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Aids for color vision deficiency: introduction to the feature issue

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Abstract: Approximately 8% of Caucasian males and 0.5% of females have congenital red-green color vision deficiencies (CVD), and a number of eye diseases are accompanied by acquired CVD. This feature issue includes ten contributions regarding existing and proposed algorithms and devices intended to help CVD subjects compensate for their color deficiencies. It also addresses limitations in the effectiveness of CVD aids for subjects with different types and degrees of color vision deficiency.

1. Introduction

To date, research concerning aids for CVD observers has taken three different approaches: the use of color selective filters typically in glasses, contact lenses, or spectrally tuned illumination (passive aids, see [1–3] for recent instances); introducing changes in the color or spatial content of images captured with a camera and projected or otherwise displayed on digital screens (active aids, also called recoloration or daltonization algorithms, [4,5]) or genetically altering the cone pigments present in the retina (successfully tested only in monkeys so far, [6,7]). Let's first consider what each approach has to offer from the perspective of the Feature Issue and then delve into the issue of quality assessment of the aids (which runs as a sort of undercurrent in most of the contributions) and into possible future directions for research in the case of active aids.

Passive aids, considered from a theoretical perspective, present some inherent limitations that are direct consequences of the principle of univariance [8]: (1) Putting a spectrally selective external filter in front of the eye is just the same as changing the illuminant. (2) No spectrally selective external filter or illuminant can extend the color gamut beyond the spectrum locus defined by the color-matching functions of the individual observer. (3) No spectrally selective external filter or illuminant can provide more information to the visual system than an equal energy spectrum, but can only take information away. In particular, selective narrow-band or cutoff filters that increase chromatic and/or luminance contrast in some wavebands must take away even more contrast in other wavebands. (4) No spectrally selective external filter or illuminant can change the spectral sensitivity curve shapes of individual cone types, but only their overall relative sensitivities. It is then clear that it is impossible for any of these devices to make the CVD observers' vision equal to the normal trichromatic subject. This has been explained repeatedly in many previous studies ([9–11]), and we find it also in some of the contributions of this Feature Issue related to the quality assessment of passive aids (Marques et al., Patterson et al. [12,13]). The companies that commercialize passive aids do not claim to offer normal color vision for CVD subjects, but they do naturally claim to be able to improve CVD's color vision to some extent. Nevertheless, the evidence found in this Feature Issue points toward quite limited enhancements for natural scenes (Nascimento and Foster [14]) or a more noticeable change in discrimination thresholds when measured with display-based tests and VINO filters (Patterson et al. [13]), and no evidence of improvement when measured with conventional color vision assessment tests (Pattie et al., [15]). In this feature issue, passive aids have been tested repeatedly

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and with markedly different experimental paradigms (see section 2 for additional insight), and the main conclusion from our initial theoretical considerations still stands: they can be useful to produce partial increases in contrast, at the cost of some information losses for different color stimuli. So, they can be useful in some particular situations or scenes (for instance they might help a protanope subject avoid confusion between pink and gray socks), but their usefulness is not universal.

The main conceptual difference between passive and active aids is that cleverly designed active aids can selectively modify colors in certain directions in a chromaticity diagram, while leaving others intact. In this way they can selectively target the colors for which chromatic discrimination is problematic instead of changing all the colors in the scene. Not all the active aids work according to this principle, but to offer this possibility is certainly appealing from the perspective of customization possibilities, something that is also considered in two of the contributions of this issue (Xu et al. [16], Muñoz-Postigo et al. [17]). The main limitations of this approach are related to the gamut that the displays can offer (specifically considered from the general point of view of adaptation in Ilic et al.'s contribution [18]), and the not trivial question related to how this customization can be carried out most effectively, as it critically depends on knowing the spectral separation between the observers' cone responsivities, as mentioned in Xu et al. [16]). There is also a second kind of customization that could also greatly enhance the practical usefulness of active aids, and that is task-related customization, as discussed in Alvaro et al. [19] in this issue.

The need for customization brings out another fundamental issue that is at the core of several of the contributions presented (Marques et al. [12], Rezeanu et al. [20], Nascimento and Foster [14]): who could the aids really benefit? Evidence, either based on psychophysical experiments (Marques et al. [12]), simulation tools (Rezeanu et al. [20]) or information theory (Nascimento and Foster [14]) suggest that anomalous trichromats might fare considerably better on average than was previously assumed. It is possible that compensating neural mechanisms can be at play and that is related as well with the importance of considering chromatic adaptation when assessing passive aids (Werner et al. [21], Muñoz-Postigo et al. [17]). But the answer to the previous question, according to the results presented in this issue, is that CVD aids should be addressed mostly to more severe anomalous trichromats or dichromats.

This leads us to the third approach: optogenetic treatments that add new photopigments to individual cones or other retinal neurons. Although tested only preliminarily, the results are rather promising, and it is undeniable that this is the only approach that we could definitely call problem-solving (for lack of a better word, because cure is not appropriate in this context). CVD subjects who perceive their condition as severely limiting or that would like to choose certain professional careers could certainly consider such treatments if controlled clinical trials provide sufficient evidence of long-term safety and effectiveness to obtain marketing approval by national regulatory health agencies.

A true restoration of normal trichromatic color vision in CVD subjects seems unlikely in the near future, but may eventually be possible if we can learn to incorporate genetic modifications and control gene expression sufficiently to replace defective genes with normal genes, regrow normal retinal tissue in place of defective tissue, and establish normal neural connections to the brain, like certain amphibians already know how to do.

2. Quality assessment of CVD aids

It is undeniable that testing the effectiveness of CVD aids is still a controversial issue (Valero et al. [22]). The passive aids companies argue against scientific studies that show aids produce little or no improvement saying that the testing has not been appropriate and that standard tests do not reflect the contrast increase that the passive aids produce, in spite of clear evidence to the contrary regarding CAD results (Patterson et al. [13]) or Ishihara's test results (Gómez-Robledo et al. [10], Pattie et al. [15]). It is also undeniable (and we find clear evidence of it in this issue)

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that the way the testing is performed can condition the outcome about the effectiveness of the CVD aid: while Pattie et al. [15] show that there is no overall improvement using Enchroma filters with either psychophysical experiments or standard clinical tests, Patterson et al. [13] show partial improvements with the CAD test (especially for the VINO filters). If a more realistic setting is used that is not conditioned by the observers' previous experience, Marques et al. [12] do not report any noticeable enhancement of discrimination. So, more effort is needed to find a systematic way of testing the efficiency and naturalness of CVD aids. Some advances have been reported in Muñoz-Postigo et al. [17] using simulation models including chromatic adaptation and a new metric that takes into account if the color changes induced by the aid are selective enough, or if the changes are too radical to affect the perception of naturalness of the scene. This metric allows the comparison of the performance of active vs passive aids. Also, a new simulation model has been presented here that considers the selectiveness of the color changes involved in different chromatic axes (Moreland et al. [23]). The accuracy of simulation models is at the core of promising approaches for quality testing, and in this regard, we must also mention the contribution by Rezeanu et al. [20] which is based on modelling anomaloscope behavior, certainly an original way that provides the possibility of using the spectral separation between L and M cones as input for the model. We think the issue of quality assessment is critical and remains an important topic for future contributions.

3. New proposals for CVD aids and the trend towards customization

As mentioned in the introduction, Xu et al. [16] report a new customized active aid method based on a modified FM-100 test to obtain the confusion index of individual observers. They then employ a model to map this index to spectral separation based on normal observers' results obtained with simulated images to find the order that most closely matches the CVD observer's setting. The active aid is based on the idea of gamut mapping between CVD and normal observers to try to expand the color contrast perceived by the CVD subject. This model is customizable and provides an initial estimation of the observers' spectral separation, which shows promise for predicting this critical parameter and incorporating it into active aids. It seems possible that this approach could lead to better ways to predict whether a given CVD aid may provide a real benefit to mild or medium-severity anomalous trichromats.

In this issue, the reader will find the most critical aspects regarding CVD aids considered from different experimental paradigms and perspectives, but we hope it will also shed some light on future research strategies while at the same time addressing from a scientific point of view the effectiveness of the two main approaches developed so far: passive and active aids.

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