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Scientific maps should reach everyone: The `cblindplot` R package to let colour blind people visualise spatial patterns

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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 the `cblindplot` R package and its founding function - `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 colour blind friendly ramp palette. The function described in this paper, 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.

"Colour is a power which directly influences the soul." (Kandinsky, 1911)

1. Introduction

Maps are widely used to convey geographical information in

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different activities ranging from day-to-day tasks such as route planning to furthering scientific studies, such as the effects of climate change or the spread of invasive species. Despite their widespread use, maps can be problematic information resources (Burrough, 1986). Any map is a generalisation, hence an imperfect representation of the features shown, as any data gathering and representation which inevitably leads to a reduction of the original data complexity (Palmer et al., 2008). A map is also typically interpreted visually, thus different people may come to dissimilar conclusions about the mapped features.

Standard procedures and good practices for map making to generally account for vagueness exist but may not always be followed or may not fully address concerns (Burrough, 1986; Fisher, 2000). Moreover, maps can be produced in a way that may, accidentally or deliberately, deceive the reader (McNoleg, 1996; Monmonier, 2018). Indeed, 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).

Showing the variation of a variable over space on a map considering the whole gamut of colours is not a simple matter (Pointer, 1980). In most cases, maps full of colours are used, because colour is a very effective coding device (Tufte, 2002). Misuse of colour could produce a misleading perception. 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 the range represented by that colour. Using it in the middle of the palette would lead the reader to see such values as maxima (Crameri 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. Such people cannot see some of the displayed colours and, consequently, cannot appreciate differences between minima and maxima in a map, as well as the full

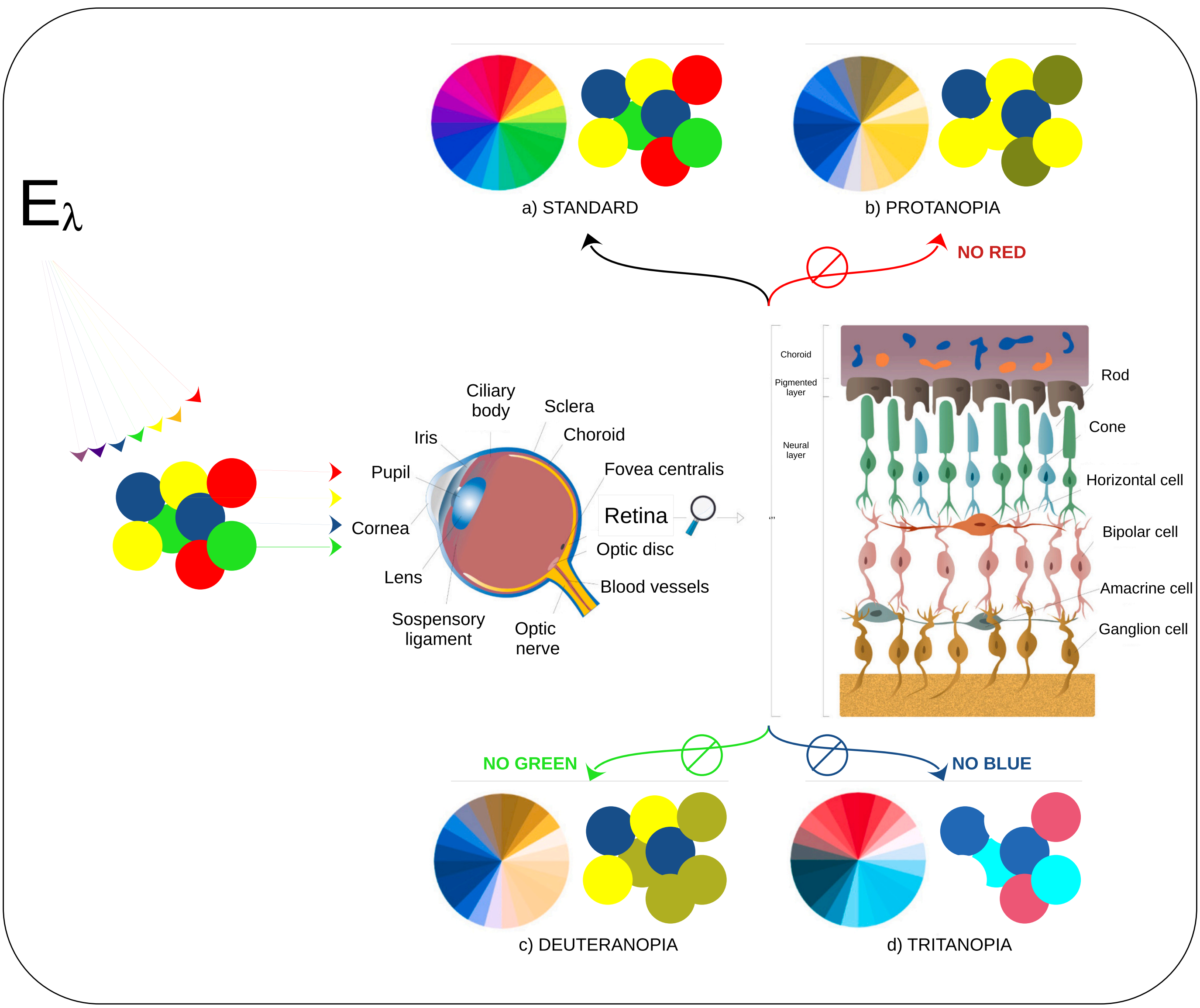

Fig. 1. Light rays coming from outside hit the cornea of the human eye, they pass through the lens and the vitreous humor and focus on the retina, which is a nerve structure. Here the translation of the light into electric signal takes place. This electrical impulse travels along the visual pathways to the occipital cortex where it is converted into a visual image. There are different manners to perceive colours, once the human eye is exposed to external light rays: (a) standard vision; (b) protanopia, i.e., the inability to perceive the red colour (560 nm); (c) deuteranopia, i.e., the inability to recognize the green colour (530 nm); (d) tritanopia, i.e., the inability to distinguish the blue colour (420 nm). Refer to Box 1 for specific information.

color gradient. This might seriously impact scholars and students of scientific learning having no proper access to graphing parts of articles and/or books (Albany-Ward and Sobande, 2015).

Colour blindness is basically represented by three main colour misperceptions: (i) protanopia, i.e., the inability to perceive the red colour (560 nm); (ii) deuteranopia, i.e., the inability to recognize the green colour (530 nm); (iii) tritanopia, i.e., the inability to distinguish the blue colour (420 nm, Fig. 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. This is the case of the frequently (mis) used rainbow colour palettes (Golebiowska and Coltekin, 2020; Stoelzle and Stein, 2021; Golebiowska and Coltekin, 2022), which are common 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 the human population (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 an extensive literature recording problems for colour blind people: from the hampering of medical profession (Spalding, 1999) to students proper learning (Ramachandran et al., 2014), and from road accidents (Cole, 2002) to unintentional injuries (Cumberland et al., 2004). Potential problems emerging from this phenomenon are somewhat disregarded in the design of scientific 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/colour_palettes.html, ColorBrewer: https://colourbrewer2.org/, Harrower and Brewer, 2003) or (ii) create them (colourschemedesigner: https://paletton.com/#uid=1000u0kllllaFw0g0qFqFg0w0aF) with an online platform dedicated to the creation of colour schemes. However, in some cases, they might appear too complex for effectively benefit colour blind people.

Furthermore, packages in R (R Core Team, 2022) - perhaps the mostly used software for statistical computing under an open source philosophy - are devoted to test for colour blindness (`colourblindcheck` package, Nowosad, 2021) or to make use of colour ramp palettes that are also interpretable by colour blind people (`viridis`, Garnier et al., 2021). However, as far as we know, no analytical and straightforward function exists to just input an image in a throughput workflow and plot it in a simple manner that is also intelligible by colour blind people. The aim of this paper is to present the `cblindplot` R package and its founding function - `cblind.plot()` - which enables colour blind people to just enter an image in a coding workflow, simply set the specific form of the colour perception discrepancy, and immediately get an output in a "colour blind friendly" format.

2. The function: step by step

2.1. Code

We implemented our idea in the `cblindplot` package (https://github.com/ducciorocchini/cblindplot). To install the package one can simply import the whole package from GitHub by making use of the devtools R package, by:

```
devtools::install_github("ducciorocchini/
cblindplot")
```

Its main function `cblind.plot()` updates the colour palette on an input image and returns a new visualization along with a new colour legend. The function has three basic steps (Fig. 2). 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, once a new colour palette is applied to the single dimension derived from PCA, the plot with a meaningful legend for colour blind people is returned (Fig. 2).

The user is asked to just choose the input image and a type of colour vision deficiency, as:

The `cvd` is a meaningful argument directly related to the type of colour blindness (Box 1 and Fig. 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 Fig. 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 make use of a rainbow-colour based - and thus incorrect - plot as in Rocchini et al. (2021), which showed the variability in space of the Similaun Glacier (Italy, Fig. 3). In that case, the rainbow colour ramp palette is going 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 would not make sense for colour blind people.

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, which is the default importing order used by the `cblind.plot()` function and can be changed at any time. As previously stated, the output is straightforward once the user declares her/his specific type of colour deficiency. For protanopia (Box 1 and Fig. 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 this 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, the `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, and deep blue-to-yellow colour ramp to tritanopia-affected people. We suggest the reader compare colours used in Fig. 3 for the different colour deficiency types with that published by Viénot et al. (1995).[2] According to Fig. 1 for protanopia and deuteranopia the colour ramp palettes can be used interchangeably (Rigden, 1999).

[2] Notice that in Viénot et al. (1995) the images for the different colour deficiency types are arranged in a clockwise manner, hence they relate to panels a), b), d) and c) in Fig. 3.

Box 1
Colour blind deficiency types

- **Protanopia:** Inability to perceive the red colour. 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 colour. 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 colour (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 colour. It has a genetic, x-linked recessive inheritance, for which it largely affects the male sex.
- **Tritanopia:** inability to distinguish the blue colour (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 colour. It has an autosomal dominant genetic inheritance, therefore independent of sex.

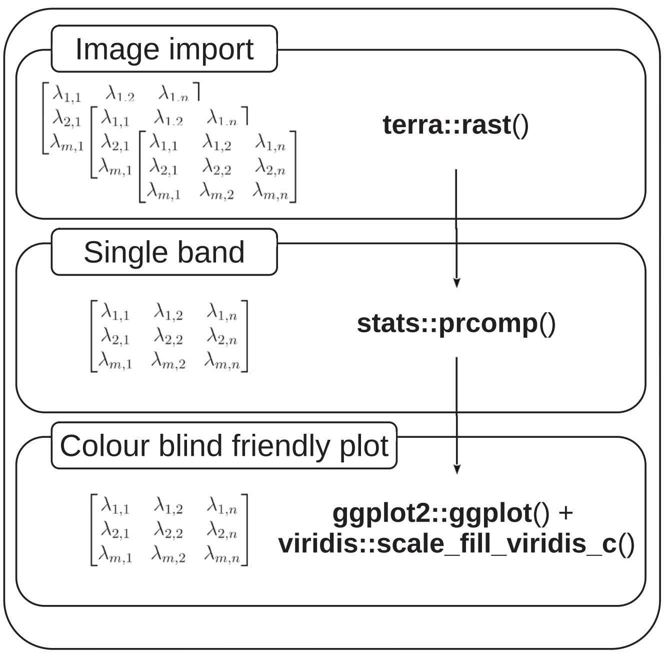

Fig. 2. The main steps composing the `cblind.plot()` function. The original image is imported by the `rast()` function in R as an RGB. Then, a PCA is applied to create a single dimension. Finally a plot is generated making use of colour ramps from the viridis package which are set explicitly considering the different colour blind deficiency types reported in Box 1 (protanopia, deuteranopia, tritanopia).

3. Outlook and take home message

3.1. Perspective and limitations

A critical step toward lowering the effort required by colour blind people to read and interpret maps is to provide them with the ability to do so with a simple function. Doing that in a free and open source environment is even more advantageous. In fact, open source software would allow the possibility to reproduce analysis exactly by guaranteeing high robustness (Rocchini and Neteler, 2012). Apart for the previously cited `viridis` package, examples exist for oceanography, in the `cmocean` package in R (Thyng et al., 2016; Thyng et al., 2020). Additional examples exist making use of Python (Van Rossum and Drake, 1995) language (Nuñez et al., 2018). However, in such cases, the workflow includes 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 colour blind friendly ramp palette.

The founding function of the `cblindplot` package described in this paper (`cblind.plot()`) 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. The focus of this manuscript was on map visualisation but the `cblindplot` package can be successfully used with any kind of graphs or images, proving to be a powerful data visualisation tool in R.

Obviously, open source code is always in motion. As an example, concerning point (i), an image might also be gathered via screenshot and sent to R, e.g. based on standalone software like flameshot (https://flameshot.org/). Moreover, additional and more sophisticated methods to let a function distinguish between minima and maxima in a rainbow colour palette like Random Forest or neural networks can be implemented in the `cblindplot` package.

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

3.2. Conclusions

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 (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 and 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

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

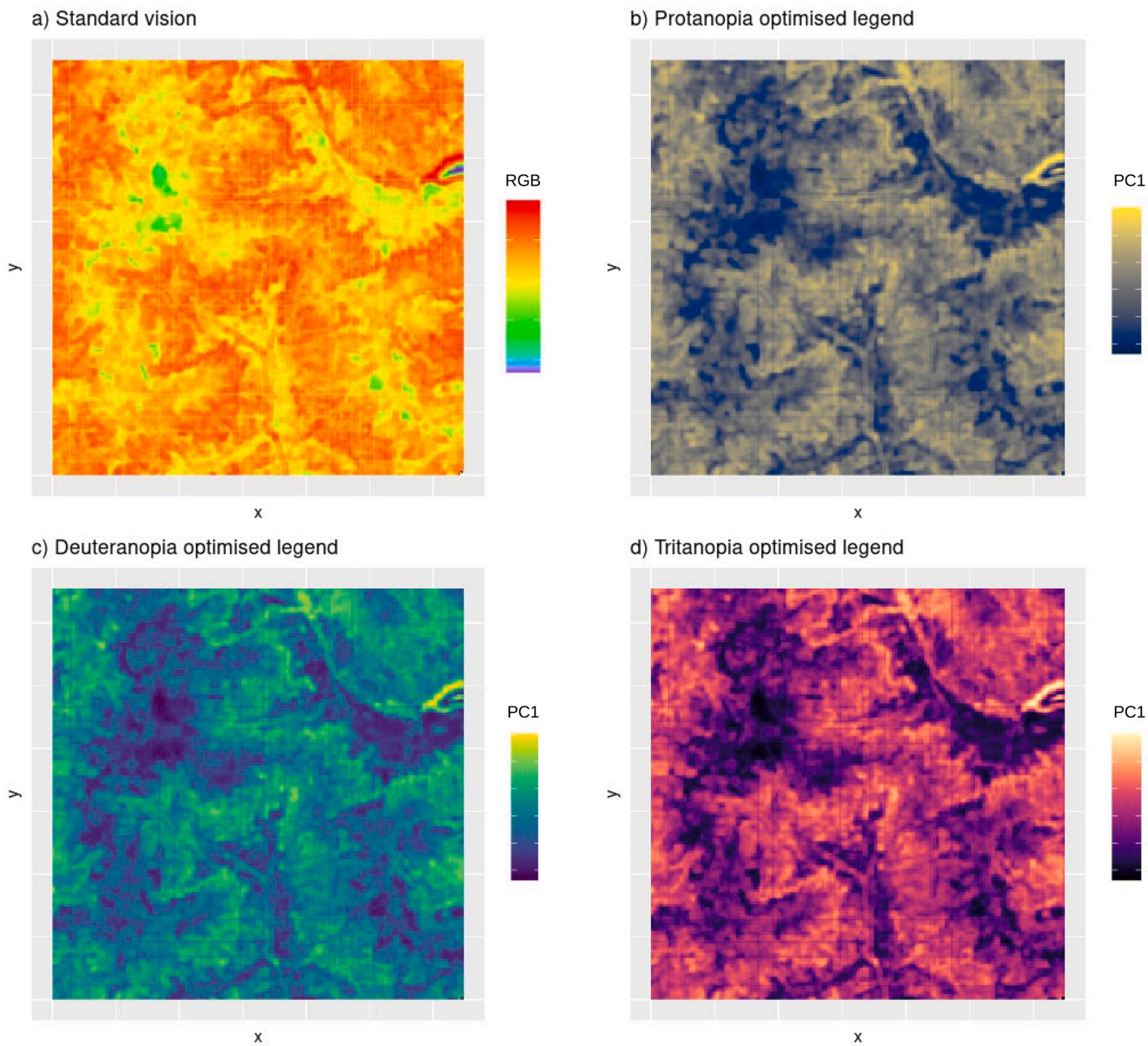

Fig. 3. The variability in space of the Similaun Glacier shown by a rainbow colour ramp palette (a) as in Rocchini et al. (2021). Low spatial variability is represented in blue and green (lake), while medium variability is in yellow (woodlands), high variability is in red (crevasses and cracks). Colour 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): (b) a smooth blue-to-yellow colour ramp to protanopia-affected people (`cividis` colour ramp in the `viridis` package, see Fig. 2), (c) sharp blue-to-yellow colour ramp to deuteranopia-affected people (`viridis` colour ramp), and (d) deep blue-to-yellow colour ramp (`magma` colour ramp) to tritanopia-affected people.

(Ekman and Sjöberg, 1965; Panek and 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 visual perception of someone else, the provided function is a straightforward tool based on well-established simulations on colour vision about the residual colour information coming out from the above described deficiency types (Brettel et al., 1997). This is just based on the fact that a certain stimulus is perceived differently by people affected by various kinds of colour blindness versus normal vision, with a well-known reaction from every single variant 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 et al., 2004).

Beside problems related to colour blind deficiency, non-perceptually uniform colour ramps, like the rainbow colour gamut, have widely been acknowledged as a fundamental problematic palette for plotting scalar values to colours. This is mainly because it introduces artifacts and obscures some data by e.g. putting yellow colours as mid values, by finally confusing the 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 way to rescale pseudocolour values and plot them in a colour blind free scheme, which is robustly grounded in 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 see output results properly.

Authors' contribution statement

D.R., J.N. and E.T.contributed to the development of the algorithms and the coding of the `colorblind` package. D.R., J.N., R.D.I. and L.C. contributed to the conceptual development of the theoretical background of this paper. All authors contributed to the writing of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The code and the data shown in this paper are available under GitHub at:https://github.com/ducciorocchini/cblindplot.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ecoinf.2023.102045.

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