5Y 5B			
	5R 5P 5G			

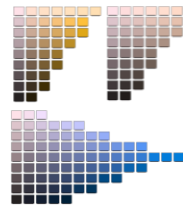
5Y 5G 5P			
5BG 5PB 5YR			
5PB 5RP 5GY			

Table 4: Recommended colour combinations for tritanopia accessibility.

To ensure clear perceptual distinction between background and foreground elements for individuals with colour vision deficiency, colour combinations must maintain sufficient contrast regardless of chroma variation. In this regard, complementary and split-complementary colour schemes are particularly effective, as they maximise perceptual differentiation across a range of visual conditions.

As this study aims to propose inclusive colour scheme strategies, the selected combinations were evaluated not only under tritanopia conditions but also with consideration of protanopia and deuteranopia. Complementary colour pairs that demonstrated clear perceptual contrast across all three types of CVD include 5R-5BG, 5YR-5B, and 5Y-5PB. Similarly, the following split-complementary combinations were identified as maintaining strong perceptual differentiation under protanopia and deuteranopia conditions: 5R-5Y-5B, 5YR-5GY-5PB, 5Y-5G-5P, 5BG-5PB-5YR, and 5PB-5RP-5GY. These combinations consistently exhibited distinguishable colour differences, supporting their applicability in inclusive colour scheme design.

Practical application of inclusive colour scheme

To demonstrate the practical applicability of the proposed design guidelines, a series of inclusive colour schemes was developed based on the perceptual characteristics and colour-planning principles identified through the tritanopia simulation analysis.

Each colour scheme was structured according to the functional roles of colour and the corresponding principles of colour harmony. Particular attention was given to satisfying key functional requirements, including identification, visual hierarchy, and information recognition, by ensuring sufficient visual contrast between the dominant background colour and the primary focal colour. Furthermore, the colour combinations were selected to maintain perceptual distinguishability between critical visual elements under simulated tritanopia conditions.

To provide an objective evaluation of functional performance, colour differences between the dominant background colour and the primary focal colour were quantified using the CIELAB colour difference metric (ΔE^*_{ab}). The calculated ΔE^*_{ab} values served as indicators of chromatic separation

between critical design elements. Larger colour differences were interpreted as reflecting stronger perceptual distinguishability and a greater capacity to support identification, visual hierarchy, and information communication functions.

In addition, the aesthetic validity of each colour scheme was examined through the application of established colour harmony principles, including complementary, split-complementary, and Munsell's Balanced Opposites relationships. This combined approach enabled the evaluation of both functional performance and aesthetic coherence, thereby assessing the practical applicability of the proposed inclusive colour schemes for accessible and visually effective design (Table 5).

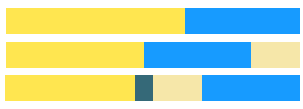
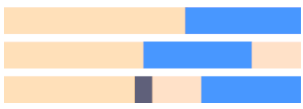
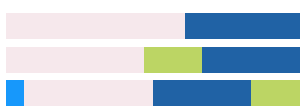
Normal	Tritanopia	Red-Green Blindness	Colour Scheme Strategy
			• Complementary colour • Law of areas
$\Delta E = 134.79$	$\Delta E = 91.56$	$\Delta E = 74.92$	
			• Complementary colour • Law of areas
$\Delta E = 98.48$	$\Delta E = 79.37$	$\Delta E = 68.54$	
			• Split complementary • Balanced opposite
$\Delta E = 74.26$	$\Delta E = 84.91$	$\Delta E = 73.68$	
			• Path of harmony • Balanced opposite
$\Delta E = 86.39$	$\Delta E = 73.21$	$\Delta E = 78.46$	

Table 5: Inclusive colour scheme examples.

To develop inclusive colour schemes, established colour harmony principles, including complementary, split-complementary, Munsell's Law of Areas, and Balanced Opposites, were applied. For the first colour scheme, bright yellow, 5Y, and its complementary hue, 5PB, were selected as the primary colours. Consistent with Munsell's Law of Areas, the high-value yellow was assigned to the dominant area, while the medium-value blue occupied a smaller proportion of the composition. To provide additional design alternatives, colours with varying values and chroma were selected from the same complementary pair, thereby enhancing visual recognition for both colour-normal and colour-deficient observers. To objectively evaluate the perceptual distinguishability of the proposed colour schemes, the colour difference between the dominant background colour and the primary focal colour was calculated using the CIELAB colour difference metric (ΔE^*_{ab}). The resulting colour differences were 134.79 under normal vision, 91.56 under simulated tritanopia, and 74.92 under simulated red-green colour vision deficiency. All values indicate substantial chromatic separation between the two primary colours, suggesting that the colour scheme effectively supports identification, visual hierarchy, and information communication functions across different visual conditions.

The second colour scheme was also based on a complementary pair, this time consisting of 5YR and 5B. Consistent with Munsell's Law of Areas, a medium-value, medium-chroma blue was used as the dominant colour, while a high-value, high-chroma orange was applied to a smaller area to create visual emphasis. The calculated colour differences were 98.48 under normal vision, 79.37 under simulated tritanopia, and 68.54 under simulated red-green colour vision deficiency. The consistently high ΔE values indicate that the visual distinction between the dominant and accent colours remained robust under each viewing condition, reinforcing the functional objectives of recognition and visual emphasis.

The third colour scheme was developed using a split-complementary colour relationship combined with Munsell's Balanced Opposites theory. Hues from the 5PB, 5RP, and 5GY families were selected. A low-chroma 5RP hue occupied the dominant area, while medium-chroma 5PB and high-chroma 5GY hues were used in smaller proportions to create visual emphasis and maintain colour harmony. The calculated colour differences were 74.26 under normal vision, 84.91 under simulated tritanopia, and 73.68 under simulated red-green colour vision deficiency. The substantial colour differences observed across all visual conditions indicate that the scheme successfully combines perceptual distinguishability with balanced colour harmony, supporting both functional and aesthetic design objectives.

The final colour scheme was developed based on Munsell's Path of Harmony in combination with the Balanced Opposites. Following the progression of values along the neutral axis, multiple shades of grey were selected as the primary background colours, while a high-chroma 5YR hue was introduced as an accent colour. The restrained use of low-chroma neutrals establishes visual cohesion, whereas the saturated orange provides a clear focal point within the composition. The calculated colour differences were 86.39 under normal vision, 73.21 under simulated tritanopia, and 78.46 under simulated red-green colour vision deficiency. These findings suggest that the scheme maintains strong perceptual contrast while achieving a harmonious balance between neutral and accent colours, making it suitable for applications requiring both visual clarity and aesthetic restraint.

The four colour schemes presented in this study are intended as illustrative examples derived from the proposed design guidelines rather than exhaustive solutions. By applying the same principles of colour function, colour harmony, and perceptual distinguishability, designers may develop a wide range of additional inclusive colour schemes tailored to diverse contexts and design objectives.

Discussion and conclusions

Discussion

This study contributes to the limited body of research on tritanopia within inclusive colour design. Although red-green colour vision deficiencies account for the majority of cases and have therefore been the primary focus of prior research, truly inclusive design practice requires that less prevalent forms, such as tritanopia, are not overlooked. The findings of this study indicate that tritanopia produces consistent hue shifts, chroma reductions, and perceptual convergence among specific hue families. Across ten Munsell hue families examined, substantial perceptual shifts were observed in hue and chroma under simulated tritanopia conditions. The results indicate that certain hue families become perceptually compressed, while others retain relatively greater visual distinctiveness.

The comparative analysis revealed that tritanopia is characterised not only by hue shifts but also by noticeable reductions in chroma in specific regions of colour space. In many instances, variations in chroma contributed substantially to perceptual differentiation, even when hue distinctions were reduced. These findings suggest that colour confusion in tritanopia is not limited to simple hue overlap

but involves a broader perceptual compression of colour space. As a result, colour distinctions that are clear under normal vision may become difficult to distinguish, potentially affecting visual communication, especially in environments where colour serves critical safety and identification functions.

Based on these observations, a set of inclusive colour scheme guidelines was developed through the integration of colour function theories and established theories of colour harmony. The proposed schemes were designed to support identification, visual hierarchy, and information communication while maintaining aesthetic coherence. Quantitative evaluation using CIELAB colour difference (ΔE^*_{ab}) demonstrated substantial chromatic separation between dominant and focal colours across normal, tritanopia, and red-green colour deficient viewing conditions. These findings suggest that effective inclusive colour schemes can maintain both perceptual accessibility and aesthetic coherence.

The practical examples presented in this study further illustrate how complementary, split-complementary, balanced opposites, and path of harmony relationships can be adapted to accommodate diverse visual abilities. Rather than prescribing specific colour combinations, the proposed framework provides a systematic approach for generating inclusive colour schemes that can be applied across a wide range of environmental and communication design contexts.

Despite its contributions, several limitations should be acknowledged. First, the study relied on a computerised simulation of tritanopia rather than observations from individuals clinically diagnosed with the condition. Although the simulation model is based on established colour vision deficiency algorithms, simulated perception may not fully replicate the visual experiences of all tritanopia observers. Second, the analysis was conducted through expert-led evaluation of perceptual changes within the Munsell colour system, which, despite its highly systematic nature, may not encompass the full range of colours encountered in complex real-world environments. Future research may incorporate multiple evaluators to further strengthen methodological rigour. Third, the effectiveness of the proposed colour schemes was assessed through colour difference analysis instead of behavioural performance measures. Future studies may evaluate the practical effectiveness of these schemes through user testing in wayfinding, signage, healthcare, educational, and other built environment applications.

Conclusions

This study examined colour perception under simulated tritanopia conditions using the Munsell colour system as a standardised analytical framework. The findings revealed consistent transformations in hue and chroma that influence the visual distinguishability of colour combinations commonly used in design applications.

Drawing upon these findings, the study proposed a set of inclusive colour design guidelines that integrate perceptual characteristics of tritanopia with established theories of colour function and colour harmony. The resulting colour schemes demonstrated substantial colour differences across normal and colour-deficient viewing conditions, suggesting their potential to support visual recognition, information communication, and accessibility.

By focusing on tritanopia, which has received relatively limited attention in design research, this research contributes to the advancement of inclusive colour design within the built environment. The proposed framework offers designers a systematic method for developing accessible and aesthetically coherent colour schemes and provides a basis for future empirical studies involving individuals with colour vision deficiencies.

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