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The importance of considering distinct characteristics of color vision in the development of digital interfaces

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Abstract: This article examines the significance of considering various aspects of color perception in the process of developing digital interfaces. Color serves as a fundamental element of human vision and perception of the environment; therefore, it is crucial to account for diverse manifestations of color vision, including color blindness, achromatopsia, and tetrachromacy. Attention is given to the impact of design standards on improving user convenience, reducing the likelihood of errors, and decreasing cognitive load. The purpose of this study is to provide recommendations for designing digital product interfaces that accommodate users with various forms of color perception.

To achieve these goals, a review of scientific literature was conducted, methodologies for color adaptation were studied, and the application of simulators for color perception deviations was examined. The focus is placed on color blindness, reduced contrast perception, and changes in visual function occurring with age.

The findings emphasize the need to create interfaces tailored to users with varying characteristics. Key directions include color schemes with contrasting elements, mechanisms for adjusting hues, and visual signals that complement core content. Automated color solutions enable the consideration of users' individual parameters.

A design approach that takes into account the specifics of color perception enhances interaction with interfaces, making them more accessible.

The information presented in this study will be of interest to developers engaged in interface design, software specialists, experts studying cognitive processes, and those working in the field of computer vision. The described methodologies find application in educational and commercial initiatives aimed at

promoting inclusivity.

Keywords: Color vision, digital interfaces, color blindness, accessibility, cognitive perception, contrast, adaptive technologies.

Introduction: Modern digital interfaces have become integral to daily life, serving as tools for accessing information, interacting with the environment, and managing technology. However, the majority of these interfaces are developed without considering users with unique color perception characteristics, limiting accessibility. In the work by Uvarov N.K. [17], it is noted that approximately 8% of men and 0.5% of women experience color vision deficiencies, emphasizing the need for interfaces that account for such features.

Various types of visual impairments, including color blindness, reduced ability to distinguish contrasting colors, and age-related changes, hinder the perception of digital information. Neglecting these factors increases interaction complexity, causes cognitive strain, and excludes certain user groups. This is particularly significant in interfaces used in medicine, education, and industrial production, where accurate interaction directly impacts outcomes.

The creation of adaptive digital systems that consider the physiological and psychological aspects of color perception is becoming increasingly important. The integration of interdisciplinary approaches, combining knowledge from neuropsychology, color theory, computer science, and interface design, paves the way for solutions that address the needs of a broader audience.

The purpose of this article is to provide recommendations for the development of digital product interfaces that accommodate users with diverse forms of color perception.

METHODS

The issues of color perception and the creation of user interfaces designed for individuals with various vision characteristics occupy a significant place in modern scientific research. An analysis of publications in this field highlights three key areas: the development of accessible interfaces for people with color blindness, the study of color perception in digital environments, and the creation of algorithms for evaluating and automating color solutions.

Many scientific studies aim to remove barriers faced by users with limitations in color palette perception when interacting with digital interfaces. Geddes C. [1] revisits the capabilities of existing color vision simulators and formulates recommendations for their improvement. Bonacin R., Reis J. C., and de Araujo R. J. [5] adopt an ontological approach to enhance the usability and accessibility of interfaces. Pinheiro M., Viana W., de Gois Ribeiro Darin T. [7] focus on the development of games suitable for users with color vision deficiencies, demonstrating the potential of simulations in this area.

The challenge of distinguishing color combinations in interfaces has become the subject of in-depth scientific investigation. Kovesdi C. R. [2] proposes a tool for analyzing the readability of color solutions, enabling the assessment of their practical value. The study by Yang J. et al. [3] explores the prediction of visual similarity between palettes. The work of Kawashima S. et al. [12] examines the influence of the visual field on color perception. Methods for analyzing reactions to color signals using electroencephalography are described by Yang C. et al. [11]. These studies contribute to understanding the mechanisms of perceiving color stimuli.

A significant portion of scientific literature is dedicated to developing tools and algorithms for working with colors. Wang Z. et al. [6] analyze perceptual differences in shades based on image processing. The study by Pereira A. et al. [8] improves metrics for color differentiation applied in computer analysis systems. Weingerl P. [9] proposes methods for the automatic generation of color themes. Wu M. [10] introduces algorithms used in image processing. Liu S. and Yin G. [4] describe the adaptation of color solutions in automotive interfaces, exploring their practical implementation. Additionally, the article by Uvarov N.K. [17] examines the challenges encountered in optimizing applications designed for use by individuals with color blindness.

Smith V. C. and Pokorny J., in their article [15], detail processes related to color perception, examining the physiological features and functioning of neural structures. The authors describe the operation of photoreceptors and the interactions of visual system cells, providing insights into the nature of color perception limitations. Materials from the Color Blindness Awareness Organization [13], published on the website www.colourblindawareness.org, explore the nature of color blindness, describing its forms and emphasizing educational and informational aspects.

Sutherland I. E. [14] highlights the role of color design in enhancing user interaction with interfaces, emphasizing how well-structured color schemes help organize the structure of visual perception. In the work of Kelley Gordon [16], available on the website www.nngroup.com, the impact of color accents on highlighting key elements in interfaces is investigated, demonstrating the importance of maintaining visual balance. The UX design principles mentioned in the article stress the necessity of a harmonious approach to color usage to improve the efficiency of user interaction with systems.

Scientific studies illustrate the diversity of approaches to exploring color characteristics and developing adapted interfaces. However, challenges remain, including the limitations of color vision simulators and the insufficient universality of proposed algorithms under real-world conditions. Greater attention is needed to integrate discoveries in color perception with technical developments and to implement automated tools into practical products.

As a methodological basis, an analysis of scientific literature was conducted, color adaptation methods were examined, and the results of applying color vision deviation simulators were reviewed.

RESULTS AND DISCUSSION

The foundation of human color perception lies in the trichromatic system, which operates through three types of retinal cone cells—S, M, and L. These cells are sensitive to short-wavelength, medium-wavelength, and long-wavelength light, respectively. However, approximately eight percent of men and 0.5 percent of women experience color vision deficiencies, such as dichromatism and anomalous trichromatism.

Color perception plays a crucial role in designing digital interfaces, as it determines usability, information comprehensibility, and accessibility for diverse user groups. The human visual system relies on three types of photoreceptors—cones, each sensitive to specific light wavelengths: red, green, and blue. This mechanism forms the trichromatic system, which underpins color models such as RGB, commonly used in display screens. Additionally, designers often employ the HSV model, which intuitively manages hue and saturation parameters, aligning with human perception [2,3].

One of the factors influencing interface perception is the physiological characteristics of users. Color vision deficiencies encompass a broad range of conditions, including protanopia, deuteranopia, tritanopia, and monochromatism. For instance, individuals with protanopia struggle to distinguish between red and green hues, while tritanopia affects the ability to differentiate between blue and yellow. For such users, interaction with interfaces becomes challenging without adaptive solutions. Developers should test projects using tools like Coblis and Color Oracle to assess their usability for individuals with vision impairments [1,5,7].

Color blindness results from the absence of one or more of the three types of cone photoreceptor cells responsible for color vision. This condition is primarily hereditary, arising from genetic abnormalities, though it may also result from various neurological injuries, degenerative nervous system diseases such as Parkinson's or Alzheimer's, or thyroid dysfunction. Retinal photoreceptors contain specific proteins known as chromoproteins, namely rhodopsin in rods and iodopsin in cones. The genes responsible for "red" and "green" iodopsins are located on the X chromosome, with women having two copies and men only one. This genetic arrangement explains the higher prevalence of color blindness in men, while women, due to the presence of a "reserve" X chromosome, exhibit the condition significantly less frequently.

Seven types of color blindness are known:

- The most common category includes four variations associated with the red-green spectrum.
- Two variations pertain to the blue-yellow spectrum.
- One variation is characterized by a complete absence of color perception.

The most common form of color deficiency is red-green color deficiency, often colloquially referred to as red-green color blindness. This category includes four distinct types:

Protanopia (red blindness): individuals lack red cone cells.

Protanomaly (red weakness): individuals possess red cones but have reduced sensitivity to certain shades of red. Figures 1 and 2 below demonstrate normal vision compared to Protanopia and Protanomaly, as well as a comparison with Deuteranopia and Deuteranomaly [13-16].

Fig. 1. Normal vision compared to Protanopia and Protanomaly.

Fig. 2. Normal vision compared to Deuteranopia and Deuteranomaly.

Individuals with a deficiency in the green spectrum often find it challenging to perceive green among shades of blue or yellow, resulting in a blurred perception. Conversely, those with difficulties in the red spectrum struggle to distinguish red from orange and brown, causing red and related hues to appear faded.

Deficiencies in the blue-yellow spectrum are less common than red-green deficiencies, and many individuals are unaware of their existence. There are two types of blue-yellow color blindness:

Tritanopia (blue blindness): individuals lack blue cone cells.

Tritanomaly (blue weakness): individuals possess blue cones but have reduced sensitivity to certain shades of blue. Figure 3 below illustrates a comparison of normal vision with Tritanopia and Tritanomaly.

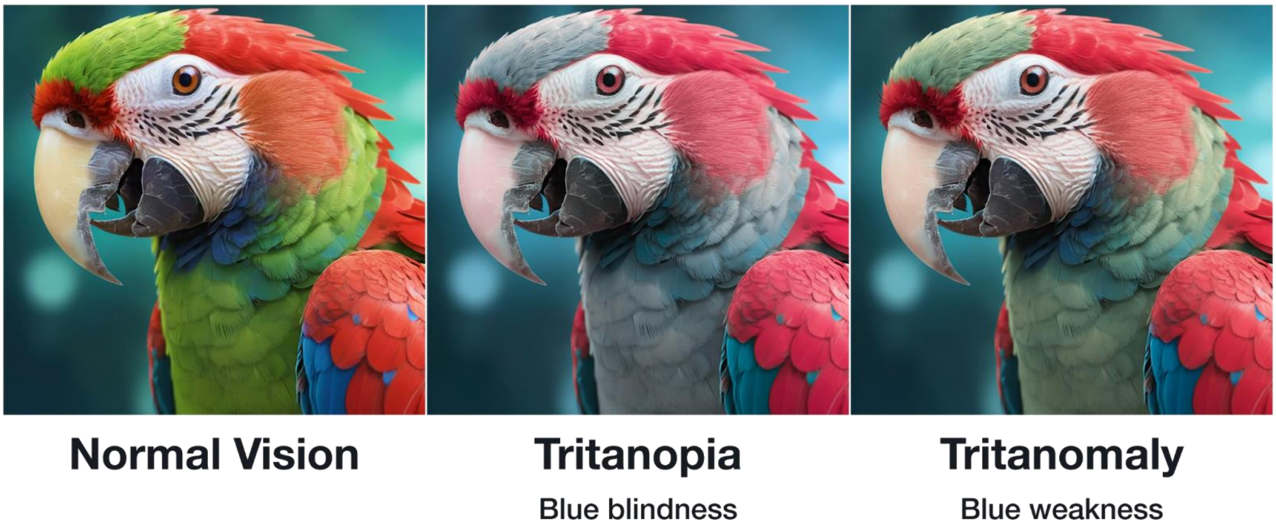

Fig. 3. Normal vision compared to Tritanopia and Tritanomaly.

Individuals with deficiencies in the blue spectrum may find it difficult to distinguish green among shades of blue or red and yellow. Monochromacy, or achromatopsia, represents a complete form of color blindness, resulting in a black-and-white perception of the world for individuals with this condition [6, 8]. Figure 4 below shows a comparison of normal vision with monochromatic vision.

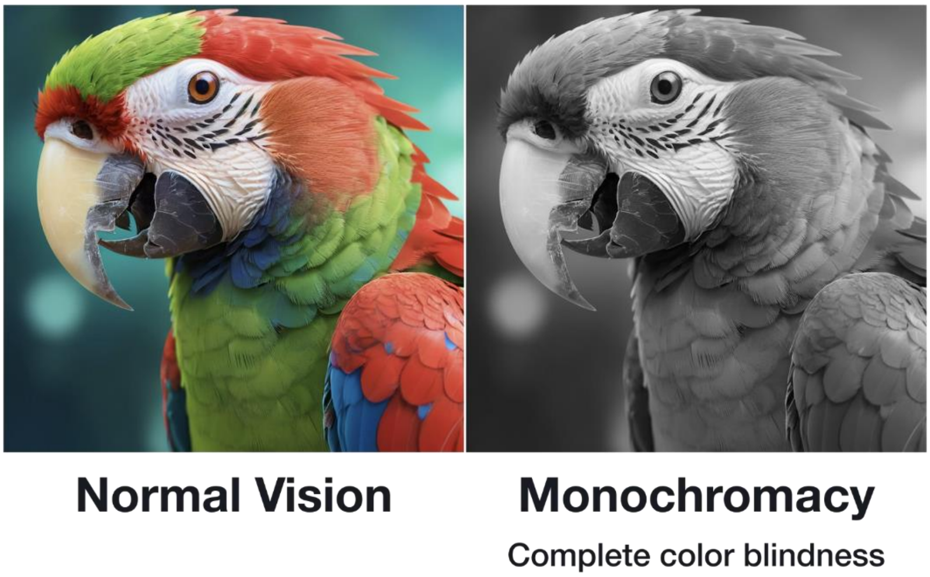

Fig. 4. Normal vision compared to Monochromacy.

Unlike the previously discussed conditions characterized by the dysfunction of one type of cone cell, tetrachromacy refers to the ability of certain individuals to perceive a broader spectrum of colors than typical "trichromatic" vision. Tetrachromacy enables some individuals to distinguish colors invisible to most. Unlike most trichromatic individuals, tetrachromats possess four types of cone cells, allowing them to perceive up to 100 million shades of color—approximately 100 times more than normal vision. Tetrachromacy is considered a rare genetic phenomenon, predominantly affecting women.

It is estimated that up to 12% of women worldwide may exhibit tetrachromacy, although no confirmed statistical data exists. The presence of a "reserve" X chromosome is critical for tetrachromatic vision; one X chromosome must carry a normal copy of the gene, while the other carries a mutated gene encoding a protein with a shifted peak sensitivity toward the short-wavelength range [11,12]. Figure 5 below illustrates a comparison of normal vision with tetrachromacy.

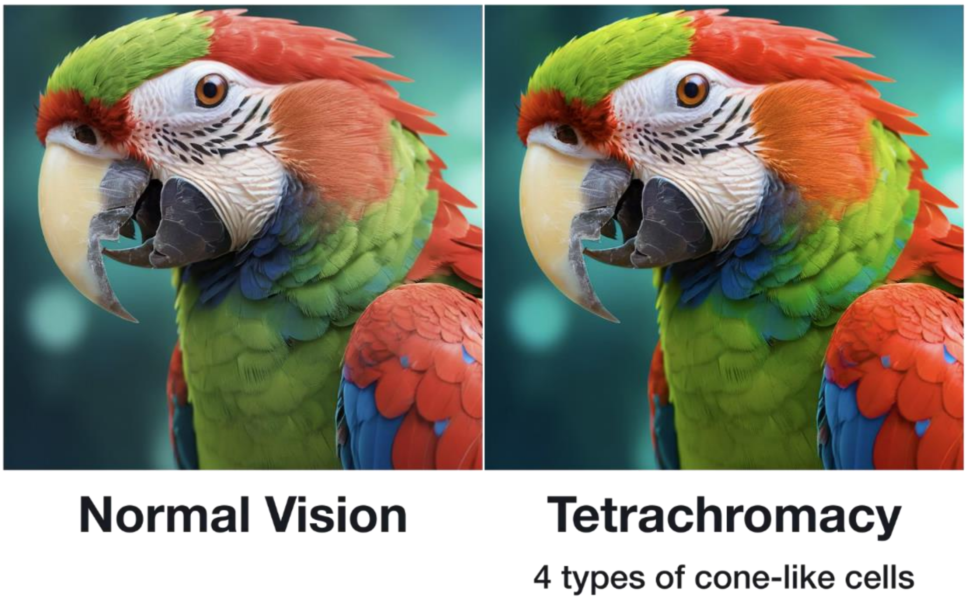

Fig. 5. Normal vision compared to Tetrachromacy.

When designing interfaces for digital products, designers must understand the differences in color perception and minimize the complexity of user interaction with the interface.

The RGB color model, widely used in digital products, leverages the human eye's response to red, green, and blue light to reproduce and organize colors, aligning them with natural color perception. There are strategies to optimize interfaces for individuals with varying visual capabilities.

Color contrast refers to the difference in brightness between foreground and background colors. To ensure optimal accessibility, it is recommended to use a contrast ratio of 4.5:1 or higher between foreground and background colors. This ratio facilitates text recognition for individuals with moderately impaired vision, enhancing their ability to distinguish between text and its background. Additionally, emphasizing high-contrast elements draws users' attention to the most critical components of the interface [2,3]. Figure 6 below demonstrates the use of high-contrast elements.

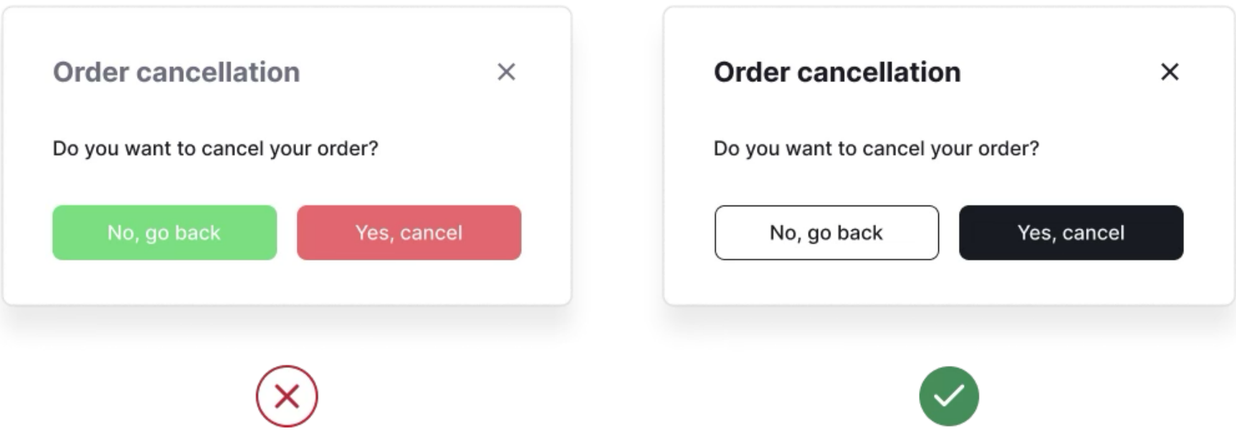

Fig. 6. Using high-contrast elements.

To create a universal interface, it is recommended to use a minimalist black-and-white design or a limited palette of high-contrast colors. Colors with low contrast for text, buttons, and backgrounds should be avoided, as they may reduce the speed of information processing. For instance, black text on a white background provides a high level of contrast, thereby improving readability.

Developing high-contrast themes is a strategy employed to enhance readability and usability for a broader audience, including individuals with normal vision, color blindness, vision impairments, and tetrachromacy. While an interface operates as an integrated structure, it is essential to organize a visual hierarchy of elements, considering principles of nonlinear reading. Hierarchy significantly influences the order in which users perceive elements and the organization of information [4,10]. Figure 7 illustrates the use of component hierarchy.

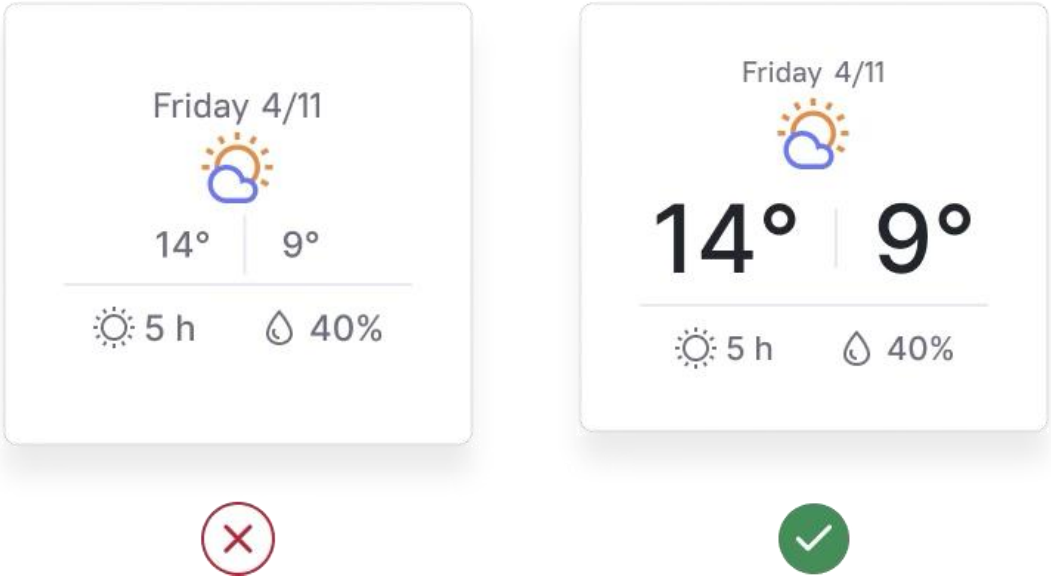

Fig. 7. Using a hierarchy of components.

Hierarchical structures not only organize content and provide order but also facilitate navigation. Emphasizing certain elements directs the visual flow and increases scanning speed, thereby highlighting key information or expediting decision-making. In specific contexts, a striking component that stands out from other design elements can even prove life-saving.

Effective use of whitespace is a best practice that highlights critical areas of an interface, guiding users on where to begin tasks and the sequence in which actions should be performed. Allocating more space to the most important design aspects can achieve greater impact.

The application of explicit and implicit grouping aids in structuring a page, directing attention to actions most relevant to the page's purpose. A lack of grouping limits the ability to emphasize standout elements; thus, it is essential to organize navigation, content, toolbars, and footers into distinct groups. Figure 8 demonstrates the use of structure [6,8,9].

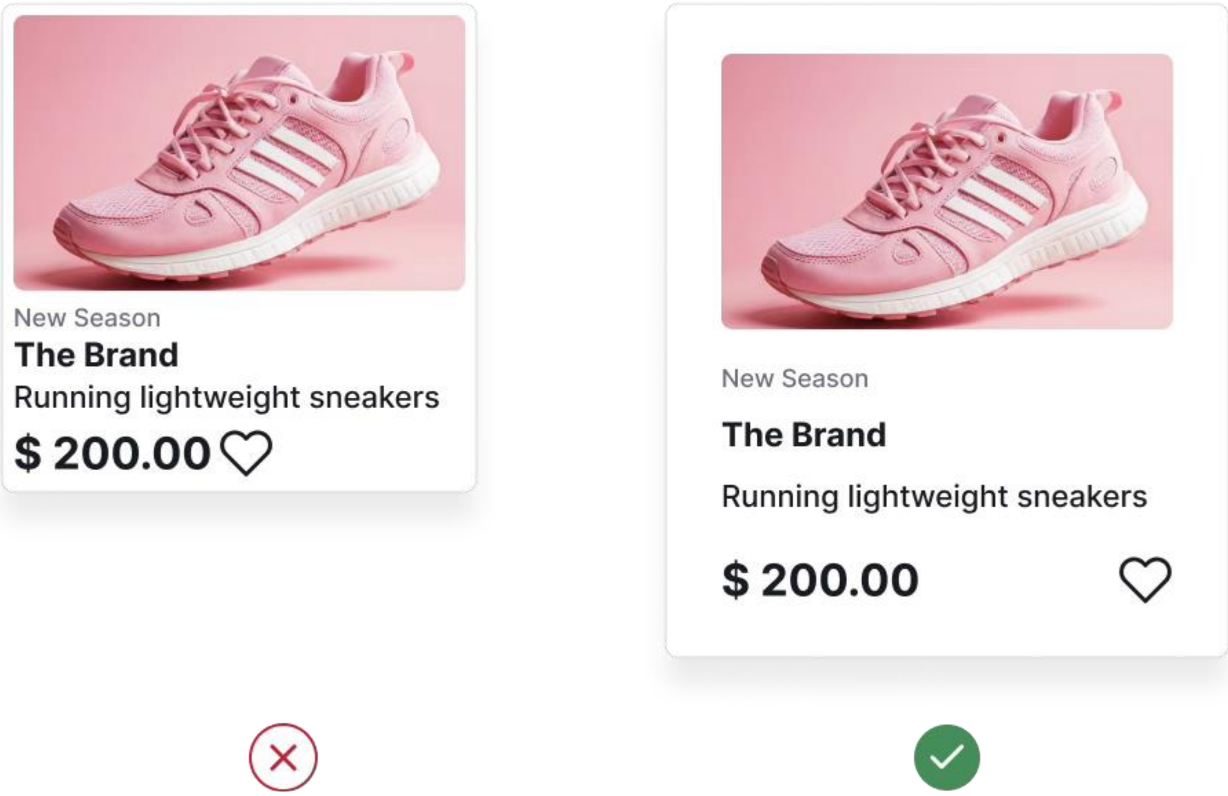

Fig. 8. Using structure.

Digital technologies enable the adaptation of interfaces to users' personal preferences. Customizing color schemes creates comfortable conditions for information perception. Switching display modes

reduces eye strain and considers external lighting conditions. Synchronization algorithms with device parameters simplify interactions and eliminate the need for manual adjustments.

Interface development requires careful consideration of the perception characteristics of different user groups. This involves employing contrasting color palettes, conducting accessibility checks, and adhering to standards that regulate usability. Additionally, tools for adjusting visual parameters are provided. This approach facilitates the creation of intuitive and universal solutions. The integration of adaptive technologies ensures that digital products are intuitive, efficient, and capable of meeting the needs of a diverse audience.

CONCLUSION

In conclusion, considering the features of color vision is of paramount importance in the development of digital interfaces to ensure accessibility and enhance user experience for a diverse audience. By understanding various forms of color perception, such as color blindness, achromatopsia, and tetrachromacy, designers can create interfaces that are not only visually appealing but also functional for all users.

The implementation of strategies prioritizing high contrast, clear hierarchical organization, and structured information can significantly improve the usability of digital products. As the global population continues to include individuals with varying degrees of color perception, it becomes increasingly important for designers to adopt inclusive approaches that promote equitable digital environments. Ultimately, accounting for these considerations will lead to the creation of more effective and user-friendly interfaces that meet the needs of all users, fostering innovation and inclusivity in the digital space.

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