Journal of Sensory Studies

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Journal of Sensory Studies

REVIEW OPEN ACCESS

Decoding Color Perception: An Eye Tracking Perspective

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Received: 7 March 2025 | **Revised:** 15 April 2025 | **Accepted:** 18 April 2025

Keywords: color | eye tracking | perception | preference | vision

ABSTRACT

Eye movements scan objects and features in our environment, with color being fundamental to visual experience. Individual variations in color vision create diverse perceptual interpretations. Eye tracking provides objective quantification of these perceptual differences through fixations and gaze patterns. This review consolidates research on eye tracking methodologies for assessing color discrimination abilities. Metrics like fixation duration, saccadic patterns, and pupillary responses have proven sensitive to variations in color perception. Distinctive eye movement patterns emerge as potential markers for color vision deficiencies, variations in color naming, and how context affects color perception. Eye tracking effectively measures color perception objectively and identifies anomalies in color vision. The technology reveals how individual differences in color processing influence visual attention, offering insights into the relationship between physiological color processing mechanisms and behavioral responses to colored stimuli.

1 | Introduction

Color perception is a complex and multifaceted aspect of human experience that varies significantly among individuals (Bosten 2022; Neitz and Neitz 2011). This variation arises from a combination of genetic, physiological, and environmental factors, leading to a spectrum of color perception abilities in the population (Emery and Webster 2019; Hurlbert and Ling 2007; Sorokowski et al. 2014; Taylor et al. 2013). At the biological level, color vision is mediated by specialized photoreceptor cells in the retina called cones. Most humans possess three types of cones, each sensitive to different wavelengths of light, allowing for trichromatic color vision (Conway et al. 2010). However, genetic variations can lead to color vision deficiencies, commonly known as color blindness, affecting approximately 8% of males and 0.5% of females (Deeb 2005). Color perception extends beyond mere physiological processes and is deeply influenced by visual experience during development (Laeng et al. 2007; Skelton et al. 2022; Webler et al. 2019), as well as cognitive and cultural factors. Research has shown that language and cultural background can shape color categorization and discrimination (Roberson et al. 2005), at least to some extent (cf. Lindsey and Brown 2009). Some cultures may have more nuanced color terminology for certain hues, which correlates with enhanced perceptual discrimination in those color ranges (Winawer et al. 2007). The importance of color in visual attention has been well documented in cognitive psychology (Bortolotti et al. 2022; Elliot and Maier 2014; Maule et al. 2023). But also, the relationship between color perception and consumer behavior in food contexts operates through multiple cognitive and emotional pathways. Eye-tracking research reveals that color influences not only initial attention capture, critical in crowded retail environments, but also affects product evaluation, taste expectations, and perceived value (Alvino et al. 2021; Bortolotti, Chen, et al. 2025; Bortolotti, Croijmans, et al. 2025; Bortolotti et al. 2023). Studies in our review demonstrate that specific colors trigger distinct emotional responses and associations that can be leveraged in marketing contexts.

> **Summary**
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> - This research has significant potential for advancing objective color vision assessment in clinical and industrial settings. Eye tracking metrics could provide non-verbal, bias-free methods for diagnosing color vision deficiencies, especially valuable for testing children, individuals with language barriers, or cognitive impairments.
> - In human factors engineering, these findings could inform the design of safety-critical visual interfaces, ensuring color-coded information is accessible to users with varying color perception abilities.
> - The technology could enhance vision screening in occupations where accurate color discrimination is essential (aviation, electrical work, healthcare).
> - Additionally, the marketing and design industries could utilize these insights to optimize product appeal across diverse populations with different color perception.
> - This objective measurement approach could support more personalized educational materials that accommodate individual differences in color vision.

This body of research highlights how color can significantly influence where and how individuals focus their visual attention. Complementing these findings, research using eye-tracking technology has revealed that certain colors, particularly those with high contrast or cultural significance, tend to attract visual attention more readily (Frey et al. 2011; Suzuki et al. 2019). Eye tracking provides a unique and objective method to quantify how individuals perceive and interact with colors. By analyzing metrics such as fixation duration, saccadic patterns, and pupillary responses, researchers can gain insights into the underlying mechanisms of color perception and the individual differences therein. The study of color perception encompasses a wide range of disciplines, from neurobiology and psychology to anthropology/paleontology and art history and design (Codispoti et al. 2012; Conway et al. 2010; Gage 1999). Understanding the complex interplay between individual differences, cultural influences, and contextual factors in color perception is crucial for advancing our knowledge in this field and applying it to real-world challenges.

1.1 | Color Perception

Color perception represents one of the most fascinating phenomena in cognitive neuroscience, involving complex interactions between physiological, neural, and cognitive processes. The pioneering research of Wilhelm Wundt and Hermann von Helmholtz laid the groundwork for our modern understanding of this fundamental perceptual process (Bortolotti et al. 2022; Kuehni 2010). Recent developments in neuroscience have significantly deepened our understanding of the mechanisms underlying chromatic perception, revealing previously unsuspected complexity (Solomon and Lennie 2007). At the neurobiological level, color perception begins in the retina, where specialized photoreceptors—cones—respond selectively to different wavelengths of visible light. Conway (2009) demonstrated how these signals are subsequently processed through complex neural pathways culminating in the visual cortex. The presence of three distinct types of cones, sensitive to short, medium, and long wavelengths respectively, forms the basis of trichromacy theory, a fundamental principle that has revolutionized our understanding of color vision (Neitz and Neitz 2011). Neural processing of color continues through the geniculate-striate pathway, where information is progressively refined and integrated with other aspects of visual experience. Gegenfurtner and Kiper (2003) identified specific neural circuits in the visual cortex responsible for processing chromatic information, demonstrating how these interact with other sensory modalities to create a coherent and integrated perception. Mullen (2019) further revealed the existence of specialized cortical areas that respond selectively to specific color attributes, suggesting a modular organization of the chromatic processing system.

The digital era has introduced new challenges and opportunities in the study of color perception. Fairchild et al. (2021) examined how color display on digital screens can affect perception, considering factors such as screen brightness, ambient lighting, and device characteristics. Subsequent research by Gegenfurtner et al. (2024) has demonstrated how display technology influences color constancy mechanisms, while Wong and Bahmani (2022) investigated the impact of different viewing devices on color discrimination thresholds.

Clinical applications of color perception research continue to expand. Studies revealed new connections between chromatic perception alterations and specific neurological conditions, paving the way for innovative diagnostic applications (Emery et al. 2021; Gegenfurtner et al. 2024). This work was further developed by (Barbur and Rodriguez-Carmona 2016) who established correlations between subtle color vision deficiencies and early markers of neurodegeneration. The advent of eye-tracking technologies has opened new frontiers in color perception research. (Holmqvist et al. 2011) utilized this methodology to objectively quantify individual differences in chromatic perception, analyzing parameters such as fixation duration, saccadic patterns, and pupillary responses. These findings were later expanded by (McCamy et al. 2014), who revealed how microsaccades contribute to color discrimination during natural viewing conditions.

1.2 | Eye Tracking and Eye Movements in Color Perception

In this context, it is essential to emphasize the importance of studying color perception using eye-tracking technology, regardless of the type of eye tracker employed. Eye-tracking devices can be broadly categorized into two types: lab-based and mobile. Lab-based eye tracking, frequently utilized in sensory and consumer science research (Gere et al. 2020), ensures the accuracy of eye movement measurements within a controlled experimental environment. However, this method may limit the external validity of the findings (Orquin and Wedel 2020). Conversely, mobile eye-tracking devices provide the advantage of capturing eye movements in real-world settings, such as during shopping activities. Most eye-tracking research in sensory and consumer science has focused specifically on fixation patterns. Eye-tracking metrics include fixation duration, pupil dilation, smooth pursuit movements, saccades, micro-saccades, and blinking (Ehinger et al. 2019).

The study of eye movements and gaze patterns has provided valuable insights into how we perceive and process color information (Ehinger et al. 2019; Holmqvist et al. 2011; Schütz et al. 2011). Eye movements during color perception are characterized by two main types: saccades (rapid eye movements between fixation points) and fixations (brief periods when the eyes are relatively stationary). Research using high-precision eye trackers has revealed that these movements are not random but are influenced by various factors, including color saliency, contrast, and personal relevance (Frey et al. 2011). Colors with high visual saliency, such as bright red or yellow, tend to attract initial fixations more quickly and frequently than less salient colors. This phenomenon, known as attentional capture (Theeuwes 2010), has significant implications for fields like advertising (Bortolotti et al. 2023) user interface design, and safety signage. Eye tracking studies have confirmed that color-based attentional capture occurs even when observers are instructed to ignore color (Anderson and Yantis 2013; Blakley et al. 2022), suggesting a somewhat automatic process in visual attention allocation. The role of color in guiding eye movements extends beyond mere saliency. Research has shown that color can facilitate visual search tasks by helping observers locate target objects more efficiently (Bortolotti et al. 2024; Chan and Hayward 2013; Müller and Krummenacher 2006; Wolfe 2020). For instance, when searching for a specific item in a cluttered visual scene, knowing the color of the target can significantly reduce search times and the number of fixations required to locate it (Wolfe 2020). Eye tracking studies have also revealed effects of color gradients and boundaries. Observers tend to fixate more on areas of gradual color change rather than uniform color regions. This suggests that the visual system is particularly attuned to detecting color transitions, which may be an evolutionary adaptation for identifying objects and boundaries in natural scenes (Hansen et al. 2009).

Research has demonstrated that the perception of color can be biased by the sequence and duration of fixations on different colored regions of a scene (Nuthmann and Einhäuser 2015). In the context of art and aesthetics, eye tracking has provided insights into how color composition influences viewing patterns of paintings and photographs. Studies have shown that areas of high color contrast or unique hues within an artwork tend to receive more fixations, influencing the overall aesthetic experience (Massaro et al. 2012). The relationship between eye movements and color perception is bidirectional. While color influences where we look, the pattern of eye movements can also affect how we perceive color.

This systematic review aims to synthesize the current state of knowledge on color perception as investigated through eye tracking, critically evaluating the existing literature, identifying key themes and gaps, and suggesting directions for future research. The findings have potential implications for fields ranging from cognitive science and neuroscience to applied areas like marketing, design, and human-computer interaction. By consolidating research on eye tracking methodologies in evaluating color discrimination abilities, this review seeks to provide a comprehensive understanding of how eye movements and gaze patterns contribute to our perception of color.

2 | Method

We conducted a systematic literature search following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al. 2021). The search was performed on January 14 2025, using the Scopus database—because all the other databases contained the same results found in Scopus. The following search string was used: eye AND tracking AND in AND color AND perception. This initial search yielded 473 documents.

In our systematic review, we carefully defined the criteria for including and excluding studies and sought to include only peer-reviewed articles published in English until January 2025, specifically targeting studies that employed eye tracking methods to investigate color perception; the entire systematic literature review process is summarized in Figure 1 following the guidelines for systematic reviews (Page et al. 2021).

3 | Results

The inclusion criteria for this review were meticulously designed following the PRISMA guidelines (Page et al. 2021) to ensure the selection of high-quality studies that provide valuable insights into the relationship between color perception and various factors such as visual comfort, age-related changes, health, digital interfaces, art, and technology. Studies that utilized eye-tracking technology to measure color perception and provided quantitative data on eye movement metrics, such as fixation duration, saccade patterns, and pupil dilation, were included. Our search strategy initially yielded 473 documents on Scopus. Although we analyzed other databases, they produced duplicates or a smaller number of documents. Through a meticulous screening process, we significantly narrowed down this group.

First, we applied filters based on our inclusion criteria—namely the use of eye-tracking technology and the measurement of color perception—reducing the number to 378 articles. Next, we conducted a thorough selection of titles, further reducing the number to 226 potentially relevant studies. We then carefully evaluated the abstracts to identify empirical studies focusing on specific aspects of color perception, such as the impact on visual comfort, developmental and age-related changes, health-related behaviors, user interaction with digital interfaces, emotional responses to art, and the integration of color perception with advanced technologies. This process allowed us to identify 89 studies.

The selected studies were divided into six groups based on their primary objective: color perception and visual comfort, color perception in children and the elderly, color perception and health, color perception and digital interfaces, color perception and art, and color perception and technology. Each group represents a distinct research area, providing a comprehensive

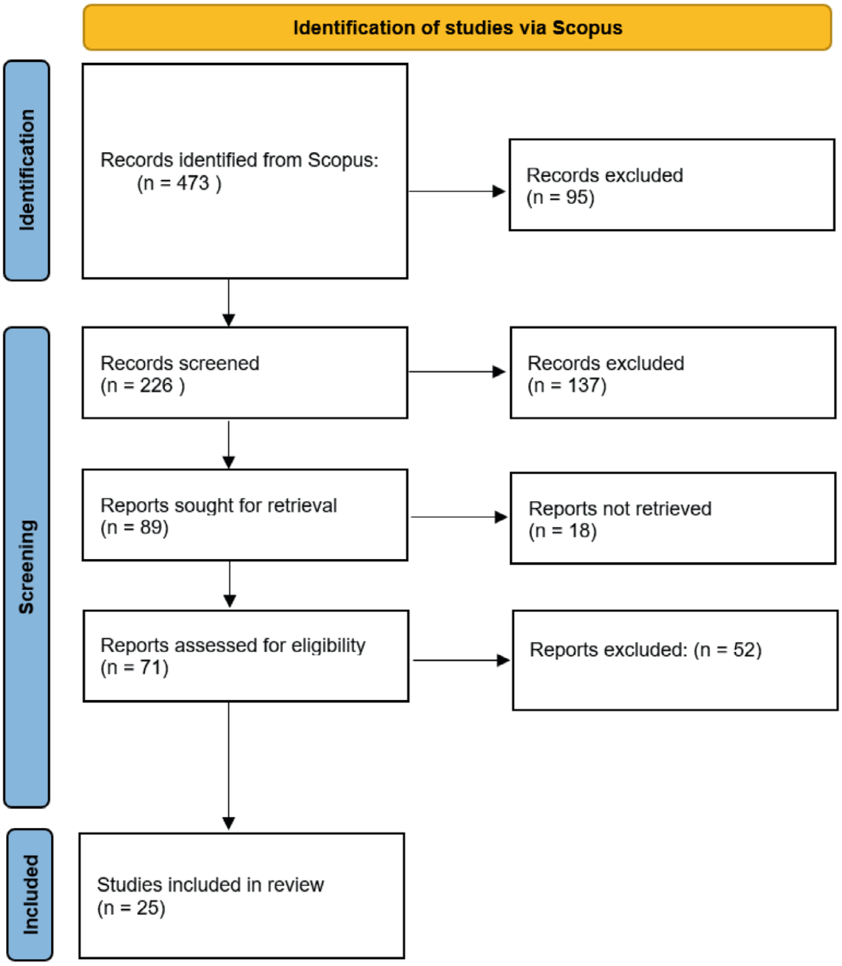

FIGURE 1 | PRISMA diagram.

overview of how eye-tracking technology has been applied to study color perception in various contexts.

We reviewed 71 articles whose full texts were available online. Once clustered, our research identified 25 relevant articles (see Table 1).

4 | Discussion

To better understand the necessity of a systematic literature review on this topic, we divided and analyzed the selected articles by clustering them. This approach facilitates a clearer comprehension of the current research areas and highlights the diverse applications of eye-tracking technology in studying color perception. The articles are categorized into six distinct clusters, each focusing on a specific research domain:

4.1 | Color Perception and Visual Comfort

The studies included in this cluster utilize eye-tracking technology to evaluate the impact of color on visual comfort in various environments, focusing on quantitative measures of visual comfort and cognitive load. Wang et al. (2024) employ eye-tracking to assess how facade color elements in old residential buildings in Shanghai affect visual comfort. Their results indicate that highly saturated colors increase cognitive load, while an optimal range of brightness enhances visual comfort. The study involves a detailed analysis of eye movement patterns and fixation durations to determine the cognitive load associated with different color schemes. The findings suggest that urban planners and architects should consider these factors when designing building facades to improve residents' visual comfort. The study also discusses the implications of these findings for urban design, emphasizing the importance of color in creating visually comfortable living environments. Zhang et al. (2022) investigate how color saturation, brightness, and hue affect visual comfort in subway spaces using eye-tracking. They identify the most comfortable color combinations by analyzing eye movement data, including fixation counts and saccade patterns. The study provides quantitative data on how different color environments influence visual experience in public underground spaces. These findings can inform the design of more visually comfortable public transportation environments, potentially reducing passenger stress and improving overall satisfaction. The study also explores the psychological impact of color in confined spaces, highlighting the importance of color in enhancing the user experience in public transportation. Gómez Sirvent et al. (2023) utilize virtual reality and eye-tracking to evaluate the influence

TABLE 1 | Studies included in the literature review and reference clusters.

Cluster	Articles	Key results	Methodological details
Color perception and visual comfort	(Wang et al. 2024). Exploring the Impact of Facade Color Elements on Visual Comfort in Old Residential Buildings in Shanghai: Insights from Eye-Tracking Technology. (Zhang et al. 2022). Research on visual comfort of color environment based on the eye-tracking method in subway space. (Gómez Sirvent et al. 2023). Pre-occupancy evaluation of a virtual music school classroom: Influence of color and type of lighting on music performers. (Tian et al. 2022). Effects of Paradigm Color and Screen Brightness on Visual Fatigue in Light Environment of Night Based on Eye Tracker and EEG Acquisition Equipment. (Deeb et al. 2015) Background and foreground interaction: Influence of complementary colors on the search task. (Kugler et al. 2015) Visual search in the real world: Color vision deficiency affects peripheral guidance, but leaves foveal verification largely unaffected. (Çöltekin et al. 2017) Perceptual complexity of soil-landscape maps: a user evaluation of color organization in legend designs using eye tracking.	(Wang et al. 2024) Highly saturated colors increase cognitive load; optimal brightness enhances visual comfort. (Zhang et al. 2022) Identified comfortable color combinations; color environment influences visual experience in public spaces. (Gómez Sirvent et al. 2023) Color and lighting combinations affect emotional and cognitive experiences of musicians. (Tian et al. 2022) Specific color and brightness combinations reduce visual fatigue. (R. Deeb et al. 2015) Complementary colors influence search task performance. (Kugler et al. 2015) Color vision deficiency affects peripheral guidance but not foveal verification. (Çöltekin et al. 2017) Evaluated color organization in legend designs for soil-landscape maps.	(Wang et al. 2024) Sample: 30 participants (15M/15F, ages 20–35); Eye-tracking: Tobii Pro Glasses 2; Analysis: ANOVA for fixation duration and count data. (Zhang et al. 2022). Sample: 42 participants (22M/20F, ages 18–45); Eye-tracking: SMI RED250; Analysis: Multiple regression, heat map visualization. (Gómez Sirvent et al. 2023). Sample: 28 musicians (12M/16F, mean age 26.3); Eye-tracking: VR-integrated Pupil Labs; Analysis: Mixed-effects modeling with Bonferroni correction. (Tian et al. 2022). Sample: 25 participants (13M/12F, ages 20–30); Equipment: EyeLink 1000 Plus and EEG; Analysis: Repeated measures ANOVA, correlation analysis between EEG and eye data. (R. Deeb et al. 2015). Sample: 36 participants (19M/17F, ages 22–41); Eye-tracking: SMI RED-m; Analysis: *t*-tests and Friedman tests for search efficiency. (Kugler et al. 2015). Sample: 48 participants (32 normal vision, 16 with color deficiency); Eye-tracking: Mobile SMI; Analysis: Linear mixed models, Bayesian statistics for search behavior. (Çöltekin et al. 2017). Sample: 34 participants (17 experts, 17 novices); Eye-tracking: Tobii TX300; Analysis: ANOVA and post hoc Tukey tests for gaze patterns.

(Continues)

TABLE 1 | (Continued)

Cluster	Articles	Key results	Methodological details
Color perception in children and the elderly	(Pueyo et al. 2024). Color perception develops throughout childhood with increased risk of deficiencies in children born prematurely. (Li and Hao 2024). Eye Tracking Study on Visual Search Performance of Automotive Human-Machine Interface for Elderly Users. (Costa et al. 2023) Reduced eye optical quality contributes to worse chromatic thresholds in aging. (Tanaka et al. 2020) Laypeople's and dental students' perceptions of a diastema between central and lateral incisors: Evaluation using scanpaths and color-coded maps. (Świda et al. 2018) Perceptions of older consumers regarding food packaging as a prerequisite for its improvement: A case study of Polish market	(Pueyo et al. 2024) Premature children are at increased risk of color perception deficiencies. (S. Li and Hao 2024) Certain color combinations enhance or hinder visual search performance in elderly users. (Costa et al. 2023) Aging reduces optical quality, worsening chromatic thresholds. (Tanaka et al. 2020) Evaluated perceptions of dental aesthetics using scanpaths and color-coded maps (Świda et al. 2018) valuated older consumers' perceptions of food packaging.	(Pueyo et al. 2024) Sample: 124 children (62 premature, 62 full-term), ages 5–12; Eye-tracking: REDn Scientific; Analysis: Age-matched comparative analysis, multivariate regression. (S. Li and Hao 2024) Sample: 45 elderly participants (ages 65–82) vs. 40 younger controls (ages 25–40); Eye-tracking: Tobii Pro Spectrum; Analysis: Two-way ANOVA, path analysis. (Costa et al. 2023). Sample: 82 participants in three age groups (20–35, 40–55, 60–75); Equipment: Custom pupillometry with Cambridge Color Test; Analysis: ANCOVA controlling for lens opacity. (Tanaka et al. 2020) Sample: 40 participants (20 dental students, 20 laypeople); Eye-tracking: SMI RED250; Analysis: Scanpath comparison algorithms, Mann–Whitney U tests. (Świda et al. 2018) Sample: 60 older adults (ages 65+); Eye-tracking: Tobii T60; Analysis: Cluster analysis of fixation patterns, qualitative coding of interviews.
Color perception and health	(Cholewa-Wójcik et al. 2024). Analysis of health warning signs on alcoholic beverage packaging using the eye-tracking method. (Potthoff et al. 2020). The color nutrition information paradox: Effects of suggested sugar content on food cue reactivity in healthy young women. (Song et al. 2021). Assessment of color perception and preference with eye-tracking analysis in a dental treatment environment. (Vincke and Vyncke 2017) Does Alcohol Catch the Eye? Investigating Young Adults' Attention to Alcohol Consumption.	(Cholewa-Wójcik et al. 2024) Position, size, and color of warning signs are crucial for effectiveness. (Potthoff et al. 2020) Color-coded nutritional information influences dietary decisions. (Song et al. 2021) Specific colors enhance patient comfort in dental settings (Vincke and Vyncke 2017) Investigated attention to alcohol consumption among young adults	(Cholewa-Wójcik et al. 2024) Sample: 52 participants (25 M/27F, ages 21–45); Eye-tracking: SMI RED 250; Analysis: Time-to-first-fixation metrics, heatmap analysis, chi-square tests. (Potthoff et al. 2020). Sample: 38 young women (mean age 23.4); Eye-tracking: EyeLink 1000 Plus; Analysis: Repeated measures ANOVA, mediation analysis. (Song et al. 2021) Sample: 50 dental patients (27F/23M, ages 25–60); Eye-tracking: Tobii Pro Nano; Analysis: Preference ranking correlation with physiological measures (pupil dilation). (Vincke and Vyncke 2017) Sample: 60 university students (ages 18–25); Eye-tracking: Tobii T120; Analysis: Multilevel analysis of viewing patterns, correlation with alcohol use questionnaires.

(Continues)

TABLE 1 | (Continued)

Cluster	Articles	Key results	Methodological details
Color perception and digital interfaces	(Y. Li et al. 2024). Assessing Gender Perception Differences in Color Combinations in Digital Visual Interfaces Using Eye tracking–The Case of HUD. (Huang et al. 2022). User Perception and Eye Movement on A Pandemic Data Visualization Dashboard. (Liu and Arakawa 2022). A Method for Generating Color Palettes with Deep Neural Networks Considering Human Perception.	(Y. Li et al. 2024) Significant gender-based differences in color preferences. (Huang et al. 2022) Color preferences and visual paths inform effective data visualization design. (Liu and Arakawa 2022) Optimized color palettes enhance user experience.	(Y. Li et al. 2024). Sample: 68 participants (34 M/34F, matched for age 20–45); Eye-tracking: Tobii Pro Fusion; Analysis: 2 × 3 factorial design, multidimensional scaling of preferences. (Huang et al. 2022) Sample: 42 participants with varying data literacy levels; Eye-tracking: EyeLink Portable Duo; Analysis: Areas of interest (AOI) comparisons, sequence pattern mining. (Liu and Arakawa 2022) Sample: 30 participants for validation study; Eye-tracking: Gazepoint GP3; Analysis: Machine learning validation with gaze data as ground truth; K-means clustering of attention patterns.
Color perception and art	(Fontoura and Menu 2021). Visual perception of natural colors in paintings: An eye-tracking study of Grünewald's Resurrection. (Massaro et al. 2012) When art moves the eyes: A behavioral and eye-tracking study. (Savazzi et al. 2014). Exploring responses to art in adolescence: A behavioral and eye-tracking study.	(Fontoura and Menu 2021) Yellow is the most salient color; colors evoke strong emotional responses. (Massaro et al. 2012) Human subjects in paintings attract more attention than natural elements. (Savazzi et al. 2014) Adolescents prioritize elements that evoke movement and action.	(Fontoura and Menu 2021) Sample: 35 participants (18 art experts, 17 non-experts); Eye-tracking: Tobii Pro Spectrum; Analysis: Dwell time comparison, sequential analysis, emotional response correlation. (Massaro et al. 2012) Sample: 28 participants (14 M/14F, ages 20–35); Eye-tracking: ASL Model 504; Analysis: ANOVA on fixation time for different painting elements, cluster analysis. (Savazzi et al. 2014) Sample: 44 adolescents (ages 14–19) compared to 23 adults; Eye-tracking: SMI RED-m; Analysis: Mixed-model ANOVA, qualitative content analysis of verbal reports.
Color perception and technology	(Güzel et al. 2023) ChromaCorrect: prescription correction in virtual reality headsets through perceptual guidance. (Bugdayci et al. 2021) Instruments of Vision: Eye-Tracking and Robotics as an Embodied Interface. (Almansouri et al. 2019). An Imperceptible Magnetic Skin.	(Güzel et al. 2023) Enhanced visual experience in VR for users with vision impairments. (Bugdayci et al. 2021) Eye-tracking is a viable method for human-robot interaction. (Almansouri et al. 2019) New possibilities for gesture control and wireless interaction.	(Güzel et al. 2023). Sample: 28 participants with color vision deficiencies; Eye-tracking: VR-integrated eye tracker (HTC Vive Pro Eye); Analysis: Paired *t*-tests for pre/post intervention, signal detection theory metrics. (Bugdayci et al. 2021). Sample: 32 participants; Equipment: Custom robotic interface with SMI eye tracking; Analysis: Response time measurements, error rate statistics, usability survey correlation. (Almansouri et al. 2019) Sample: 25 participants testing various interface designs; Eye-tracking: Custom setup with IR cameras; Analysis: Efficiency metrics, NASA-TLX workload assessment, comparative analysis of control methods.

of color and lighting type on the emotional and cognitive experiences of musicians in a virtual music school classroom. The study measures eye movements, pupil dilation, and fixation durations to assess how different color and lighting combinations affect performers' comfort and performance. The results highlight the importance of considering both color and lighting in the design of educational and performance spaces to enhance the user experience. The study also discusses the potential applications of these findings in designing virtual environments for various educational and professional settings. Tian et al. (2022) combine eye-tracking and EEG to analyze the effects of color paradigms and screen brightness on visual fatigue in nighttime light environments. The study measures eye movement metrics such as fixation duration and saccade amplitude, along with EEG data to assess cognitive load and visual fatigue. The findings suggest that specific combinations of color and brightness can reduce visual fatigue, providing guidelines for optimizing visual environments to minimize eye strain, particularly in settings where individuals are exposed to screens for extended periods. The study also explores the implications of these findings for designing more comfortable and visually ergonomic digital interfaces. Deeb et al. (2015) investigate the impact of complementary colors between the background and text on the readability of cartographic labels and the efficiency of users' search tasks, using eye-tracking to study visual behavior. The results show that the use of complementary colors can improve readability and search task efficiency, providing useful insights for the design of maps and other visual interfaces. Çöltekin et al. (2017) compare two legend designs on a soil-landscape map to support map reading tasks, using eye-tracking to analyze user performance. The results highlight how the perceptual complexity of maps can influence user performance, providing guidelines for designing more effective legends. Kugler et al. (2015) examine how color vision deficiencies affect peripheral guidance in visual search, using eye-tracking to analyze visual search performance in a naturalistic environment. The results suggest that color vision deficiencies can affect peripheral guidance but not foveal verification, providing insights for designing more accessible visual environments.

4.2 | Color Perception in Children and the Elderly

This cluster includes studies that investigate color perception in specific age groups (children and the elderly) using eye-tracking technology, focusing on developmental and age-related changes in color discrimination abilities. Pueyo et al. (2024) examine the development of color perception in children, particularly those born prematurely, using eye-tracking to assess their color discrimination abilities. The study involves tracking eye movements to determine how children fixate on and differentiate between colors. The findings indicate that premature children are at increased risk of color perception deficiencies, highlighting the importance of early detection and intervention. The study provides valuable data on the developmental trajectory of color perception in children and the potential impact of prematurity on visual development. The study also discusses the implications of these findings for early childhood education and intervention programs. Li and Hao (2024) use eye-tracking to analyze the visual search performance of elderly users in automotive human-machine interfaces. The study measures metrics such as fixation duration, saccade patterns, and search times to determine how icon colors influence search speed. The findings reveal that certain color combinations can enhance or hinder visual search performance in elderly users, providing insights for designing more user-friendly interfaces for elderly drivers. The study emphasizes the need for age-appropriate design considerations in automotive interfaces to improve safety and usability. The study also explores the potential applications of these findings in designing other types of interfaces for elderly users. Costa et al. (2023) investigate how aging affects eye optical quality and color perception, using eye-tracking to measure chromatic thresholds. The study involves detailed measurements of eye movements and fixation patterns to assess how aging impacts the ability to perceive and discriminate between colors. The results show that reduced optical quality in aging contributes to worse chromatic thresholds, emphasizing the need for age-appropriate visual aids and environment designs. The study provides important data on the visual challenges faced by the elderly and potential solutions to mitigate these challenges. The study also discusses the implications of these findings for designing more accessible and visually comfortable environments for the elderly. Tanaka et al. (2020) in their study use eye-tracking to analyze the visual perception of a diastema between the central and lateral incisors, comparing the perceptions of dental students and laypeople. The results indicate that as the width of the diastema increased, both students and laypeople focused more on the diastema region. The two groups of evaluators presented different perceptions of smiles in cases of diastema, highlighting the importance of understanding how different audiences perceive dental aesthetics.

Świda et al. (2018) examine the preferences of older consumers regarding food packaging design, using eye-tracking to analyze how older adults perceive and interact with packaging information. The results show that older consumers have specific preferences for packaging types and designs. For example, they prefer glass bottles, simple graphics, and subdued colors. The study also found that older consumers often have difficulty finding expiration dates on packaging, and their ability to locate this information depends on its placement. These insights are crucial for designing more user-friendly packaging for older adults.

4.3 | Color Perception and Health

The studies in this cluster explore the relationship between color perception and health-related factors using eye-tracking technology, focusing on the effectiveness of health warnings and the impact of color on health-related behaviors. Cholewa-Wójcik et al. (2024) use eye-tracking to analyze how health warning signs on alcoholic beverage packaging are perceived by consumers. The study measures eye movement metrics such as fixation duration, saccade patterns, and pupil dilation to determine the effectiveness of different warning sign designs. The findings emphasize the importance of the position, size, and color of warning signs in capturing attention and conveying health messages effectively. The study provides valuable insights for designing more effective health warnings to improve public health outcomes. The study also discusses the implications of these findings for regulatory policies and public health campaigns. Potthoff et al. (2020) examine how colored nutritional information affects food cue reactivity in healthy young women, using eye-tracking to measure attention and preferences. The study involves tracking eye movements to determine how different color schemes influence the perception and interpretation of nutritional information. The findings highlight the paradoxical effects of color-coded nutritional information on food choices, suggesting that certain color schemes may influence dietary decisions. The study provides important data for designing more effective nutritional labels to promote healthier eating habits. The study also explores the potential applications of these findings in designing other types of health-related information. Song et al. (2021) use eye-tracking to analyze color preferences and perception in a dental treatment environment. The study measures eye movement metrics such as fixation duration and saccade patterns to determine how different colors influence patient comfort. The findings indicate that specific colors can enhance patient comfort, providing guidelines for designing more pleasant and calming healthcare environments. The study emphasizes the importance of color in creating a positive patient experience in dental and other healthcare settings. The study also discusses the implications of these findings for designing other types of healthcare environments. Vincke and Vyncke (2017) use eye-tracking to investigate whether drinking behavior attracts young adults' attention. The results show that both young men and young women pay special visual attention to male and female drinking behavior. Additionally, a recall experiment confirmed that observed drinking behavior is better remembered than non-signaling, functional behavior. Moreover, alcoholic beverages receive more attention than nonalcoholic drinks, and this attention is clearly linked to the alcohol element of the drinking behavior. These findings suggest that drinking behavior functions as an attention-attracting cue, highlighting the symbolic aspects of alcohol use among young adults.

4.4 | Color Perception and Digital Interfaces

This cluster includes studies that investigate how color perception affects user interaction with digital interfaces using eye-tracking technology, focusing on user experience and interface design. Li et al. (2024) use eye-tracking to analyze gender differences in color combination perception in digital visual interfaces, with a focus on head-up displays (HUD). The study measures eye movement metrics such as fixation duration, saccade patterns, and pupil dilation to determine how different color combinations are perceived by male and female users. The findings reveal significant gender-based differences in color preferences, providing insights for designing more inclusive digital interfaces. The study emphasizes the need for considering gender differences in interface design to improve user experience and satisfaction. The study also explores the potential applications of these findings in designing other types of digital interfaces. Huang et al. (2022) use eye-tracking to analyze user perception and interaction with a pandemic data visualization dashboard. The study measures eye movement metrics such as fixation duration, saccade patterns, and visual paths to determine how users interact with different color schemes and data visualizations. The findings highlight color preferences and visual paths, offering recommendations for designing more effective and user-friendly data visualization tools. The study provides valuable insights for improving the design of data dashboards to enhance user engagement and comprehension. The study also discusses the implications of these findings for designing other types of data visualization tools. Liu and Arakawa (2022) combine eye-tracking and deep neural networks to develop a new method for generating color palettes based on human perception. The study involves tracking eye movements to determine how different color combinations are perceived and using this data to train neural networks to generate optimized color palettes. The findings suggest that this approach can optimize color palettes for digital interfaces, enhancing user experience and satisfaction. The study provides important data for developing more effective and user-friendly color design tools. The study also explores the potential applications of these findings in designing other types of digital interfaces.

4.5 | Color Perception and Art

The studies in this cluster explore the interaction between color perception and art using eye-tracking technology, focusing on how color influences visual attention and emotional responses to artworks. Fontoura and Menu (2021) use eye-tracking to analyze how natural colors in paintings affect visual perception and emotions. The study measures eye movement metrics such as fixation duration, saccade patterns, and pupil dilation to determine how different colors influence the viewer's emotional response. The results indicate that yellow is perceived as the most salient color and that colors are associated with strong emotional content, providing insights into the aesthetic experience of art. The study emphasizes the importance of color in creating emotional and visual impact in artworks. Massaro et al. (2012) examine how bottom-up and top-down processes influence visual behavior when observing representative paintings. The study measures eye movement metrics such as fixation duration, saccade patterns, and visual paths to determine how different elements in paintings attract attention. The findings show that human subjects in paintings attract more attention than natural elements, contributing to the understanding of visual attention in art perception. The study provides valuable insights for artists and curators on how to create visually engaging artworks. Savazzi et al. (2014) use eye-tracking to explore how adolescents respond to paintings, highlighting that they prioritize elements that evoke movement and action. The study measures eye movement metrics such as fixation duration, saccade patterns, and visual paths to determine how different elements in paintings attract attention. The results suggest that nature images are rated as more attractive, providing implications for art education and exhibition design. The study emphasizes the importance of considering the preferences and perceptions of different age groups in art education and curation.

Fontoura and Menu (2021) use eye-tracking to analyze the visual perception of natural colors in paintings, focusing on Grünewald's "Resurrection." The results indicate that although orange and red colors are perceived faster, yellows and browns are focused on for a more extended period and visited more frequently. The study highlights that yellow remains the most salient color and is associated with light and transcendent content, providing insights into the emotional and visual impact of colors in artworks. Massaro et al. (2012) use eye-tracking to analyze behavioral and perceptual responses to artistic stimuli. The results show that content-related top-down processes prevail over low-level visually driven bottom-up processes when a human subject is represented in the painting. Conversely, bottom-up processes, mediated by low-level visual features, particularly affect gazing behavior when looking at nature-content images. The study provides valuable insights into the interaction between bottom-up and top-down processes in art perception, emphasizing the role of embodied simulation in aesthetic experiences.

4.6 | Color Perception and Technology

This cluster includes studies that integrate color perception with advanced technologies using eye-tracking technology, focusing on the enhancement of visual experiences and human-machine interaction. Güzel et al. (2023) develop a prescription-aware rendering approach to improve image quality in virtual reality headsets for users with vision problems, using eye-tracking to optimize images for clearer vision. The study measures eye movement metrics such as fixation duration, saccade patterns, and pupil dilation to determine how different rendering techniques affect visual clarity. The findings suggest that this approach can significantly enhance the visual experience in virtual environments, providing guidelines for designing more effective VR headsets for users with vision impairments. Bugdayci et al. (2021) explore the use of eye-tracking to control a robotic creature, analyzing how eye movements can be used as an interface for robotics. The study measures eye movement metrics such as fixation duration, saccade patterns, and visual paths to determine how effectively users can control the robotic creature using their gaze. The findings suggest that eye-tracking can be a viable method for human-robot interaction, offering new possibilities for intuitive and hands-free control mechanisms. The study provides insights into the potential of integrating eye-tracking technology with robotics to enhance user experience and interaction. Almansouri et al. (2019) present a biocompatible magnetic skin that can be used for remote control functions, including eye movement tracking. The study involves the development and testing of the magnetic skin, measuring its effectiveness in tracking eye movements and controlling devices. The findings suggest that this technology offers new possibilities for gesture control and wireless interaction, enhancing the integration of visual perception with innovative control mechanisms. The study highlights the potential applications of magnetic skin in various fields, including assistive technology and human-computer interaction.

5 | Discussion

This systematic review has consolidated current knowledge on the use of eye-tracking technology to investigate color perception, highlighting how ocular metrics can reveal individual differences and contextual influences. The results show that eye-tracking is an effective tool for objectively measuring color perception and identifying anomalies in color vision. However, the variability in methods and experimental designs limits direct comparability between studies. To overcome these limitations, it is essential to develop standardized protocols and conduct further research that considers the diversity of samples and real-world conditions. These efforts will contribute to improving our understanding of color perception and developing practical applications in various fields, from cognitive psychology to digital interface design. As demonstrated by classic studies on eye movements, the trajectory taken by the eye to reach a target position does not follow a straight line between the saccade starting and ending points (Hunt et al. 2019; Sheliga et al. 1994, 1995). Instead, these trajectories often exhibit curved paths, which are influenced by various factors such as the presence of distractors, the complexity of the visual scene, and the underlying neural mechanisms controlling eye movements.

Saliency, in this context, refers to the distinctiveness or prominence of certain visual features that make them stand out and attract attention more readily (Castellotti et al. 2023). Characteristics such as color play a significant role in determining saliency (Bortolotti 2023, 77–78). For example, bright or contrasting colors can capture attention more effectively than muted or similar hues. This concept is fundamental to understanding how the visual system prioritizes and processes information, allowing organisms to respond quickly to important stimuli in their environment. The ability to efficiently detect and focus on salient features, including color, is essential for tasks such as locating food, avoiding predators, and navigating complex environments. By studying the patterns and trajectories of eye movements, researchers can gain insights into the cognitive and neural processes that underlie visual attention and perception. Eye tracking studies have shown that colors with high visual saliency, such as bright red or yellow, tend to attract initial fixations more quickly and frequently than less salient colors. This phenomenon, known as attentional capture, highlights the importance of color in guiding visual attention and underscores the role of saliency in visual processing.

Our comprehensive review has revealed significant methodological heterogeneity across eye-tracking studies investigating color perception. While analyzing the literature, we observed that this variability demonstrates the versatility of eye-tracking technology across diverse research contexts, yet simultaneously creates substantial challenges for meaningful cross-study comparisons and comprehensive meta-analyses. The methodological landscape of current eye-tracking research in color perception is characterized by considerable variation in several key aspects. Studies employ different eye-tracking systems—ranging from Tobii Pro and SMI RED to EyeLink systems—each with different technical specifications including sampling rates that vary from 60 to 1000 Hz, diverse spatial resolution capabilities, and inconsistent calibration procedures. This equipment diversity alone introduces a layer of complexity when attempting to compare findings across studies.

Beyond hardware considerations, we noted that experimental setups rarely follow consistent protocols. Environmental conditions such as ambient lighting, viewing distance, and screen properties—all critical factors that directly influence color perception—are reported inconsistently or sometimes omitted entirely. This lack of standardization in experimental conditions makes it difficult to determine whether differences in findings stem from genuine perceptual phenomena or merely methodological variations. The selection of eye movement metrics represents another area of substantial inconsistency. Researchers employ various measures, including fixation duration, saccade amplitude, scan paths, and areas of interest analysis, often without clear justification for why particular metrics were selected in relation to specific research questions about color perception. This creates a fragmented methodological landscape where findings cannot be easily synthesized into a cohesive understanding.

Reporting practices across studies show similar variability. Detailed information about calibration quality, data filtering methods, and participant exclusion criteria is inconsistently presented, which significantly limits reproducibility efforts. Statistical approaches range from basic t-tests to sophisticated multilevel modeling, frequently without standardized effect size reporting that would facilitate meta-analysis. Given these observations, we believe the field would greatly benefit from developing and implementing standardized eye-tracking protocols specifically tailored to color perception research. Such standardization would not restrict methodological creativity but rather provide a common foundation upon which specialized methods could be built.

For hardware and experimental setup considerations, researchers should report comprehensive technical specifications including sampling rate, spatial resolution, and accuracy of eye-tracking systems. Based on our analysis of temporal requirements for detecting subtle shifts in attention to color elements, we recommend a minimum sampling rate of 120 Hz for studies examining detailed color perception processes. Calibration procedures should follow standardized protocols, preferably using 5-point or 9-point calibration with clearly defined acceptance criteria to ensure data quality.

Environmental documentation deserves particular attention in color perception research. The same color can appear markedly different under varying lighting conditions, so detailed reporting of ambient illuminance levels, color temperature, viewing distance, and screen specifications becomes crucial for interpretation and replication. Moving beyond device-dependent RGB values to standardized color spaces such as CIE Lab* would significantly improve precision in stimulus description and enhance reproducibility. Procedural aspects of eye-tracking studies would also benefit from standardization. Our review revealed inconsistent approaches to screening participants for color vision deficiencies, despite the obvious impact this would have on results. Implementing consistent screening using established tests like Ishihara plates or the Farnsworth-Munsell 100 Hue Test would address this concern. Additionally, incorporating standardized adaptation periods to experimental lighting conditions before data collection would control for visual adjustment effects that might otherwise confound results.

The analysis of eye-tracking data presents perhaps the most critical opportunity for standardization. We found that researchers often use different event detection algorithms to identify fixations and saccades, with parameters rarely reported in sufficient detail for replication. Standardizing preprocessing pipelines and establishing a core set of essential metrics specifically relevant to color perception would greatly enhance comparability. For instance, metrics such as time to first fixation on specific color elements, duration of fixations on different colored regions, and transition patterns between color areas could form a standardized measurement framework for the field. For color perception research specifically, several targeted recommendations emerge from our analysis. Color categorization tasks would benefit from verified stimulus sets that span perceptual color space uniformly. Cross-cultural considerations should be systematically addressed through protocols sensitive to differences in color perception and naming across cultural contexts. Age-appropriate modifications to standard protocols are necessary when working with children or elderly participants, as developmental and aging effects on oculomotor behavior can significantly influence data interpretation.

Implementing these standardization efforts would require a collaborative approach. We envision a three-phase implementation strategy beginning with consensus development among experts in both eye-tracking methodology and color perception research. This would be followed by validation studies conducted across multiple research sites to assess the feasibility and sensitivity of proposed protocols. Finally, developing accessible guidelines, templates, and software tools would facilitate widespread adoption of standardized approaches.

The benefits of such standardization extend beyond mere methodological rigor. By enhancing the comparability and reproducibility of findings, standardized protocols would accelerate the accumulation of knowledge about color perception across diverse contexts. This would ultimately lead to more robust theories and more effective applications in fields ranging from educational design to therapeutic interventions and technological innovations. While promoting standardization, we acknowledge the importance of methodological innovation and recognize that novel research questions may require adaptations of standard protocols. The framework we propose is intended to provide a foundation of best practices that can be built upon rather than a rigid set of constraints. By balancing standardization with innovation, the field of eye-tracking research in color perception can advance with both methodological coherence and creative exploration.

6 | Limitation

Despite the valuable insights provided by this systematic review, several limitations must be acknowledged. Firstly, the heterogeneity of methodologies and experimental designs across the included studies poses a significant challenge to direct comparability. Different eye-tracking technologies, ranging from lab-based to mobile devices, can yield varying levels of precision and reliability, potentially affecting the consistency of the findings. Additionally, the diversity in sample populations, including variations in age, cultural background, and health conditions, may influence the generalizability of the results.

Another limitation is the controlled laboratory settings in which many eye-tracking studies are conducted. These environments may not accurately reflect real-world conditions, thereby limiting the ecological validity of the findings. Furthermore, the potential for publication bias, where studies with positive results are more likely to be published, could skew the overall understanding of the field.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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