Scientific maps should reach everyone: a straightforward approach to let colour blind people visualise spatial patterns

Duccio Rocchini[1,2,*], Jakub Nowosad[3,*], Rossella D'Introno[4], Ludovico Chieffallo[1], Giovanni Bacaro[5], Roberto Cazzolla Gatti[1], Giles M. Foody[6], Reinhard Furrer[7,8], Lukáš Gábor[9,10], Gabor Lövei[11,12], Marco Malavasi[2], Matteo Marcantonio[13], Elisa Marchetto[1], Vıtezslav Moudry[2], Giovanna Pezzi[1], Carlo Ricotta[14], Petra Sımova[2], Michele Torresani[15], and Elisa Thouverai[1]

[1] *BIOME Lab, Department of Biological, Geological and Environmental Sciences, Alma Mater Studiorum University of Bologna, via Irnerio 42, 40126, Bologna, Italy, * Authors equally contributed to the manuscript*

[2] *Czech University of Life Sciences Prague, Faculty of Environmental Sciences, Department of Spatial Sciences, Kamýcka 129, Praha - Suchdol, 16500, Czech Republic*

[3] *Institute of Geoecology and Geoinformation, Adam Mickiewicz University, Krygowskiego 10, 61-680, Poznan, Poland, * Authors equally contributed to the manuscript*

[4] *Luigi Sacco Hospital, Via Giovanni Battista Grassi, 74, 20157, Milan, Italy*

[5] *Department of Life Sciences, University of Trieste, Trieste, Italy*

[6] *School of Geography, University of Nottingham, University Park, Nottingham NG7 2RD, UK*

[7] *Department of Mathematics, University of Zurich, Zurich, Switzerland*

[8] *Department of Computational Science, University of Zurich, Zurich, Switzerland*

[9] *Department of Ecology and Evolutionary Biology, Yale University, New Haven, CT, USA*

[10] *Center for Biodiversity and Global Change, Yale University, New Haven, CT, USA*

[11] *ELKH-DE Anthropocene Ecology Research Group, University of Debrecen, H-4010 Debrecen, Hungary*

[12] *Department of Agroecology, Aarhus University, Flakkebjerg Research Centre, Forsoegsvej 1, DK-4200 Slagelse, Denmark*

[13] *Group of Evolutionary Ecology and Genetics, Biodiversity Research Centre, Earth and Life Institute, Université Catholique de Louvain (UCLouvain), Louvain-la-Neuve, Belgium*

[14] *Department of Environmental Biology, University of Rome "La Sapienza", 00185 Rome, Italy*

[15] *Libera Università di Bolzano - Freie Universität Bozen, Bolzano/Bozen, Italy*

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Abstract

Maps represent powerful tools to show the spatial variation of a variable in a straightforward manner. A crucial aspect in map rendering for its interpretation by users is the gamut of colours used for displaying data. One part of this problem is linked to the proportion of the human population that is colour blind and, therefore, highly sensitive to colour palette selection. The aim of this paper is to present a function in R - `cblind.plot` - which enables colour blind people to just enter an image in a coding workflow, simply set their colour blind deficiency type, and immediately get as output a colour blind friendly plot. We will first describe in detail colour blind problems, and then show a step by step example of the function being proposed. While examples exist to provide colour blind people with proper colour palettes, in such cases (i) the workflow include a separate import of the image and the application of a set of colour ramp palettes and (ii) albeit being well documented, there are many steps to be done before plotting an image with a colur blind friendly ramp palette. The function described in this paper (`cblind.plot`), on the contrary, allows to (i) automatically call the image inside the function without any initial import step and (ii) explicitly refer to the colour blind deficiency type being experienced, to further automatically apply the proper colour ramp palette.

1 Introduction

Maps are widely used to convey geographical information. Various map types exist and are used in activities from day-to-day tasks such as route planning to furthering scientific studies of such topics as climate change and the spread of invasive species. Despite their widespread use, maps can be problematic information resources. Any map is a generalisation, hence an imperfect representation of the features shown. A map is also typically interpreted visually, and hence different people may come to dissimilar conclusions about the mapped features. Standard procedures and good practices for map making exist but may not always be followed or may not fully address concerns. Moreover, maps can be produced in a way that may, accidentally or deliberately, deceive and lie to the reader (Monmonier, 2018). Indeed, it has been suggested that maps are "the most used and least understood documents of modern civilisation" (Brown, 1953, cited in Maling, 1989, p.144, and, more recently, in Foody, 2021).

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Hence, showing the variation of a variable over space in a map considering the whole gamut of colours is not a simple matter in its very nature (Pointer, 1980). In most cases maps full of colours are used, to catch the eye of the reader in a straightforward manner.

The misuse of colour could be dangerous, by producing a misleading perception of the achieved results. As an example, yellow is expected to catch the human retina more than other colours. If used in the wrong palette position, it would lead the eye to assign more importance to that particular range. For instance, using it in the middle of the palette colour ramp would lead the reader to see such values as maxima (Cramieri et al., 2020).

One common problem with contemporary mapping is that software packages often offer a range of colour palettes for data display, and these may vary in suitability for both a mapping task and the target audience. One part of this problem is linked to the proportion of the human population that is colour blind and, therefore, highly sensitive to colour palette selection. *Colour vision impairments*, also known as *colour vision deficiency* (CVD, Simunovic, 2010) (hereafter even referred to as *colour blindness*), should seriously be taken into account. In fact, the impossibility to see some of the displayed colours by some people does not allow them to appreciate the differences between minima and maxima on a map. Furthermore, this might seriously impact scholars' and students' scientific learning affected by such deficiencies having no proper access to graphing parts of articles and/or books (Albany-Ward & Sobande, 2015).

Colour blind deficiencies are basically represented by three main colour misperceptions: (i) protanopia, i.e., the inability to perceive the red color (560 nm); (ii) deuteranopia, i.e., the inability to recognize the green color (530 nm); (iii) tritanopia, i.e., the inability to distinguish the blue color (420 nm, Figure 1, Viénot et al., 1995; Gordon, 1998; Gegenfurtner, 2003). Box 1 explains every deficiency type in detail. This leads to the impossibility of recognizing some types of colour ramps in which there is a gradient from blue to green/yellow to red. For instance, this is the case of frequently (mis)used rainbow colour palettes (Golebiowska & Coltekin, 2020; Stoelzle et al., 2021), which are part of a bunch of papers in the scientific literature (e.g., Mesgaran et al., 2014; Gardner et al., 2019; Ellis-Soto et al., 2021; Feilhauer et al., 2021; Rocchini et al., 2021).

Inherited colour blindness affects more than 5% of human population (i.e., 8% of males and 0.5% of females, being inherited as X-linked recessive disease) mainly because of founder events and genetic drift (Simunovic, 2010; Birch, 2012). There is a wide literature in different fields of research presenting problems for colour blind people: from the hampering of medical profession (Spalding, 1999) to students proper learning (Ramachandran, 2014), and from road accidents (Cole et al., 2002) until unintentional injuries (Cumberland et al., 2004). On the contrary, this phenomenon is somewhat disregarded in scientific rendering in form of maps. In order to implement routines to help colour blind people, website examples exist to (i) choose colour ramp palettes (seaborn: `https://seaborn.pydata.org/tutorial/color_palettes.html`, ColorBrewer: `https://colorbrewer2.org/`, Harrower & Brewer, 2003) or (ii) create them (colorschemedesigner: (`https://paletton.com/#uid=1000u0kllllaFw0g0qFqFg0w0aF`) with an online platform dedicated to the creation of colour schemes. However, they seem to be too much complicated, in our opinion, for colour blind people.

Furthermore, packages in R are devoted to test for colour blindness (`colorblindcheck` package, Nowosad, 2021) or to make use of colour ramp palettes for colour blind people (`viridis`, Garnier et al., 2021). However, as far as we know, no analytical and straightforward function exists that allows to input an image and plot it for colour blind people simply and straightforwardly. This paper aims to present a package cblindplot and its main function - `cblind.plot()` - which enables colour blind people to just enter an image in a coding workflow, specify their colour blind deficiency type, and immediately get a colour blind friendly plot as output.

2 The function: step by step

2.1 Code

We implemented our idea in the cblindplot package (`https://github.com/ducciorocchini/cblindplot`). Its main function `cblind.plot()` updates the color palette on an input image and returns a new visualization along with a new color legend. The function has four basic steps. In the first step, an image is imported into R. Then, a Principal Component Analysis (PCA) is performed on the input image, and only the first principal component is extracted. In the third step, a new color palette is applied to the single dimension derived from PCA. Lastly, the plot with a meaningful legend for color blind people is returned.

The user is asked to just choose the input image and a type of color vision deficiency: "protanopia", "deuteranopia", or "tritanopia":

```
cblind.plot <- function(im,
                    cvd = c("protanopia", "deuteranopia", "tritanopia")
                    r = 1, g = 2, b = 3,
                    crop_manual = FALSE,
                    select_class = FALSE
```

The `cvd` is a meaningful argument directly related to the type of colour blindness (Box 1 and Figure 1): `cvd=c("protanopia", "deuteranopia", "tritanopia")`. They will directly link to the `cividis`, `viridis` and `magma`, respectively, palettes that are going to enhance the main colours seen by people affected by such deficiency types. We chose such colour schemes following Viénot et al. (1995), who developed a simulation of the reduced colour gamut of colour defective people, explicitly considering the three aforementioned colour blind deficiency types (see also Box 1 and Figure 1). The `cblind.plot()` function also allows to change the order of the RGB bands (by default, the first image band relates to the red colour, the second to the green colour, and the third to the blue colour), manually crop the input image (the `crop_manual()` argument), and the `select_class()` makes it possible to select only certain colours in the image for the further processing.

The complete code of the cblindplot package is available at `https://github.com/ducciorocchini/cblindplot`, while we provide an empirical example of its application in the next section.

2.2 Empirical example

In order to test the function we decided to directly get in the game by making use of a (wrong) plot that we published in Rocchini et al. (2021), where a rainbow colour palette was used to show the variability in space of the Similaun Glacier (Italy, Figure 2). In that case, a rainbow colour ramp palette was used passing from: (i) low spatial variability, represented by blue and green, related to a small lake at north-east and snow at north-west, respectively; (ii) medium variability (yellow) related to woodlands and high elevation grasslands; and (iii) high variability (red), related to crevasses and cracks of the calcareous rock composing the glacier. All of this description makes no sense for colour blind people.

Hence, the issue can be solved in a straightforward manner by storing a screenshot of the image and import it in R by the `cblind.plot` function. No previous import is required but a direct call is done into the function under the argument `im`. The three bands composing the RGB of the image are generally mounted as: red in the first band, green in the second, and blue in the third one; this is the order used by the `cblind.plot` function to import them by default, which can be changed at any time. As previously stated, the output is straightforward once the user declares her/his deficiency type. For protanopia (Box 1 and Figure 1) a `viridis` colour ramp palette from the `viridis` package is applied to enhance the contrast between blue and yellow which can easily be seen by people affected by such a deficiency, for deuteranopia a `cividis` colour ramp palette is used to smoothly pass from blue to green to yellow, all colours that can easily be seen, and for tritanopia a `magma` colour ramp palette is used to avoid the use of pure blue. As previously stated, this is in line with the simulation screen figure of the 'Jardin des Plantes' (photo: Jean Le Rohellec; Grande Galerie, FNAC) seen by colour-blind people provided by Viénot et al. (1995), associating a smooth blue-to-yellow colour ramp to protanopia-affected people, sharp blue-to-yellow colour ramp to deuteranopia-affected people, to deep blue-to-yellow colour ramp to tritanopia-affected people. We suggest the reader to compare colours used in Figure 2 for the different deficiency types with that published by Viénot et al. (1995)[1]. Following Figure 1 for protanopia and deuteranopia the colour ramp palettes can be used interchangeably (Rigden, 1999).

[1]Notice that in Viénot et al. (1995) the images for the different deficiency types are arranged in a clockwise manner, hence they relate to panels a), b), d) and c) in Figure 2

3 Outlook and take home message

Providing for the possibility to appreciate coloured maps to everybody by a single function is priceless in our opinion. Doing that in a free and open source environment is mandatory. In fact, open source software would allow the possibility to exactly reproduce analysis by guaranteeing high robustness (Rocchini & Neteler, 2012). Apart for the previously cited `viridis` package, examples exist for oceanography, with the `cmocean` package in R (Thyng et al., 2016, 2020). Additional examples exist making use of Python () language (Nuñez et al., 2018). However, in such cases, the workflow include a separate import of the image and the application of a set of colour ramp palettes (Garnier et al., 2021). Furthermore, albeit being well documented, there are many steps to be done before plotting an image with a colur blind friendly ramp palette. The function described in this paper (`cblind.plot`), on the contrary, allows to (i) automatically call the image inside the function without any initial import step and (ii) explicitly refer to the colour blind deficiency type being experienced, to further automatically apply the proper colour ramp palette.

Additional R packages have been devoted to improve mapping (and colours) of various scientifically sound response variables like biodiversity (Féret & de Boissieu, 2020) or species distributions (Schuetz et al., 2020a,b). Connecting the `cblind.plot` with such packages would be an enormous advantage for color blind people. Hence, the authors of the present paper have contacted the developers of such packages to implement such function in their packages.

How the magnitude of spatial variation of data is represented in a map has a high impact on the perception of the main processes shaping it, since different colour signals are processed differently by the human visual system (Rogowitz et al., 1996). From this point of view monotonic palettes based on a monotonic continuous gradient (sensu Stevens, 1966) - like those used in the presented function `cblind.plot` from the `viridis` R package - rather than on abrupt thresholds - like the rainbow colour ramp palette (Borland & Ii, 2007) - must be preferred not only referred to colour blindness problems, but also for the common perception of spatial variability. In fact, this is generally based on a monotonic increase in eye stimulus intensity, as well established by pioneering papers on psychological perception of colour variation (Ekman & Sjöberg , 1965; Panek & Stevens, 1966).

Based on previous observation, the `cblind.plot` function guarantees to avoid perceptual discontinuities and thus the appearance of false spatial features (Kovesi, 2015) - in most cases related to noise in the original images/maps - being based on a continuous monotonic colour ramp, i.e. on an incremental and uniform change of colours over the whole output image/map. Although one cannot be certain about the real vision of someone else, the provided function is providing a straightforward tool based on well established previous simulations on colour vision about the residual colour information coming out from the above described deficiency types (Brettel, 1997). This is just based on the fact that a certain stimulus is perceived differently in colour blind deficiencies versus normal vision, with a well known reaction from every single deficiency type considered in this paper. That is why we avoided, at the time being, a test with colour blind people, relying rather on medical papers on the matter (Capilla, 2004).

Beside problems related to colour blind deficiencies, the rainbow colour map has widely been acknowledged as a fundamental problem-full palette for plotting scalar values to colours. This is mainly because it introduces artifacts and obscure some data by e.g. putting yellow colours as mid values, by finally confusing any user, despite her/his ability to properly see colours, if there is any proper manner to see colours (Moreland, 2009).

Colour gamut is of primary importance to synthesise the information contained in a dataset/map. Summarising, there are three main important elements/steps when applying a colour gamut to data rendering: (i) the possibility of using different colour palettes in a software, (ii) the choice made by the map producer about one of the possible palettes, and (iii) how such a choice is perceived by users. From this point of view, awareness of the uncertainty and potential limitations of the use of colours in maps may enhance map interpretation and use. While colour-coding guidelines are needed, we are far from having an etiquette on this theme, especially when considering continuous pseudocolour maps, i.e. maps coming out from analytical processes on geographical data (Reda et al., 2018). The `cblind.plot` function partially solves this issue by providing a direct manner to rescale pseudocolour values and plot them in a colour-blind free scheme, which is robustly grounded on optical theory. One of the main strengths of the function is that users are not required to exit their analysis process and enter e.g. internet sites but they can integrate the function in their throughput code to properly see output results.

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Box 1 - Colour blind deficiency types

- **Protanopia:** Inability to perceive the red color. Due to genetic mutations that cause the "L" type retinal cones to fail, or those photoreceptors sensitive to large wavelengths (560 nm), which allow the vision of the red color. It has a genetic transmission of the x-linked recessive type, for which it largely affects the male sex.

- **Deuteranopia:** inability to recognize the green color (the most common). Caused by genetic mutations that result in the failure of the "M" cones, those photoreceptors sensitive to medium wavelengths (530 nm), that is, which allow the vision of the green color. It has a genetic, x-linked recessive inheritance, for which it largely affects the male sex.

- **Tritanopia:** inability to distinguish the blue color (the rarest). Given by genetic mutations that cause the failure of the "S" cones, photoreceptors sensitive to radiation of short wavelengths (420 nm), or that allow the vision of the blue color. It has an autosomal dominant genetic inheritance, therefore independent of sex.

414 # Figures

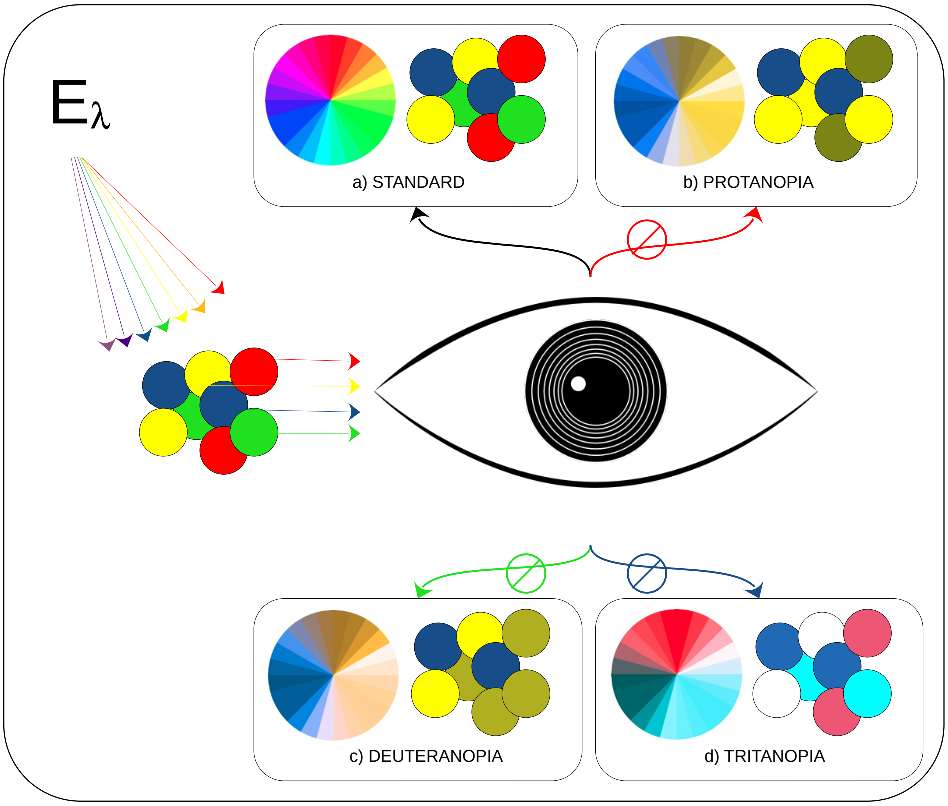

Figure 1: Different manners to perceive colours by the human eye: (a) standard vision; (b) protanopia, i.e., the inability to perceive the red color (560 nm); (c) deuteranopia, i.e., the inability to recognize the green color (530 nm); (d) tritanopia, i.e., the inability to distinguish the blue color (420 nm). Refer to Box 1 for specific information.

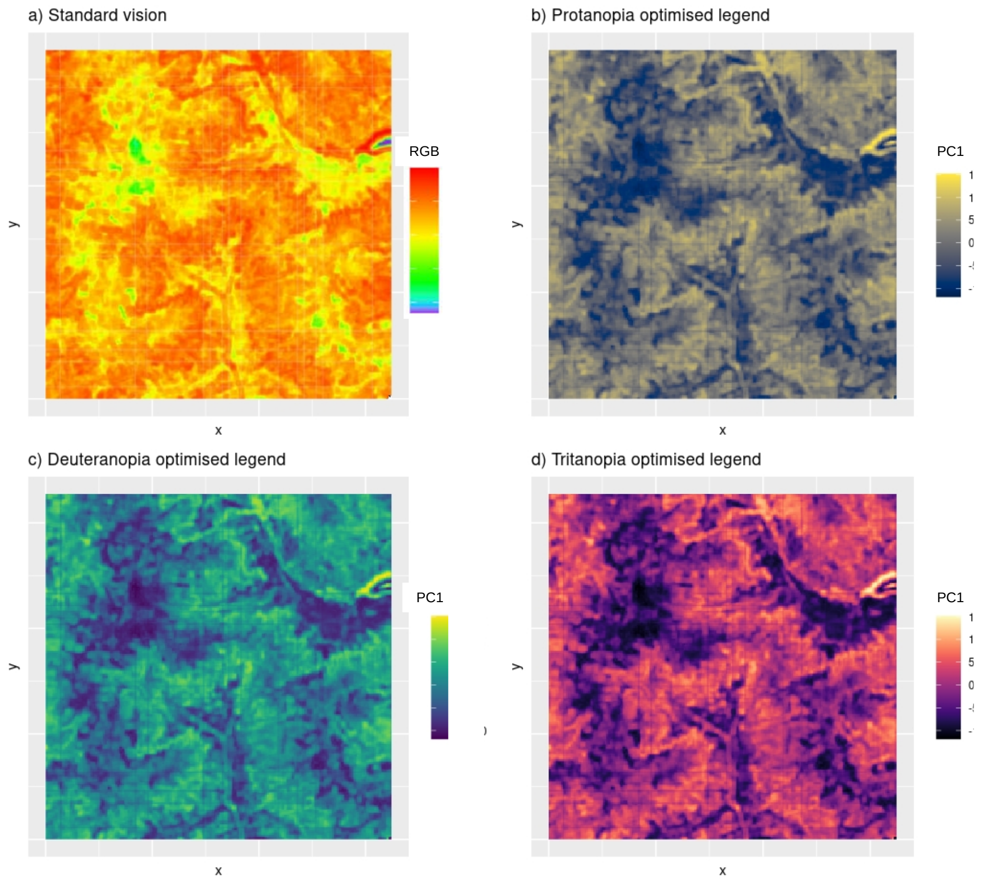

Figure 2: The variability in space of the Similaun Glacier shown by a rainbow colour ramp palette (a) as in Rocchini et al. (2021). Low spatial variability is represented in blue and green (lake), while medium variability is in yellow (woodlands), high variability is in red (crevasses and cracks). Colour blind people cannot ascertain differences between minima (blue) and maxima (red). Hence, different colour ramps are applied considering the different diseases, according to previous tests by Viénot et al. (1995): a smooth blue-to-yellow colour ramp to protanopia-affected people (`cividis` colour ramp in the `viridis` package, sharp blue-to-yellow colour ramp to deuteranopia-affected people (`viridis` colour ramp), to deep blue-to-yellow colour ramp (`magma` colour ramp) to tritanopia-affected people.