Chapter 2
Uncertainty Visualization and Color Vision Deficiency

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Abstract Color vision deficiency (CVD) affects a large number of individuals around the world, compromising their ability to effectively interpret color-coded information. This directly impacts the way these individuals perceive visualizations, often introducing ambiguities and uncertainties. This article provides an overview of the causes of color vision deficiency and discusses the main tools and techniques available for helping designers to create more effective visualizations for individuals with CVD. It also discusses the limitations of the existing techniques and presents some open questions for guiding research efforts in improving visualization experiences for larger audiences.

2.1 Introduction

Current estimates indicate that approximately 200 million individuals worldwide have some form of color vision deficiency (CVD) [10, 11]. Such condition compromises their ability to effectively perform color-related tasks, which impacts their private lives and professional activities [8]. Since visualizations tend to make intensive use of colors to convey information, many visualizations are not perceived by individuals with CVD as they are intended to be (e.g., Figs. 2.1 right, and 2.2b). This leads to uncertainties, forcing those individuals to make important decisions based on ambiguous information, which may have catastrophic implications. Thus, the perceptual limitations imposed by color vision deficiency is a relevant subject to the visualization community, but one that has not yet received all the attention it deserves. To produce more effective visualizations, we need to devise techniques that avoid excluding this significant fraction of the population. This article briefly discusses the the causes of color vision deficiency and the main techniques available to help the affected individuals to recover, as much as possible, the loss of color contrast. After pointing out the inherent limitations of these techniques, the article presents some open questions that should guide research efforts in this area.

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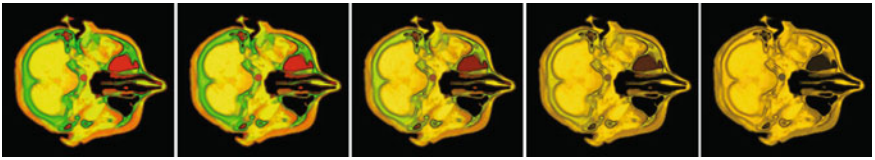

Fig. 2.1 Simulation of the color perception of individuals with CVD. A reference image (*left*) is followed by the simulation of the perceptions of anomalous trichromats (protanomalous) with various degrees of severity (spectral shifts of 2, 8, and 14 nm). The perception of a protanope is shown on the *right*. All images were simulated using the model described in [4]

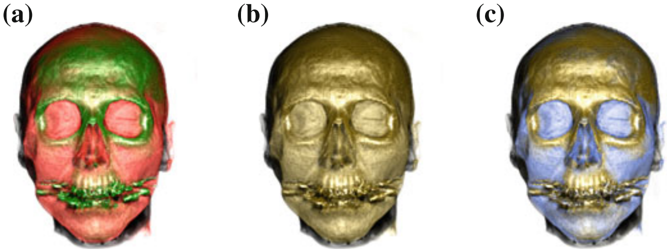

Fig. 2.2 Example image recoloring: **a** reference image. **b** Simulated perception of a deuteranope, using [4]. **c** Recolored version of the reference image for deuteranopes, using [5]. Note the significant enhancement of color contrast with respect to **b**. Since the color gamut of deuteranopes is a subset of the RGB color space, this image is perceived the same way both by deuteranopes and by normal trichromats. The case of recoloring for other dichromats is similar

2.1.1 Color Vision Deficiency

Human normal color vision requires three kinds of retinal photoreceptors. These are called *L*, *M*, and S cone cells, and have higher sensitivity to the long, medium, and short wavelengths of the visible spectrum, respectively. The specific type of photopigment contained in each kind of cone cell determines its spectral response. Some natural variations in the composition of these photopigments can shift their spectral sensitivities to different bands of the visible spectrum [11]. In this case, the affected individuals are called *anomalous trichromats*, and can be further classified as *protanomalous*, *deuteranomalous*, or *tritanomalous*, if the affected photopigment is associated with the L, M, or S cones, respectively. The bigger the shift, the more the individual's color perception will vary with respect to the perception of an individual with normal color vision (*normal trichromat*). In case one type of photopigment is missing, the individual is called a *dichromat*. Likewise, (s)he can be classified as *protanope*, *deuteranope*, or *tritanope*, according to the type of missing photopigment (L, M, or S, respectively). Much rarer conditions include the cases of individuals with a single kind of photopigment (*cone monochromats*) or no functional cone cells at all (*rod monochromats*).

As a consequence of the existence of three types of photoreceptors, normal color vision spans a 3-D color space. The color gamut of a dichromat, on the other hand, is only two-dimensional and can be represented by a surface patch in the same 3-D color space. Such a reduced gamut is the cause of the ambiguity experienced by dichromats: many different colors are perceived as the same, when projected onto such patches. For anomalous trichromats, the color gamut falls in between these two extremes, moving towards the gamut of a dichromat as the degree of severity of the anomaly increases. For spectral shifts of approximately 20 nm, the perception of an anomalous trichromat becomes similar to the perception of a dichromat [6, 11].

Currently, there is no clinical or surgical treatment for color vision deficiency. Given the relevance of the problem, a few techniques have been recently proposed to simulate the perception of individuals with CVD [2, 4, 7], and to enhance image contrast through recoloring [3, 5, 9]. Next, I briefly discuss these techniques, showing how they can assist the design of more inclusive visualization experiences, but also discussing their inherent limitations, which calls for more research.

2.2 Tools for More Inclusive Visualizations

The first step to produce more effective visualizations for individuals with CVD is to understand their perceptual limitations. Meyer and Greenberg [7], and Brettel et al. [2] presented simulation techniques for the color perception of dichromats. Machado et al. [4] introduced a physiologically-based model that supports the simulation of dichromatic as well as anomalous trichromatic vision (with arbitrary degrees of severity) in a unified way. This simulation model works in real time and can be quickly incorporated into existing systems. Thus, a visualization designer can get instantaneous feedback on how it would be perceived by individuals with CVD (Fig. 2.1). Such knowledge allows the designer to refine the visualization, making it more effective for wider audiences. While simulation models help to increase the awareness of the perceptual limitations due to CVD, they do not directly help the affected individuals to recover the loss of color contrast.

To address the problem of enhancing color contrast, a few automatic image-recoloring techniques for dichromats have been proposed in recent years [3, 5, 9]. Essentially, all these approaches define ways of mapping the colors in the original image to a new set of colors in the dichromat's gamut. This is done while trying to preserve the perceptual color differences among all pairs of colors in the original image. Rasche et al. [9] proposed an approach that uses a constrained multivariate optimization procedure applied to a reduced set of quantized colors. The resulting algorithm does not scale well with size of the input image and the number of quantized colors, and is not applicable to interactive applications. Kuhn et al. [3] present a solution based on a mass-spring optimization that achieves interactive rates, and tries to preserve the naturalness of the original images (i.e., preserve the colors that can already be perceived by dichromats). More recently, Machado and Oliveira [5] introduced a projection-based recoloring approach that works in real time, enforces

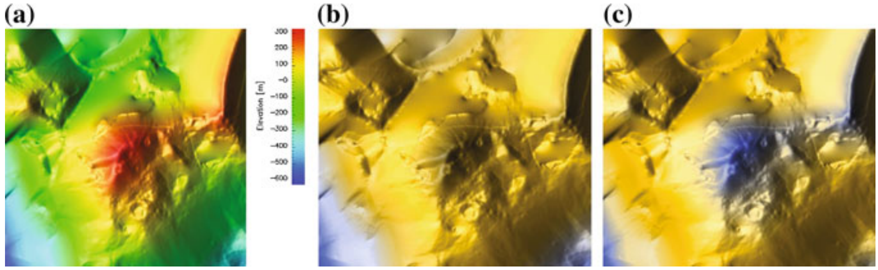

Fig. 2.3 Limitation of recoloring techniques. **a** Original image with colors over most of the RGB color space. **b** Simulated perception of a deuteranope. **c** Due to the dichromat's limited color gamut, by trying to solve some color ambiguities, recoloring techniques may introduce new ones

temporal coherence, and can be easily integrated with existing visualization applications. This makes it suitable for use in interactive visualizations. Figure 2.2 shows an example of image recoloring produced by this technique.

All recoloring techniques for dichromats share an inherent limitation: *they define mappings from a 3-D color space to a 2-D color gamut*. Thus, such techniques tend to become ineffective as the original image content spans the entire or most of the 3-D color space. In those situations, trying to solve some ambiguity by rearranging colors on the dichromat's 2-D color space might introduce new ambiguities (Fig. 2.3). Moreover, current recoloring techniques are restricted to the set of colors found in each input image or video. Thus, mappings between pairs of colors in one image or video may not be preserved in different ones (e.g., some cell structures may be recolored in blue in one image, while appearing yellow in another).

2.2.1 Open Research Questions

In order to address the limitations discussed in the previous paragraph, we need to consider the following open research questions:

- Q1 How can one enhance visualizations by encoding additional information in order to compensate for the reduced color gamut of dichromats? Or, in other words, how can one lift the two-dimensional color gamut restriction?
- Q2 Can the experiences learned from addressing the previous question also be exploited to enhance visualizations for normal trichromats?
- Q3 How can one obtain content-independent solutions that can be consistently used over different images and videos?
- Q4 Is it possible to satisfactorily extend these solutions to also represent natural scenes, where colors have some associated meanings to the viewers?

We have started to explore some of these questions. In one initial effort, we have investigated augmenting colors with simple patterns to encode information for dichromats [1]. Our results suggest that such combination can improve the performance of individuals with CVD in some visualization tasks, besides increasing their confidence in making color-based choices. We have also noticed that the use of patterns can help normal trichromats to fine tune color-related decisions. The use of patterns is, however, just one option in wide space of possibilities, and many creative solutions are waiting to be discovered.

2.3 Conclusion

Color-vision-deficient individuals routinely experience uncertainty visualizations, both in their private lives and professional activities. This article discussed the causes of such perceptual limitations, and briefly described the tools and techniques currently available that try to address this issue. Most of the illustrations and discussions focused on the case of dichromats, since, in general, they face stronger restrictions than anomalous trichromats. After analyzing the limitations of the existing techniques, the article presented a list of open questions that need to be considered in our quest for more inclusive visualizations. By understanding how to effectively deal with the restrictions faced by individuals with CVD, we should also be able to produce richer visualizations experiences for normal trichromats.

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