More on color blindness

To the Editor: In a recent issue of *Nature Methods*[1] Albrecht raised awareness of the need to carefully design graphic data representation so data can also be appropriately perceived by the many individuals who have color perception deficiencies. Appropriate color selection is not only important for effective communication to a wide audience, but there are also equity implications when developing effective teaching methods and communication strategies.

The *Nature Methods* editors in their reply[2] suggested using the Vischeck plugins for ImageJ and Photoshop platforms "for recoloring" purposes. By simulating color blindness, the Vischeck plugins are excellent for giving trichromatic ('normal' vision) observers an insight into how dichromatic viewers may see color images. However, on their own, these simulations do not provide a direct solution to the inverse problem of efficiently recoloring images in a way that allows dichromatic observers to discriminate the color-based information. At best, they may help with trial-and-error attempts at recoloring.

It is seriously problematic to recolor any arbitrary image so it can be perceived unambiguously by all types of dichromatic viewers simultaneously. However, in images with a limited number of hues, such as two-channel confocal images (additive colors) or two-dye bright-field histological stains (subtractive colors), digital imaging techniques now exist to reposition the color information so it is optimally targeted to hues that can be discriminated by the available functional retinal receptors. Below we provide suggestions on how to design the recoloring to resolve this problem in additive and subtractive color images.

Wong[3] in a subsequent article on graphics design accounting for those with color vision deficiencies suggests using, for additive color images (typically two-channel confocal images), the method proposed by Okabe and Ito (http://jfly.iam.u-tokyo.ac.jp/color/). This consists of representing the image data as magenta-green pairs instead of the unfortunately common red-green pairs that are difficult for protanope and deuteranope (red and green color-blind; RGCB) observers to perceive. However this recoloring strategy in itself introduces another unexpected problem: RGCB observers tend to perceive the original magenta channel as a bluish color and the original green channel as a yellow-brownish color. That means that although the colors can be discriminated, in the absence of figure legends indicating the actual name of the colors, their descriptions become confusing in communication between trichromatic and RGCB observers. We suggest that instead blue-yellow color pairs are preferable to green-magenta ones because (i) they preserve the discrimination between channels, and (ii) both trichromatic and RGCB observers agree on the color names. This strategy can be easily applied to red-green channel pairs by first copying the green-channel data into the blue channel and duplicating the red channel in the green one.

In the case of two-dye histological stains (subtractive colors), we developed two other methods to reposition the original dye colors into the available visual discrimination space[4] and proposed guidelines for the design of 'RGCB-safe' look up tables for false-coloring greyscale images[5] (for instance, ultrasound, X-ray and infrared images). Examples of these approaches are available at http://dentistry.bham.ac.uk/cb/. We hope those resources will be useful to authors for designing more inclusive and effective scientific images.

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The authors declare no competing financial interests.

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Wong replies: Making color information accessible to individuals with color vision deficiencies is a beneficent graphic design practice. Although I appreciate the suggestion by Landini and Perryer to use yellow-blue color pairs to preserve discriminability and correspondence between color and name for color-blind individuals, I see shortcomings with this approach as it relates to human perception. At least for confocal images, in which color information is typically displayed on a black background, blue is difficult to see on black and may result in loss of information (Fig. 1). The colors found in red-green and magenta-green images suffer less from this problem because they tend to be brighter. Another challenge with yellow-blue color pairs is in seeing areas where the colors mix to produce white. When this happens, white tends to blend in with yellow and is difficult to see. Whereas overlap between magenta and green also

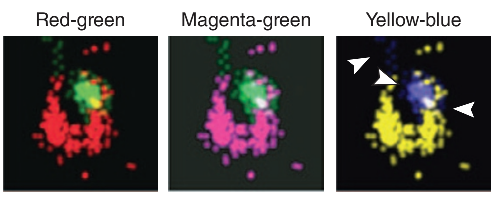

Figure 1 | Alternatives to red-green color coding in false color images. Whereas yellow-blue (as well as magenta-green) color pairs make it possible for individuals with red-green color blindness to discriminate the colors, blue is difficult to see against black, and the white produced by the overlap of yellow and blue is nearly indistinguishable from yellow (arrowheads). These brightness and contrast problems are less pronounced with magenta-green color pairs. Image adapted from reference 2.