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A Visual Grammar for Fine-Grained Color Identification by People with Color Vision Deficiency: Design and Empirical Validation

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Abstract

Purpose
This study investigates the effectiveness of a newly developed visual grammar designed to enhance the identification of color sub-ranges among individuals with Color Vision Deficiency (CVD). While numerous accessibility tools exist, prior research reveals a gap in addressing the subtle distinctions within color families that individuals with CVD often struggle to perceive.
Methods

The study employs a quantitative descriptive methodology complemented by qualitative analysis to assess the impact of the proposed visual grammar. The grammar integrates symbols, CMYK color codes, and percentage-based tonal values. Data were collected through controlled experiments using standardized visual stimuli and refined instructional protocols, measuring user accuracy, clarity, confidence, perceived utility, and cognitive load.
Results
The results demonstrate improved clustering of correct responses among participants, along with a noticeable reduction in cognitive load. Participants showed increased accuracy and confidence when identifying color sub-ranges, indicating that the visual grammar enhanced clarity and usability in digital environments.
Conclusion
The findings highlight the potential of this visual grammar to reduce common frustrations experienced by individuals with CVD and to promote greater autonomy in color-dependent decision-making. This research contributes to the broader accessibility discourse and introduces a replicable framework for improving color perception across diverse contexts, aligning with contemporary accessibility standards.

Keywords: Color Vision Deficiency (CVD), Color Blindness, Color Identification, Accessibility,, Visual Grammar

1 Introduction

Color is a fundamental channel for encoding information in various contexts, including signage, packaging, educational materials, and digital interfaces. Effective use of color improves visual search efficiency and improves accuracy, particularly when combined with thoughtful layout design that focuses user attention [1, 2]. In digital environments, the coexistence of additive (RGB) and subtractive (CMYK) color systems underscores the necessity for consistent information presentation across different media [2–4].

However, an exclusive reliance on color for information encoding presents challenges, particularly against variations in lighting conditions, screen calibration, and color proximity. Consequently, the literature on accessibility and Human-Computer Interaction (HCI) advocates for the implementation of redundant encoding and systematic verification through contrast thresholds to enhance interpretation in real-world scenarios [3, 5]. This approach aligns with established best practices derived from the Web Content Accessibility Guidelines (WCAG), which specify that color should not serve as the sole means of conveying information (SC 1.4.1) and establish minimum contrast requirements for text (SC 1.4.3) [6]. Evaluations in the context of Color Vision Deficiency (CVD), e-commerce, and public interfaces reveal that audit tools identify contrast issues in accordance with WCAG standards, recommending systematic verification shortcuts and specific metrics tailored for interfaces utilized by individuals with CVD [3, 7].

CVD manifests itself in various forms, including deficiencies in protan, deutan, and tritan, resulting from alterations in spectral sensitivity and the balance of opponent pathways, leading to perceptual overlaps among specific color ranges. In contrast, luminance (light-dark) is generally better preserved, highlighting the importance of emphasizing contrast and redundant signals within inclusive systems [8]. Congenital CVD affects approximately 8% of men (1 in 12) and approximately 0.5% of women (1 in 200). Specifically, among male subtypes, an estimated 5% exhibit deutan deficiency and 1% exhibit protan deficiency, while tritanopia is comparatively rare (≈ 0.008%; 1 in 12,500) and affects both genders equally [8, 9]. Beyond congenital conditions, age-related deterioration selectively impacts the blue-yellow axis; studies using pseudoisochromatic plates, such as SPP-3, demonstrate peak performance between ages 10 and 24, with a decrease observed from the third decade onward, particularly affecting items aligned with the tritan confusion line [8].

In parallel, frameworks advocating universal design, rights, and accessibility promote strategies that do not rely solely on color, thereby supporting the implementation of inclusive visual grammars in informational and constructive contexts. These frameworks provide concrete guidelines aimed at reducing barriers without stigmatization [3]. In the realm of HCI and web accessibility, there is a critical emphasis on providing non-chromatic cues and ensuring sufficient contrast to ensure comprehension is not dependent on color. This perspective aligns with contemporary guidelines for accessibility evaluation in public and academic websites [7, 8].

In everyday life, CVD can lead to significant frustration and reliance on others for tasks such as grocery shopping, identifying packaging, interpreting traffic signals, reading safety signs, and utilizing applications. This dependence extends to leisure activities, such as choosing clothing or playing video games, resulting in decreased confidence and exclusion, which has far-reaching implications in educational, occupational, and daily contexts [5]. In e-commerce and other interfaces, when color serves as the sole indicator for attributes such as states, sizes, or discounts, CVD individuals may not be able to perceive the signal, leading to increased errors, mistrust, and abandonment of the interface [7, 10].

In light of these challenges, various sectors have developed strategies to mitigate accessibility barriers through supportive symbolic systems. Among these, ColorADD stands out as a graphic language that employs geometric symbols to identify color families and shades (light-dark-metallic), having been implemented across multiple domains [3, 5]. Although ColorADD provides valuable criteria for standardization, numerous evaluations and analyzes highlight its limitations when addressing very similar hues within the same family and potential ambiguities arising from symbol orientation—issues that are particularly critical in interfaces featuring a wide range of color categories [10].

Against this backdrop, there is a compelling justification for designing and validating a complementary visual grammar that builds on the contributions of ColorADD while seeking to overcome its limitations in tonal precision and optimizing performance for visual search tasks characteristic of interfaces and digital workflows. This proposal must adhere to WCAG 2.2 guidelines and incorporate semantic and symbolic signals that reduce ambiguity between closely related tones, while also maintaining

legibility in grayscale. Methodologically, its validation will involve testing metrics for identification by family and value, success in search tasks, perceived preference based on intuition, and consistency across various media, ensuring that the system is robust, comprehensible, and applicable in real-world contexts.

2 Related Work

2.1 Review of the literature and Methodological Approach

The theoretical foundation was constructed through a structured literature review following the PRISMA methodology (Preferred Reporting Items for Systematic Reviews and Meta-Analyzes). The phases of identification, screening, eligibility, and inclusion were implemented as follows: Identification: A search was conducted on Scopus, an academic database that specializes in accessibility, color vision, graphic design, visual systems, and education. Combinations of terms such as color, vision deficiency, color blindness, color coding, alternative color codes, accessibility, WCAG, UX, inclusive design, and luminance were used. Screening: Records were filtered by document type (scientific articles, research papers, book chapters, and theses) and organized by thematic relevance, excluding works that did not directly address CVD, visual accessibility, or color coding systems. Eligibility: Abstracts were reviewed and, when necessary, full texts were examined to ensure that the works contributed relevant information on at least one of the following aspects: mechanisms of color vision, accessibility, heuristic methods for low vision, alternative color codes, educational experiences related to color, optical aids, or inclusive design. Inclusion: Ultimately, a selection of approximately 30 documents was made, comprising articles from indexed journals, book chapters, case studies, and standards proposals, which form the theoretical and methodological basis for this work. This review not only mapped the state of the art, but also systematically identified a specific research gap: the absence of a simple, replicable, and empirically validated visual grammar for identifying subranges within the same color family in everyday decision-making contexts. In addition, this process provided key insights into the experiences of CVD individuals, highlighting the magnitude of the issue, the frequent dependence on others for color-related decisions, and the emotional impact associated with these challenges. These findings served as the basis for defining the research problem and designing the proposed visual grammar.

2.2 Color Vision Deficiency and Functional Impact

The reviewed literature consistently indicates that color vision deficiency (CVD) is a common, often underdiagnosed, condition with significant functional consequences in daily life. Its global prevalence is estimated to be between 8 and 10% % in men and approximately 0.5% in women, making it one of the most prevalent sensory limitations in the global population [9]. Various studies accurately describe CVD profiles: protan, deutan, and tritan deficiencies, explaining how alterations in opponent mechanisms and the spectral response of cones compromise fine discrimination among specific chromatic ranges. In particular, luminance tends to be preserved, presenting opportunities to construct perceptually stable systems based on contrasts and tonal values

[11]. Beyond the physiological dimension, functional impacts are reported in multiple domains, including difficulties in reading maps, interpreting color-coded diagrams, understanding states in digital interfaces, identifying risks in signage, following color-intensive educational materials, and making basic decisions in purchasing or product selection processes [4, 5]. These studies agree that using color as the sole channel reinforces the dynamics of exclusion and dependence, forcing CVD-affiliated individuals to seek assistance for tasks as simple as comparing color variations, selecting clothing, interpreting indicators, or distinguishing visual states in interfaces. This dependence directly affects their autonomy, decision-making safety, and confidence in their own perception [10, 12]. Collectively, the findings indicate that CVD is not merely a perceptual condition, but a significant interaction and accessibility issue that restricts the' full participation of individuals in physical and digital environments. This underscores the urgent need to develop complementary color coding systems that reduce these barriers and enhance autonomy in decision-making.

2.3 Alternative Color Codes and Technological Solutions

Several authors have explored alternative color codes, defined as coding schemes that integrate symbols, patterns, or typography to complement or replace color as the primary communicator of information. Systems such as ColorADD, utilized in signage and educational contexts, along with proposals aimed at graphic design and advertising, demonstrate that the introduction of additional symbols can enhance information comprehension and reduce interpretation errors among CVD-positive individuals, particularly in printed materials and pedagogical resources [12, 13]. However, these studies also reveal a lack of standardization, leading to fragmentation. Existing systems operate under heterogeneous symbolic logics designed for very specific contexts, complicating their interoperability and broad adoption. Most of these systems focus on differentiating general color families (e.g., red, green, or blue) or global contrasts such as light/dark, without providing consistent mechanisms for discriminating fine subranges within the same color family. This gap is critical, as many real-world decisions regarding comparison, purchase, and selection of products depend on distinguishing closely related variations, which these systems do not systematically address [12]. In addition, the literature documents a range of technological solutions aimed at mitigating CVD limitations, including integrated correction filters in operating systems, color remapping applications, and lenses with specialized coatings. Some studies report specific improvements in color discrimination when using these devices, particularly in controlled tasks or under certain experimental conditions [14, 15]. However, evidence also indicates that their effectiveness is highly dependent on external factors, such as ambient lighting, screen calibration, the type of visual scene, or the specific profile of CVD. Furthermore, these solutions often entail high costs per user, require individual adoption, and do not create a shared visual language that can be consistently integrated into graphic products, labeling, or digital interfaces. For these reasons, while valuable, these technological tools cannot replace the need for a universal, replicable, and accessible system capable of supporting all users, both with and without CVD, on the same physical and digital mediums. They also do not explicitly address the

challenge of coding subranges within the same color family, one of the most significant gaps identified in this review.

TABLE 1

Table 1: Solutions Overview

Solution	**Type**	**Effective in All Lighting Conditions**	**Distinguishes Primary Colors**	**Distinguishes Secondary Colors**	**Distinguishes Tertiary Colors**	**Identifies Color Variants (Subranges within the Same Color)**
ColorADD ref	Coding System (Symbols)	Yes (depends on the contrast of the medium)	Yes	Yes	Partial (for combinations)	No, distinguishes family and light/dark-/metal, not close tones
FEELIPA Color Code ref	Coding System (Symbols)	Yes	Yes	Yes	Partial (defines ranges)	Partial, better granularity than ColorADD, but not all fine tones
Universal Colorblind Code (This proposal)	Coding System	Yes	Yes	Yes	Partial	Yes

Note: Solutions that involved hardware components, such as lenses and VR equipment, were excluded from the table.

From Table 1, we can determine the following:

- The central issue lies in the range, not the family: Existing solutions aid in identifying color families (e.g., yellow vs. blue), but do not guaranty consistent discrimination of variants within the same family (e.g., closely related shades of blue).
- Optical lenses and filters: These can enhance color discrimination for some users under specific lighting conditions. However, their effectiveness is not universal and does not systematically address fine ranges; their impact varies depending on the type of color vision deficiency (CVD), the visual scene, and the lighting conditions. System filters and applications: On-screen filters increase contrast, rename or remap colors, and provide partial assistance with ranges. However, their effectiveness depends on the quality of the camera, the lighting conditions, and the algorithms used, and they do not effectively translate to physical media, failing to reliably resolve fine tonal separations. Coding systems: These systems reduce color dependence and identify families and some general variations (light/dark, metallic, ranges). However, they do not systematically distinguish very close variants within the same family.

2.4 Language, Play, and Color Learning

Studies that examine how blind and sighted individuals construct chromatic concepts indicate that language, metaphors, and verbal associations play a central role in the formation of color knowledge. Even in the absence of direct visual experience, individuals can develop coherent representations of chromatic relationships through verbal descriptions, usage contexts, and structural analogies. These findings underscore the importance of incorporating brief, precise, and systematic textual labels into inclusive coding systems [10, 16]. Furthermore, the literature on visual education highlights the value of gamified methods; proposals such as card games designed for color perception and inclusion utilize symbols, explicit rules, and collaborative dynamics to raise awareness of visual diversity and teach chromatic differentiation strategies. Such activities have proven effective in helping users internalize patterns, combine multimodal information, and construct a ”color language” applicable to daily decision-making [17]. Collectively, these works agree that the combination of consistent symbols, concise text, and repetitive structures facilitates comprehension and learning, particularly when the color discrimination capacity is limited. This principle suggests that a visual grammar system can function not only as a perceptual support but also as a cognitive tool that aids in the integration and recall of information across different media [8, 12].

2.5 Accessibility, Heuristics, and UX Evaluation

In the field of digital accessibility, the Web Content Accessibility Guidelines (WCAG) 2.1/2.2 represent the widely adopted standard, establishing criteria that include prohibiting the use of color as the sole means of conveying information and ensuring minimum contrast levels. These guidelines have spurred the development of multiple heuristic methods and automated evaluation tools aimed at identifying accessibility errors and supporting inclusive design [1, 7, 19]. Empirical studies involving users with Color Vision Deficiency (CVD) demonstrate that introducing redundant cues reduces perceptual errors, improves visual search efficiency, and improves comprehension in interfaces where color is a key element [4, 5]. Additionally, research focusing on luminance adjustment and color spaces shows that chromatic discrimination improves when systems minimize hue dependence and favor stable tonal relationships, emphasizing the importance of designing solutions that function effectively in both color and grayscale [20]. However, the majority of this research focuses on general legibility, element identification, or visual navigation, rather than on fine distinctions between sub-ranges within the same chromatic family—one of the most critical challenges in the user experience of individuals with CVD. The present work specifically addresses this gap by proposing and evaluating an explicit visual grammar designed to support the interpretation of color ranges and sub-ranges in everyday selection and comparison contexts [12, 21].

2.6 Gap Identified in the Literature

The systematic review conducted following the PRISMA methodology reveals a consistent gap: although alternative codes, technological filters, heuristic methods, and

studies focused on contrast or legibility exist, no work directly addresses or empirically evaluates the identification of tonal sub-ranges within a single color family. This specific area is where CVD-positive individuals report the highest frequency of errors, uncertainty, and negative impact on autonomy. The current literature is oriented towards differentiating broad chromatic families, correcting perception through optical aids, improving visibility via contrast, or facilitating general visual search. However, it lacks a proposal for an explicit, replicable, and redundant visual grammar that allows for structured reasoning about color ranges independent of altered chromatic perception.

3 Experimental Study

To evaluate and characterize how an inclusive visual grammar based on symbols, CMYK, color families, and percentage tonal values supports the identification of sub-ranges within the same color family in individuals with Color Vision Deficiency (CVD), with the aim of determining its impact on accuracy, clarity, confidence, and perceived utility in representative contexts of color selection within digital environments. Hypothesis: The implementation of a visual grammar based on symbols, CMYK, and percentage tonal values will enhance the performance of individuals with Color Vision deficit (CVD) in identifying color sub-ranges. This enhancement is expected to increase the system's clarity, user confidence, and perceived utility for everyday color decisions. The Independent Variable (IV) is the introduction of visual grammar; the Dependent Variables (DV) are accuracy, clarity, confidence, and perceived utility.

3.1 General Study Design

The study adopted a quantitative descriptive approach, complemented by a qualitative interpretive analysis based on the content. All phases used stimuli developed using the proposed visual grammar, with color mixing tasks administered in a digital environment.

The process included: Three Remote Pilots (N1=67; N2=58; N3=74): Focused on refining symbols, luminance settings, textual labels, and mixing instructions. A Final Test with the Target Population (N=34 with CVD): Focused on measuring accuracy, tonal consistency, and perceived clarity, utility, and confidence.

3.2 Participants

The pilot phase involved 199 participants whose color vision status was not verified, as the primary objective was prototype refinement.

Table 2 shows the number of participants involved in the final evaluation. It should be noted that the sample includes five women with color blindness (CVD), which is a significant number. The final phase included 34 individuals with Color Vision Deficiency (CVD), classified using an online-administered Hardy, Rand, and Rittler (HRR) test. This sample comprised 15 participants with mild CVD and 19 participants with moderate to severe CVD.

Table 2: Participants

CVD Type	Severity	Errors in HRR	n	Gender
Protan	moderate	≧ 3	2	6 male, 0 female
	severe	≧ 8	4	
Deutan	moderate	≧ 3	0	2 male, 0 female
	severe	≧ 8	2	
Tritan	moderate	≧ 3	5	2 male, 3 female
	severe	≧ 8	0	
Red–green	moderate	≧ 3	3	3 male, 2 female
	severe	≧ 8	2	

3.3 Tools and Visual Grammar

The proposed visual grammar was constructed using a set of conceptual and digital materials designed to ensure its coherence, reproducibility, and perceptual robustness. The system was explicitly engineered to function effectively in grayscale, thus reducing dependence on chromatic perception through CMYK decomposition and information redundancy.

3.3.1 Geometric Symbols (Structural Component)

A set of simple and highly distinguishable symbols was designed to serve as visual anchors representing the structural components involved in color formation. These symbols utilize basic, familiar shapes—aiding in recall—and maintain a constant, proportional stroke, allowing for identification even under low-contrast conditions or in grayscale. The symbols do not represent colors directly, but rather structural color concepts, enabling interpretation as a grammar independent of the visual stimulus.

Various methods for displaying color percentages were tested. Initial iterations utilized squares and numerical percentages; however, participant feedback indicated that graphical figures associated with colors were the most effective option. Subsequent testing revealed that these figures needed to be circular, as participants otherwise misperceived the color proportions relative to the shape's geometry

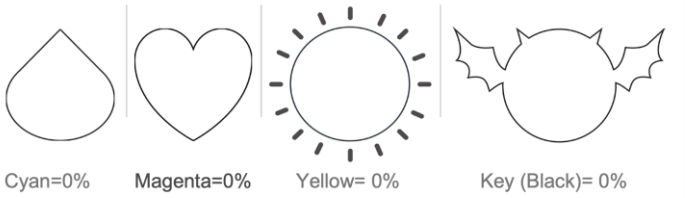


Fig. 1: Baseline representation of the proposed chromatic coding system, where each geometric figure corresponds to a color family (Cyan/Blue, Magenta/Red, Yellow, Black) at 0% chromatic load.

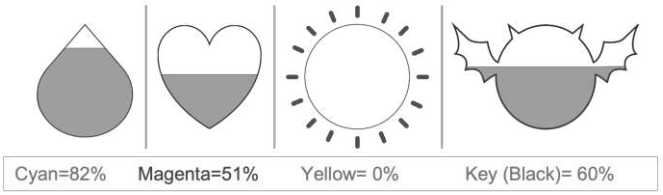


Fig. 2: Parametrized representation of the system, showing the same figures with intermediate chromatic values (Cyan/Blue = 82%, Magenta/Red = 51%, Yellow = 0%, Black = 60%) to assess interpretation of mixtures and tonal variations.

3.3.2 CMYK Decomposition (Chromatic Mixing Component)

The grammar incorporates a second fundamental element: the decomposition of color into CMYK (Cyan, Magenta, Yellow, and Black) channels. This approach was adopted because it allows color to be described using numerical values independently of perception, facilitates robust representation in grayscale, and directly links the system to real-world processes like printing and graphic reproduction. The conversion followed the flow of HEX → RGB → CMYK, which represented each color as an objective percentage combination. In the grammar, this decomposition is expressed using CMYK symbols accompanied by percentages, enabling the user to read the color's structural composition beyond their perceptual experience.

3.3.3 Tonal Values and Sub-ranges (Semantic Component)

Differences within the same chromatic family were expressed using tonal percentages and accessible labels. These labels were selected for their naturalness in the everyday language and their comprehensibility to users regardless of technical color knowledge. Furthermore, the percentage structure improves the cognitive consistency of the system, helping users infer order, hierarchy, and distance between tones. To maximize clarity, broad chromatic families were defined and named using a direct and accessible scheme. Each label is presented as "family + tonal value," allowing users to reason about the sub-range without relying exclusively on the visual stimulus.

3.3.4 Digital Tools Employed

Grammar Design: The system's visual construction was executed in Figma to ensure typographic and geometric consistency, control over luminance and contrast, and uniform export conditions for all materials.

Test Application: Empirical validation was conducted through Google Forms, which enabled sequential presentation of tasks, structured data collection, seamless integration of images and grayscale figures, and direct upload of the HRR test captures from the participants.

CVD Vision Simulators: To confirm the comprehensibility of the stimuli across various forms of color blindness, CVD vision simulation tools (protan, deutan, tritan) were utilized. These simulators allowed researchers to preview how stimuli would be

perceived by CVD individuals, fine-tune luminances, verify distinguishability on the grayscale, and anticipate potential perceptual errors prior to the study.

3.4 Procedure

The study comprised two main phases: an initial iterative refinement phase, which included three pilots with the general population, and a validation phase with the target population of individuals with confirmed CVD. All tests were performed remotely using online forms for the standardized collection of quantitative and qualitative data. Before the final large-scale questionnaire, three moderated tests were conducted with the first CVD participants to observe a detailed interaction with grammar, resolve queries in real-time, and gather qualitative feedback in-depth on clarity, cognitive load, and potential usage.

3.4.1 Pilot 1 – Exploration of the Base Idea (N = 67)

Objective: To examine whether the initial conceptual structure (CMYK symbols + percentages + neutral labels in gray) could be interpreted spontaneously by users without the need for extensive instructions.

Procedure: Participants viewed mixing configurations represented by geometric figures (circle, triangle, rhombus, rectangle), each containing a grayscale fill percentage symbolizing the corresponding CMYK proportion. The task required them to select the closest resulting tonal sub-range from a set of options.

Findings

- Variability in Geometric Interpretation: Variability was observed in the interpretation of the geometric fill, with responses suggesting that some figures were perceived as ”fuller” than others, despite having equivalent percentages.
- Inconsistent Reading Coherence: The reading coherence (left → right; the final mixture of composition of the figure →) was not uniform; some participants began by examining the final color option before reading the composition details.
- Confusion on the Black Component (K): Comments indicated confusion regarding the representation of black (K), specifically whether it denoted a tonal value of the final color or a percentage value of the CMYK component.

Derived Adjustments:

- Symbol Standardization: Shapes, sizes, and fill proportions were standardized to mitigate geometric biases.
- Mini-Reading Guide: An explicit three-step instructional guide was introduced (view mix → read percentage→ choose sub-range), deemed essential for subsequent phases.

Pilot Contribution:

This pilot confirmed the promise of the base logic but highlighted the critical need for formal and linguistic clarity before proceeding to accuracy evaluation.

3.4.2 Pilot 2 – Refinement of Instructions and Task Structure (N = 58)

Objective: To mitigate ambiguities, stabilize the user reading experience, and standardize the interaction protocol to improve response consistency.

Procedure: Participants engaged with a refined version of the questionnaire, which included revised instructions and normalized visual figures. A mandatory, fixed action sequence was introduced: 1) observe the color mixture, 2) interpret the percentages, and 3) select the resulting tonal sub-range. The response options were designed to be highly distinct from each other, allowing for a more precise detection of the error patterns.

Findings

- A significant increase in the clustering of correct responses was observed compared to Pilot 1.
- The reduction in response dispersion suggested a clearer understanding of the task requirements.
- Qualitative feedback still indicated specific uncertainties regarding the interpretation of certain percentage values, particularly in three-component CMYK mixtures.

Derived Adjustments:

- The textual consistency of the semantic labels (”light yellow,” ”medium green,” ”intense blue”) was strengthened.
- The visual hierarchy was optimized by standardizing the visual weight of percentages, icons, and descriptive text to effectively guide the reading sequence.
- Discrete prototype percentages (e.g. 20%, 50%, 80%) were introduced. This approach facilitated sub-range discrimination while minimizing user cognitive load.

Pilot Contribution: This phase was instrumental in stabilizing the core reading experience and establishing the fundamental parameters for visual interaction (order, repetition, symmetry, perceptual hierarchy).

3.4.3 Pilot 3 –Consolidation of the Visual Grammar (N = 74)

Objective: Compare multiple variations of the grammar to select the most clear, accurate, and comprehensible version prior to the final evaluation with the target population.

Procedure: The participants were presented with five distinct system configurations, which varied depending on the following factors: (i) The type of geometric symbol utilized.(ii) The degree of reliance on the symbol versus the accompanying textual information. (iii) A comparison between the full-color system and the grayscale rendition. Participants completed color sub-range identification tasks and responded to a system preference question. Quantitative and qualitative evidence was collected.

Findings

- Textual information proved to be a critical complementary element in reducing ambiguities, particularly when distinguishing similar tones.

- Triple redundancy (symbol + percentage + textual label) was demonstrated to be significantly more effective than any dual combination.

Result: This triple redundant configuration was selected as the final version for the CVD-specific test, as it collectively provided superior perceptual clarity, cognitive stability, and greater consistency in results.

Pilot Contribution: This phase empirically validated the most robust structure of the system and enabled the isolation of the optimal configuration for subsequent targeted evaluations.

3.4.4 Moderation with Individuals with CVD (n = 3)

Objective: To mitigate ambiguities, stabilize the user's reading experience, and standardize the interaction protocol to improve response consistency.

Procedure: Participants engaged with a refined version of the questionnaire, which included revised instructions and normalized visual figures. A mandatory fixed action sequence was introduced: 1) Observe the color mixture; 2) Interpret the percentages; and 3) Select the resulting tonal sub-range. The response options were designed to be highly distinct from each other, allowing for a more precise detection of the error patterns.

Findings

- A significant increase in the clustering of correct responses was observed compared to Pilot 1.
- The reduction in response dispersion suggested a clearer understanding of the task requirements.
- Qualitative feedback still indicated specific uncertainties regarding the interpretation of certain percentage values, particularly in three-component CMYK mixtures.

Derived Adjustments:

- The textual consistency of the semantic labels (”light yellow,” ”medium green,” ”intense blue”) was strengthened.
- The visual hierarchy was optimized by standardizing the visual weight of percentages, icons, and descriptive text to effectively guide the reading sequence.
- Discrete prototype percentages (e.g. 20%, 50%, 80%) were introduced. This approach facilitated sub-range discrimination while minimizing user cognitive load.

Pilot Contribution: This phase was instrumental in stabilizing the core reading experience and establishing the fundamental parameters for visual interaction (order, repetition, symmetry, perceptual hierarchy).

3.4.5 Validation Phase with the CVD Population (n = 34)

The validation phase constituted the experimental core of the study, designed to assess the actual performance of visual grammar among people with Color Vision deficit (CVD). A standardized protocol was utilized to classify the participants, measure the accuracy per color range, and analyze the subjective perception of the system.

Participation required an initial diagnostic verification process via an HRR-type test administered at the beginning of the questionnaire. Each participant was required to complete the test, view their result, and upload a screenshot of the report, which allowed them to assign to three severity levels (mild, moderate, or severe) based on their pattern of correct and incorrect responses. The final sample comprised 19 individuals with moderate to severe CVD and 15 with mild CVD, providing a balanced distribution to examine performance differences between subgroups.

Subsequently, participants performed four chromatic mixing tasks designed to simulate real-world decision-making scenarios in retail and digital environments where tonal discrimination is critical. Each item included: symbols, CMYK components presented in grayscale, percentages associated with each component, a textual color family label, and several options corresponding to different sub-ranges within that family. Users were instructed to read the symbols and their percentages, interpret the chromatic family, compare the proposed options, and select the sub-range that best represented the suggested mixture. This procedure allowed us to evaluate the grammar's capacity to guide the fine discrimination of tones within the same family, independently of the user's color perception.

Upon completion of the tasks, a Likert-type survey (1–5 scale) was administered, consisting of four dimensions: system clarity, ability to differentiate color ranges, confidence in decision-making, and perceived utility in everyday contexts. In addition, an open question was included to gather qualitative impressions on the overall user experience.

All stimuli used in this phase were pre-verified using vision simulators for protan, deutan, and tritan deficiencies. This ensured the legibility of the symbols, stability in grayscale, distinguishability of percentages, and the absence of visual bias in the response options. This prior control ensured that the tasks evaluated perceptual conditions equivalent to those experienced by the actual participants, thereby guaranteeing consistency and validity in the interpretation of results.

3.5 Ethical Considerations

Participation in all phases of the study was strictly voluntary. Participants were informed that the collected data would be used solely for academic and research purposes and that sensitive personal information would not be stored. The study adhered to the ethical standards applicable to non-clinical user research, safeguarding privacy, informed consent, and responsible use of data.

3.6 Variables and Metrics

The evaluation process was structured using the Goal–Question–Metric (GQM) model, which allowed the explicit alignment of the study's objectives with operational research questions and observable metrics. The General Goal was to assess whether a visual grammar improves color sub-range identification in individuals with CVD, increasing clarity, confidence, and perceptual autonomy during tonal decision tasks.

Question 1 (Q1). Accuracy by Range (Related to H1): This aimed to measure identification precision. The quantitative metrics used included the percentage of correct responses per mixture, the overall precision per participant, and the precision segmented by CVD severity. These metrics characterized both the system's precision and the stability of performance across different color families.

Question 2 (Q2). Robustness in Grayscale Stimuli (Related to H5): This examined the system's stability when presented without color. Analysis included performance differences between color and non-color stimuli, consistency in value identification, and qualitative comments demonstrating comprehension independent of the chromatic channel. This combination of indicators determined whether the grammar effectively fulfilled the principle of perceptual redundancy.

Question 3 (Q3). Perceived Clarity and Confidence (Related to H2, H3): This addressed the subjective dimension of the system. Quantitative metrics were derived from Likert scales for clarity, differentiation, and confidence, analyzing both means and the percentage of responses scoring 4 or higher. In addition, testimonials describing feelings of autonomy, reduced uncertainty, and declared reading strategies were analyzed to interpret the subjective dimension of the decision process.

Question 4 (Q4). Perceived Usability and Utility (Related to H4): This evaluated the system's applicability. The metrics included the Likert mean associated with utility, the percentage of ratings ≥4, and the platform data where available. Qualitatively, comments related to everyday applicability, perceived cognitive load, and suggestions to improve the user experience were analyzed.

Question 5 (Q5). Performance by Families and Sub-ranges (Related to H5): This focused on detailed performance. Quantitative metrics included accuracy per chromatic family, accuracy per sub-range type, variability between families, and an internal coherence index based on the consistency between successive decisions. This dimension determined whether the grammar operated uniformly across different chromatic ranges and offered stable support for fine color decisions.

Collectively, the use of the GQM model allowed a precise correspondence to be established between the study hypotheses, the operational questions, and the quantitative and qualitative indicators necessary to evaluate the effectiveness of visual grammar, providing a solid framework for interpreting results in subsequent phases.

4 Results

This section presents the results of the validation phase described in Section 3.4.5. A total of 19 participants completed the six proposed tasks aimed at evaluating the designed visual grammar. Table 2 reports the descriptive statistical values for the six tasks/tests. Mean values, expressed as percentages, represent the level of accuracy achieved in task performance. Specifically, the results were as follows: Task 1 (73.9%), Task 2 (81.7%), Task 3 (67.2%), Task 4 (83.0%), Task 5 (81.7%), and Task 6 (87.2%).

The Shapiro–Wilk normality test was applied, confirming that the sample does not follow a normal distribution ($p \leq 0.05$). For each of the six tests, a comparison was conducted between the participants according to the type of color blindness (Deutan, Protan, or Tritan). In addition, a fourth category (Red–Green) was considered,

Table 3: Descriptive statistical values

Test	Statistic	Value	Std. Error
Test1	Mean	,739	,0672
	Variance	,081	
	Std. Deviation	,285	
Test2	Mean	,817	,0901
	Variance	,146	
	Std. Deviation	,382	
Test3	Mean	,672	,0874
	Variance	,137	
	Std. Deviation	,370	
Test4	Mean	,830	,090
	Variance	,147	
	Std. Deviation	,383	
Test5	Mean	,817	,0901
	Variance	,146	
	Std. Deviation	,382	
Test6	Mean	,872	,0766
	Variance	,106	
	Std. Deviation	,325	

which included participants whose classification could not be conclusively identified as Deutan or Protan. The objective of this comparison was to determine which group achieved greater accuracy in identifying the color presented in each visual grammar task. Given the non-normal distribution of the data, the Kruskal–Wallis test for independent samples (color-blindness categories) was applied to each of the six tasks.

Table 4: Summary of hypothesis testing

Null Hypothesis	Test	Sig.[a,b]
The distribution of Test1 is the same across Color-Blindness categories.	Independent-Samples Kruskal–Wallis Test	,003
The distribution of Test2 is the same across Color-Blindness categories.	Independent-Samples Kruskal–Wallis Test	,382
The distribution of Test3 is the same across Color-Blindness categories.	Independent-Samples Kruskal–Wallis Test	,349
The distribution of Test4 is the same across Color-Blindness categories.	Independent-Samples Kruskal–Wallis Test	,142
The distribution of Test5 is the same across Color-Blindness categories.	Independent-Samples Kruskal–Wallis Test	,240
The distribution of Test6 is the same across Color-Blindness categories.	Independent-Samples Kruskal–Wallis Test	,439

Table 3 shows that, for all tests except the first, there is no significant difference (p-value ≥ 0.05) between the color blindness categories in reading and the precision in visual grammar. However, a detailed pairwise analysis of the color blindness categories reveals that, in the first test, a significant difference (p-value ≤ 0.05) is observed in the Red-Green/Tritan pair. Considering that the Red-Green category consists of

participants whose classification as Deutan or Protan is not certain, and given that the Deutan-Tritan and Protan-Tritan comparisons show no significant differences, the Red-Green category as a whole could also be considered non-significant. Table 4 presents a detailed statistical pairwise comparison analysis using the Kruskal-Wallis test for independent samples for Test 1.

Table 5: Test 1 pairwise comparisons by color-blindness category

Sample 1–Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Sig. ajust.[a]
Deutan–Red/Green	-,300	4,196	-,072	,943	1,000
Deutan–Protan	7,500	4,094	1,832	,067	,402
Deutan–Tritan	-10,500	4,196	-2,503	,012	,074
Red/Green–Protan	7,200	3,037	2,371	,018	,106
Red/Green–Tritan	-10,200	3,172	-3,216	,001	,008
Protan–Tritan	-3,000	3,037	-,988	,323	1,000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same. Asymptotic significance (two-sided tests) is displayed. The significance level is 0.05.
[a] Significance values have been adjusted using the Bonferroni correction for multiple tests.

Tables 5, 6, 7, 8, and 9 show the detailed statistical pairwise comparison analysis using the Kruskal-Wallis test for independent samples for Tests 2, 3, 4, 5, and 6.

Table 6: Test 2 pairwise comparisons by color-blindness category

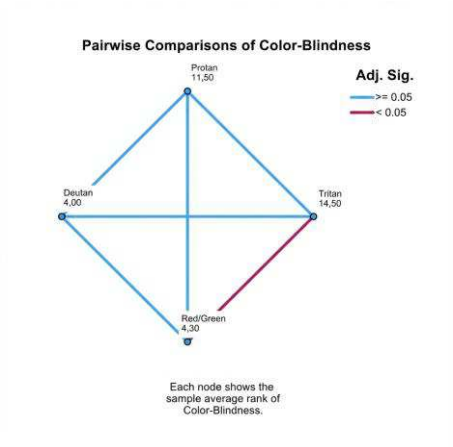
Sample 1–Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Sig. ajust.[a]
Deutan–Red/Green	,233	2,345	,099	,921	1,000
Deutan–Protan	3,400	3,240	1,049	,294	1,000
Deutan–Tritan	-3,400	2,449	-1,388	,165	,991
Red/Green–Protan	-3,167	3,162	-1,001	,317	1,000
Red/Green–Tritan	-3,167	2,345	-1,350	,177	1,000
Protan–Tritan	,000	3,240	,000	1,00	1,000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same. Asymptotic significance (two-sided tests) is displayed. The significance level is 0.05.
[a] Significance values have been adjusted using the Bonferroni correction for multiple tests.

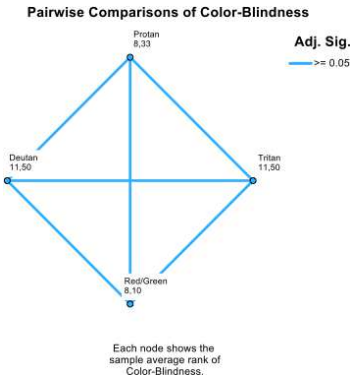
Figure 3 graphically displays the pairwise comparison of color blindness categories. The blue lines indicate pairs with no significant differences. Based on the success rates indicated at the beginning of this section, it can be confirmed that all pairs in the six tests demonstrate a high level of precision in interpreting the visual grammar.

5 Discussion

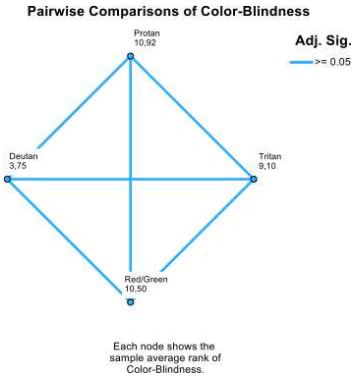
The findings demonstrate that a redundant visual grammar can improve the identification of color sub-ranges in individuals with color vision deficiency (CVD) and



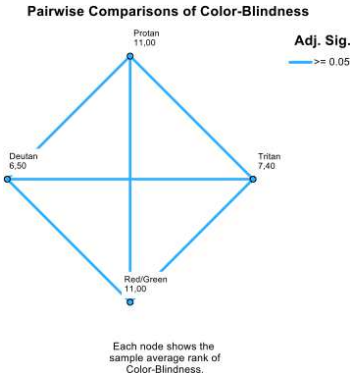
(a) Test 1



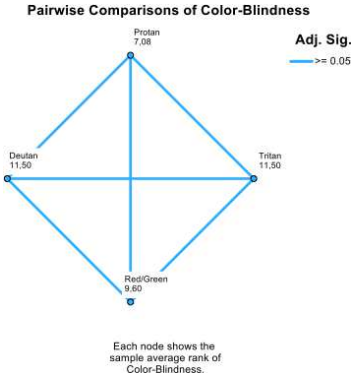
(b) Test 2



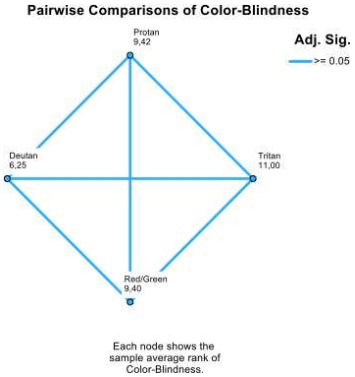
(c) Test 3



(d) Test 4



(e) Test 5



(f) Test 6

Fig. 3: The pairwise compariso1ngof color blindness by categories.

Table 7: Test 3 pairwise comparisons of color-blindness

Sample 1–Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Sig. ajust.[a]
Deutan–Red/Green	-5,350	4,225	-1,266	,205	1,000
Deutan–Protan	-6,750	4,225	-1,598	,110	,661
Deutan–Tritan	7,167	4,123	1,738	,082	,493
Red/Green–Protan	1,400	3,194	,438	,661	1,000
Red/Green–Tritan	1,817	3,058	,594	,552	1,000
Protan–Tritan	,417	3,058	,136	,892	1,000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same. Asymptotic significance (two-sided tests) is displayed. The significance level is 0.05.
[a] Significance values have been adjusted using the Bonferroni correction for multiple tests.

Table 8: Test 4 pairwise comparisons of color-blindness

Sample 1–Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Sig. ajust.[a]
Deutan–Red/Green	-,900	2,888	-,312	,755	1,000
Deutan–Protan	4,500	2,818	1,597	,110	,662
Deutan–Tritan	-4,500	2,888	-1,558	,119	,715
Red/Green–Protan	3,600	2,090	1,723	,085	,510
Red/Green–Tritan	3,600	2,183	1,649	,099	,595
Protan–Tritan	,000	2,090	,000	1,000	1,000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same. Asymptotic significance (two-sided tests) is displayed. The significance level is 0.05.
[a] Significance values have been adjusted using the Bonferroni correction for multiple tests.

Table 9: Test 5 pairwise comparisons of color-blindness

Sample 1–Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Sig. ajust.[a]
Deutan–Red/Green	-2,517	2,345	-1,073	,283	1,000
Deutan–Protan	-4,417	3,162	-1,397	,163	,975
Deutan–Tritan	-4,417	2,345	-1,883	,060	,358
Red/Green–Protan	1,900	3,240	,586	,558	1,000
Red/Green–Tritan	-1,900	2,449	-,776	,438	1,000
Protan–Tritan	,000	3,240	,000	1,000	1,000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same. Asymptotic significance (two-sided tests) is displayed. The significance level is 0.05.
[a] Significance values have been adjusted using the Bonferroni correction for multiple tests.

help reduce perceptual uncertainty. The accuracy rates, which remain around 70% even in cases of moderate to severe CVD, indicate that the system allows users to reason about color mixing using symbols and percentages, independent of their chromatic vision limitations.This grammar does not function as a perceptual correction like lenses or filters would; instead, it operates as a structured visual language that

Table 10: Test 6 pairwise comparisons of color-blindness

Sample 1–Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Sig. ajust.[a]
Deutan–Red/Green	-3,150	2,898	-1,087	,277	1,000
Deutan–Protan	3,167	2,828	1,120	,263	1,000
Deutan–Tritan	-4,750	2,898	-1,639	,101	,607
Red/Green–Protan	,017	2,098	,008	,994	1,000
Red/Green–Tritan	-1,600	2,191	-,730	,465	1,000
Protan–Tritan	-1,583	2,098	-,755	,450	1,000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same. Asymptotic significance (two-sided tests) is displayed. The significance level is 0.05.
[a] *Significance values have been adjusted using the Bonferroni correction for multiple tests.*

shifts some aspects of chromatic reasoning towards design rather than placing the burden on the user. This alignment with the accessibility guidelines of WCAG 2.2 makes it a valuable tool for integration into physical labels and digital interfaces.Positive feedback on clarity, differentiation, confidence, and utility suggests that, in addition to improving objective performance, grammar provides emotional benefits by decreasing reliance on others and increasing autonomy in everyday decision-making.Some limitations remain in distinguishing extremely close sub-ranges, which is expected since these represent the most challenging area of chromatic discrimination. However, the consistency in grayscale perception and stability across color families indicate that the grammar achieves its fundamental goal: to offer stable visual and cognitive support for individuals who perceive color differently.

5.1 Limitations and Future Work

The study presents several limitations that should be considered when interpreting the results and guiding future developments. First, although the sample of 34 individuals with color vision deficiency (CVD) allowed for the assessment of the grammar's performance, its size remains limited for making broad population generalizations. It will be necessary to increase the number of participants and balance the profiles among the different types and levels of CVD. Additionally, working with clinically characterized groups through laboratory-administered tests would provide more robust data. Second, the designed tasks were discrete exercises focused on mixing and selection, aimed at evaluating the comprehensibility of the grammar in controlled scenarios. The behavior of the system in complex interaction flows—such as product purchasing, color configurators, textile catalogs, or interfaces with multiple elements coded simultaneously—has not yet been explored. These scenarios would introduce cognitive loads, divided attention, and navigation challenges. Based on these limitations, several lines of future work are proposed:

Validation in Real Digital Interfaces: Implement the grammar in color selectors, e-commerce catalogs, or design apps, and evaluate its impact on task completion times, success rates, and user satisfaction.

Application to Physical Labels: Collaborate with companies in the textile, cosmetic, or food industries to test grammar in real labeling situations and study its effects on immediate comprehension, error reduction, and perceived autonomy.

Educational Extension: Develop pedagogical materials that utilize grammar to teach basic concepts of color mixing and chromatic structure in school contexts or visual literacy programs.

Implementation in the Medical Field: Explore the application of visual grammar in medical contexts, potentially enhancing patient communication and understanding in areas such as medical imaging or color-coded health information.

6 Conclusion

The findings of this study underscore the potential of a structured visual grammar to enhance color-related decision-making for people with color vision deficiency (CVD). By addressing fine tonal discrimination—a critical source of error and uncertainty—the proposed system demonstrates measurable improvements in accuracy and user confidence. Empirical evidence from multiple pilot phases and a final evaluation confirms that grammar is perceived as clear, useful, and reliable, contributing to reduced dependency on third parties and fostering a greater sense of autonomy. Importantly, this approach does not seek to replace color perception, but rather to complement it through a design-oriented visual language aligned with the accessibility principles of WCAG 2.2. Its adaptability to grayscale and applicability across physical and digital contexts position the grammar as a versatile accessibility layer. Beyond functional benefits, the emotional impact reported by the participants highlights the broader social relevance of inclusive design strategies. These results represent a significant step toward a paradigm in which color coding is not exclusively dependent on color vision, but instead promotes equitable, operable standards for all users. The proposed grammar offers a robust foundation for future research and development that aims to advance inclusive, standardized, and emotionally conscious design practices.

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