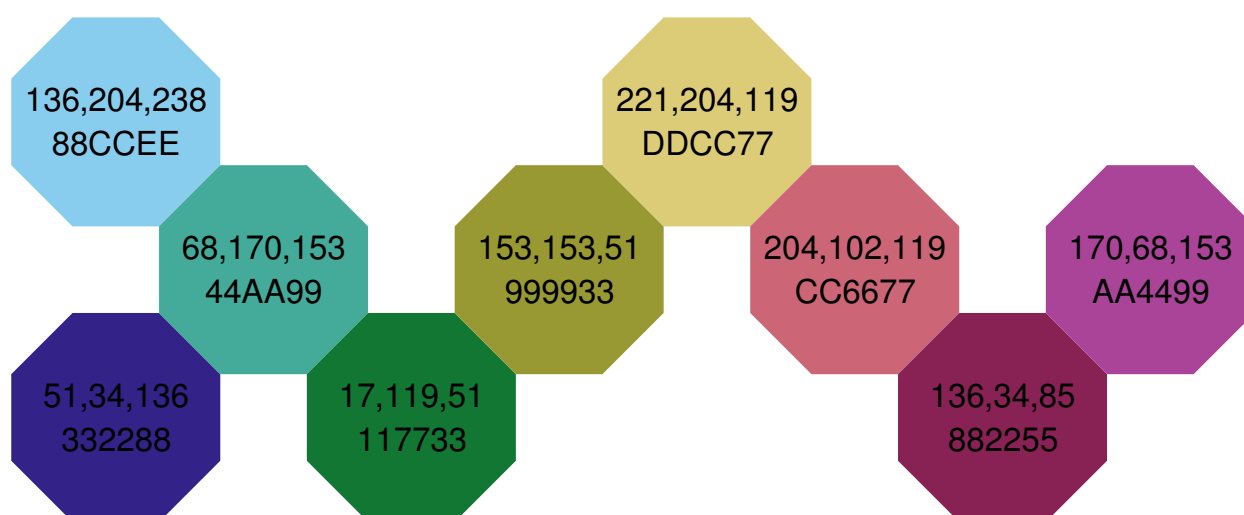
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Colour Schemes

Prepared by: Paul Tol



Document Change Record

Issue	Date	Changed Section	Description of Change
1.0	18 November 2009	All	Initial version
1.1	23 November 2009	Fig. 6	Improved green on grey background
2.0	17 January 2010	All	Print-friendlier schemes
			Added commands to simulate colour-blindness
2.1	17 August 2010	Fig. 3	Different choice of 8-colour set
		p. 4	Remark added on background grey
		p. 5	Remark added on NEN colour set
		Section 5	Added section on palette check
2.2	29 December 2012	Section 4	Added a banded rainbow scheme

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1 Introduction

Graphics with scientific data become clearer when the colours are chosen carefully. It is convenient to have a good default scheme ready for each type of data, with colours that are distinct for all readers, including colour-blind people. This document shows such schemes as a function of the number of colours needed, with some examples. It also gives a conversion of colour coordinates to simulate approximately how any colour is seen if you are colour-blind.

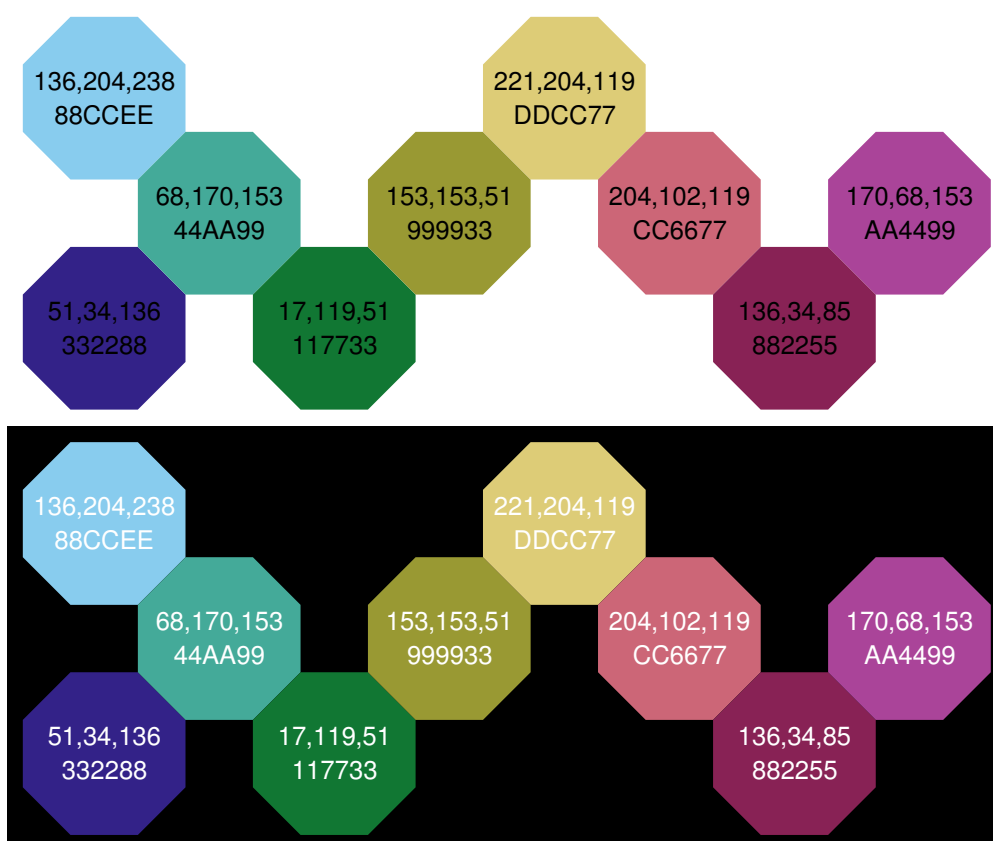


Figure 1: Palette I of printable websmart colours that are as distinct as possible in both normal and colour-blind vision, but also match well together. The same colours are shown on a white and a black background, marked with their decimal RGB values and hexadecimal HTML colour codes.

2 Distinct Colour Palettes

Palette I in Fig. 1 consists of colours that are as distinct from each other as possible, while also:

- distinct in colour-blind vision;
- distinct from black and white;
- distinct on computer screen and paper;
- matching well together.

Colour coordinates (R, G, B) are given in the RGB colour system (red R , green G and blue B), decimal at the top and hexadecimal at the bottom. Alternative palette II in Fig. 2 is more regular: colours in each row have the same shade (light, medium or dark) and in each column the same hue (azure, cyan, teal, yellow, orange, red or pink). This palette has been optimized for the medium shades, so some combinations with light or dark shades, shown in Table. 1, are best avoided. If palette I is used, colours can be chosen at random, but

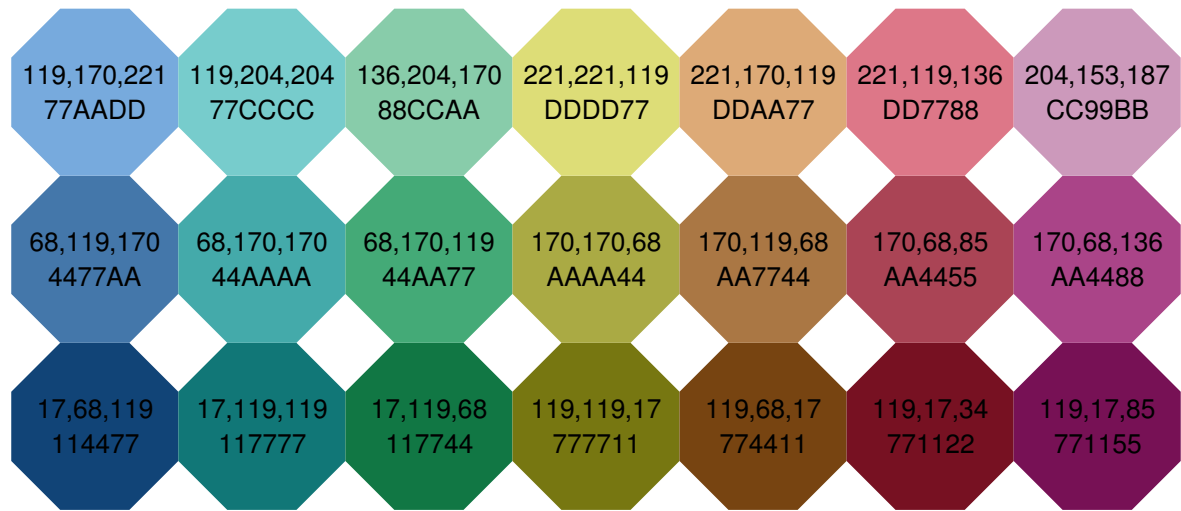


Figure 2: Palette II with a more regular pattern of hues (columns) and shades (rows).

Table 1: Colour combinations from palette II (Fig. 2) that are least distinct in colour-blind vision. These should be avoided, especially the top two.

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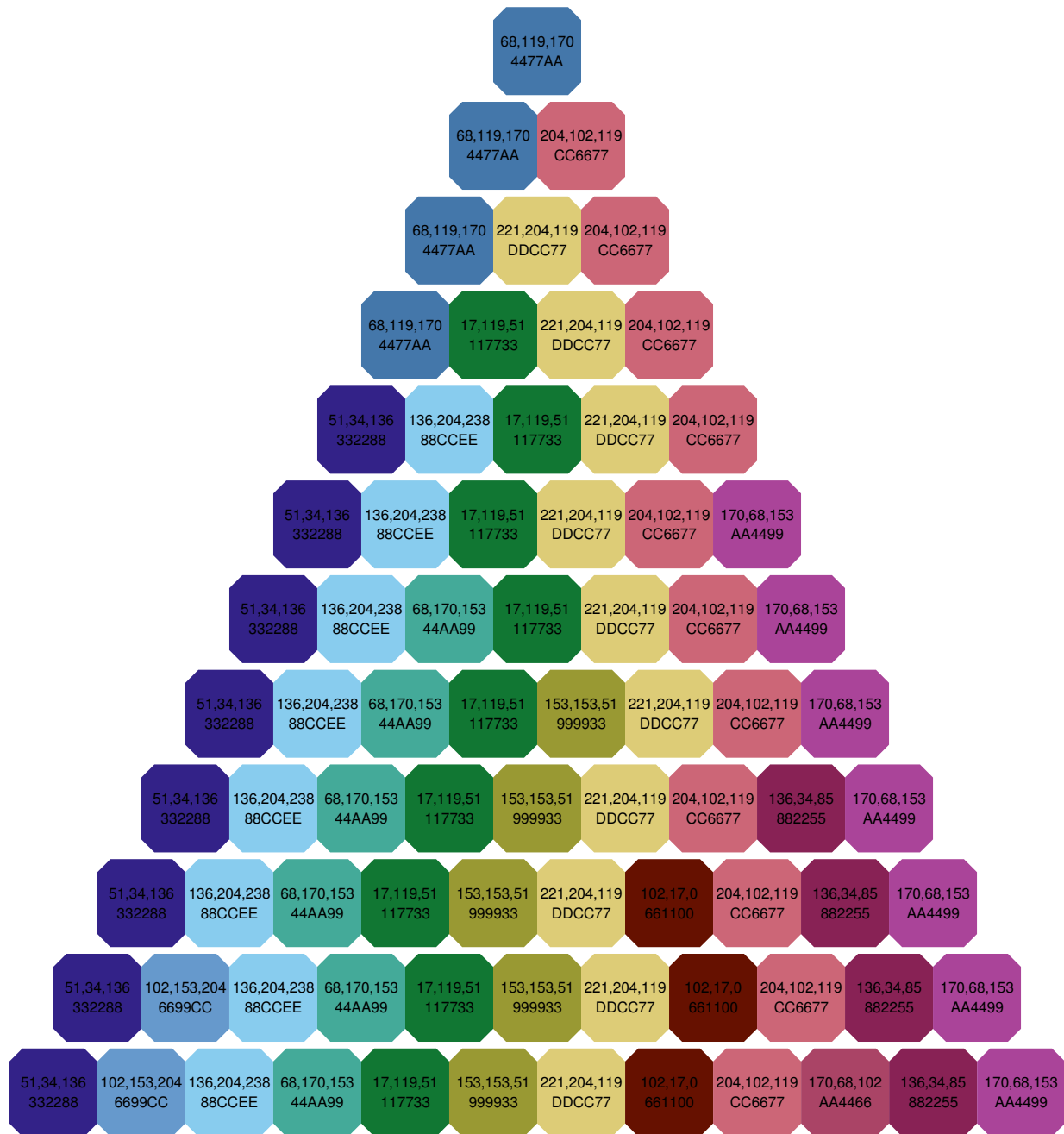


Figure 3: Scheme examples for qualitative data. Each row is a scheme for a different number of colours.

even here some combinations are more distinct than others. Some of the most distinct subsets, depending on the number of colours, are given in Fig. 3. When there are more than nine colours, some extra colours outside palette I have been defined. For subsets of fewer than five colours, the dark blue has been replaced by medium azure from palette II. Data gaps can be indicated with light grey DDDDDD (221, 221, 221). The four-colour set in Fig. 3 is reasonably distinct when printed in grey, but a set optimized for this purpose is shown in Figure 4.



Figure 4: A four-colour subset of palette I that is optimized for printing in grey scale. Tip: if used for lines, also use dashed and dotted lines.

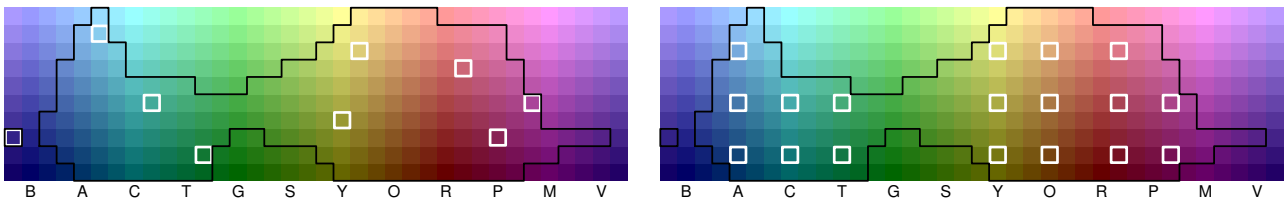


Figure 5: All websmart sRGB colours with vividness 0.4 with printable colours enclosed by a black line. Initials stand for blue, azure, cyan, teal, green, spring, yellow, orange, red, pink, magenta and violet. Colours in palette I (left) and palette II (right) are indicated by white squares. Three light shades in palette II have been made less vivid (out of the plane of the figure) to put them inside the CMYK gamut, and are therefore not indicated. Geometric distance does not indicate perceptual colour distance, especially not if colour-blindness is taken into account.

The design of these palettes involved four types of calculations:


- for the distance between colours the CIEDE2000 colour difference ΔE_{00} is used [1];
- red-blind and green-blind vision is simulated by the method described in section 6;
- colours with the same product of saturation S and value V in the HSV colour system (same ‘vividness’) match well together;
- colours are called ‘printable’ if they are within the CMYK gamut provided by colour profile ‘ISO Coated v2 300%’ (discussed below).

To reduce the number of calculations without much loss of choice, only websmart colours were considered, meaning the hexadecimal RGB coordinates are only 00, 11, . . . , FF. The vividness was chosen to be $SV = 0.4$. With a smaller value colours become too grey, with a larger value there is not enough range of shades for palette II and in general there are fewer printable colours.

All colours in this document are defined in sRGB colour space, the default used by most software and displays. Printers work in a different colour space that also varies from model to model. When they conform to international standard ISO 12647-2 and the exact printing conditions are not known beforehand, it is recommended to assume the CMYK colour space provided by colour profile ‘ISO Coated v2 300%’ [2]. All palette colours are taken from the overlap between this and the sRGB colour spaces. More specifically, the two colour blocks in Fig. 5 show all sRGB colours with vividness 0.4, while the colours enclosed by a black line are also in the CMYK colour space defined above and therefore printable. Pure blue of this vividness (column above B) is not printable. Magenta, green and light cyan are also problematic for printers. The palette colours are indicated by squares. They are not equally spread over the figure within the black lines, because geometric distance in this figure does not correspond to perceptual colour distance, even in normal vision.

The Netherlands Standardization Institute NEN has issued a code of practice which includes a recommended palette with eight colours, three greys and white [3]. Differences between them are often much smaller than the smallest difference in palette I, two colours are not printable and they cannot be quoted without infringing copyright.

This section ends on an SRON-specific topic: PowerPoint presentations on a dark grey background. In this case the light shades (top row) in palette II could be used. However, the original SRON template already

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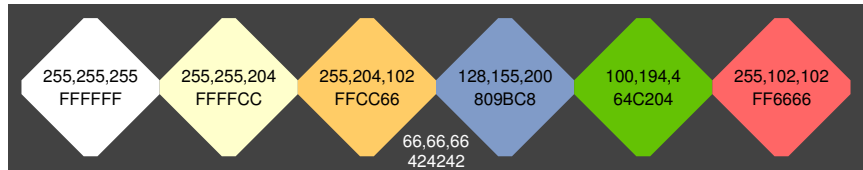


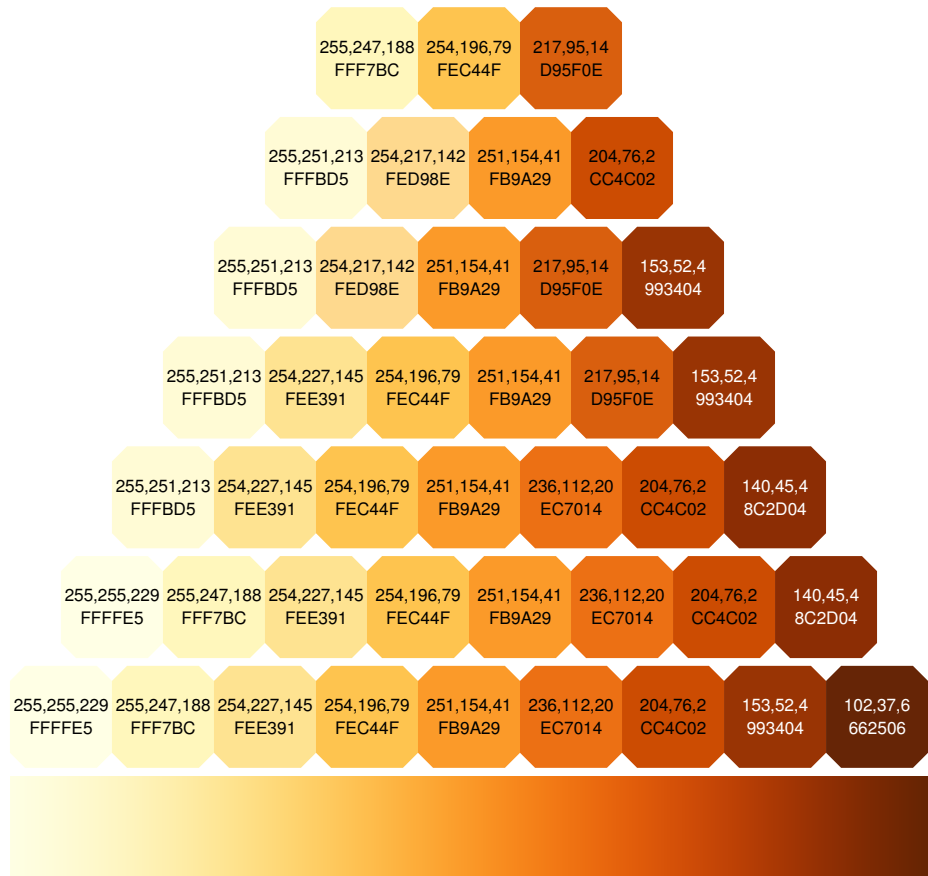
Figure 6: SRON PowerPoint colours on a dark grey background, with the left four taken from the original template. Colours from the top row in Fig. 2 also work on this background.


defines three colours: white for titles, light yellow for normal text and orange for highlighted text. If the light blue from the footer is added, two extra hues are green and red. The complete palette optimized for projection is shown in Fig. 6. The red is rather pale, because it becomes darker on a projection screen. The green is carefully chosen so it differs from orange in red-blind vision and differs from red in green-blind vision.

3 Best Colour Scheme for Different Data Types

A colour scheme should reflect the type of data shown. There are three basic types of data:

1. Qualitative data—nominal or categorical data, where magnitude differences are not relevant. This includes text in presentations and lines in plots. Use palette I (Fig. 3) or different hues (colours from a row) in palette II (Fig. 2).
2. Sequential data—data ordered from low to high.



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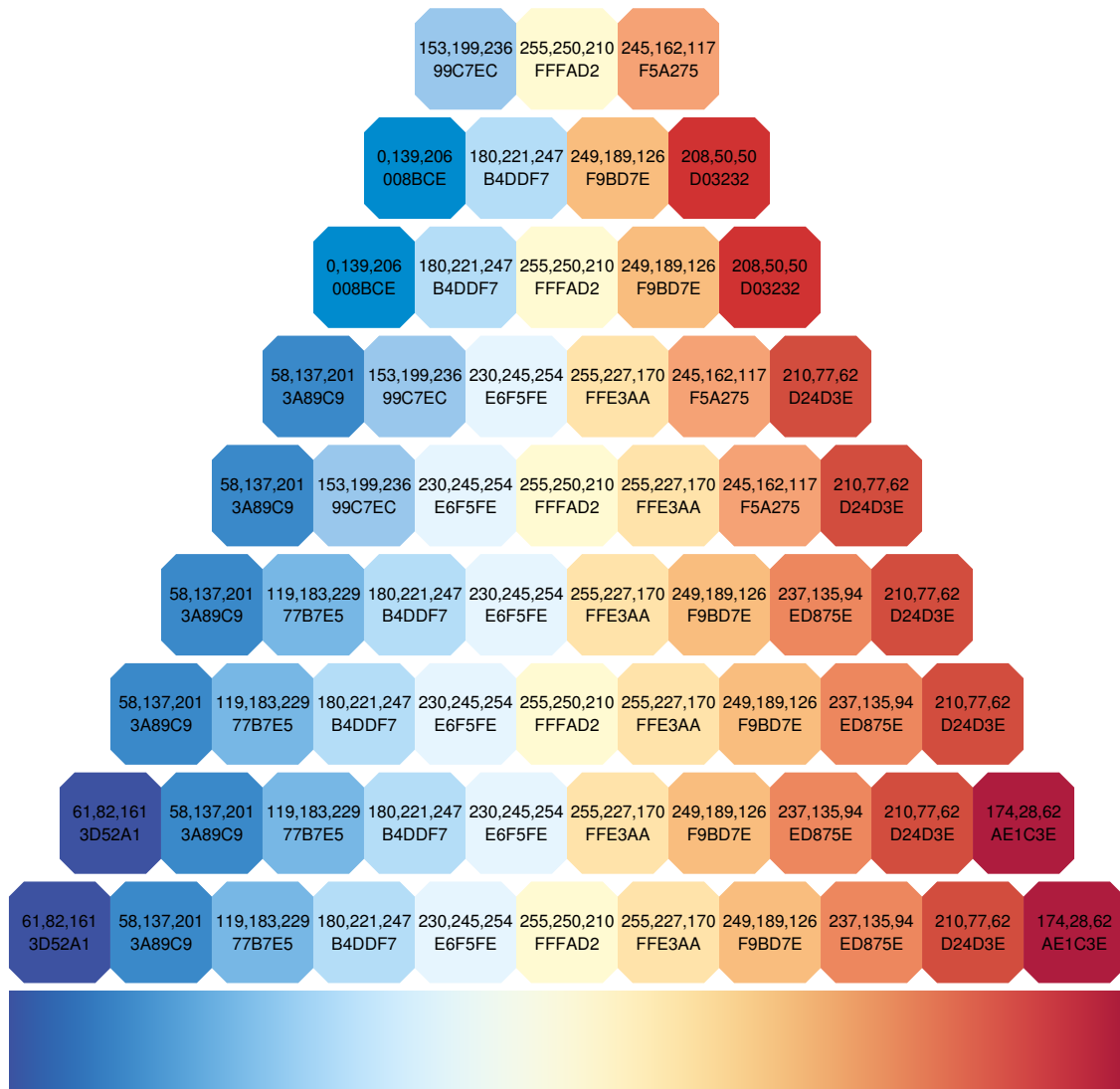


Figure 8: Scheme for diverging data [4]. The smooth version at the bottom is produced with Eq. (2).

- (a) If there are two or three classes, it is possible to use different intensities of the same hue (colours from a column) in palette II (Fig. 2).
- (b) For three or more classes, use a scheme as given in Fig. 7.
3. Diverging data—data ordered between two extremes where the midpoint is important, e.g. positive and negative deviations from zero or a mean. Use a scheme as given in Fig. 8.
- Plot examples of qualitative data, sequential data and a combination are given in Figs. 9, 10 and 11, respectively. An example of diverging data is shown in Fig. 12. The smooth version of the yellow-orange-brown scheme in Fig. 7 is produced by

$$R/255 = 1 - 0.392(1 + \text{erf}[(x - 0.869)/0.255]), \quad (1a)$$

$$G/255 = 1.021 - 0.456(1 + \text{erf}[(x - 0.527)/0.376]), \quad (1b)$$

$$B/255 = 1 - 0.493(1 + \text{erf}[(x - 0.272)/0.309]), \quad (1c)$$

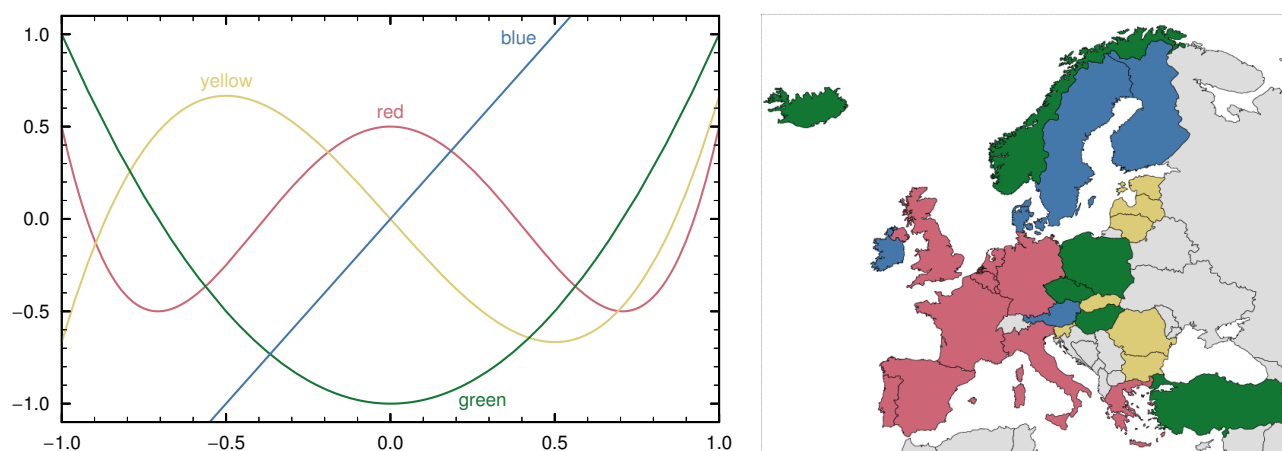


Figure 9: A qualitative colour scheme: distinct colour hues with modest intensity differences for data where magnitude differences are not relevant. Left: four curves and labels that are distinguishable from each other and clear on a white background. Right: members (red), associate members (green), observers (blue) and associate partners (yellow) of the Western European Union. The four-colour set from Fig. 3 is used.

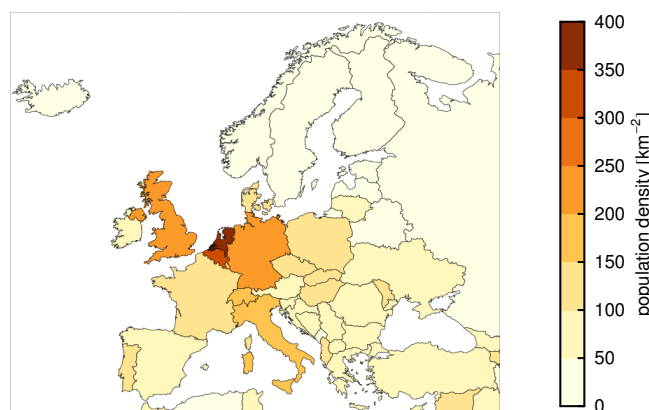


Figure 10: A sequential colour scheme: variation of colour intensity for data that are ordered from low to high, in this case the population density. The hue can also vary to some extent, as long as the intensity differences dominate. (On this map there are no countries in the class 250–300 km^{-2} .)

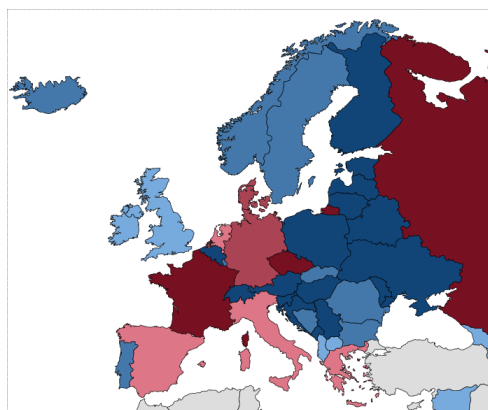



Figure 11: A combination of a qualitative and a sequential colour scheme. As in Fig. 9, different categories have different hues: European Football Championship winners are red. As in Fig. 10, within each category, data are ordered from low to high by different intensities: the suicide rate per 100,000 is < 10 (light), 10–15 (medium) or > 15 (dark). Three shades of two hues from Fig. 2 are used.

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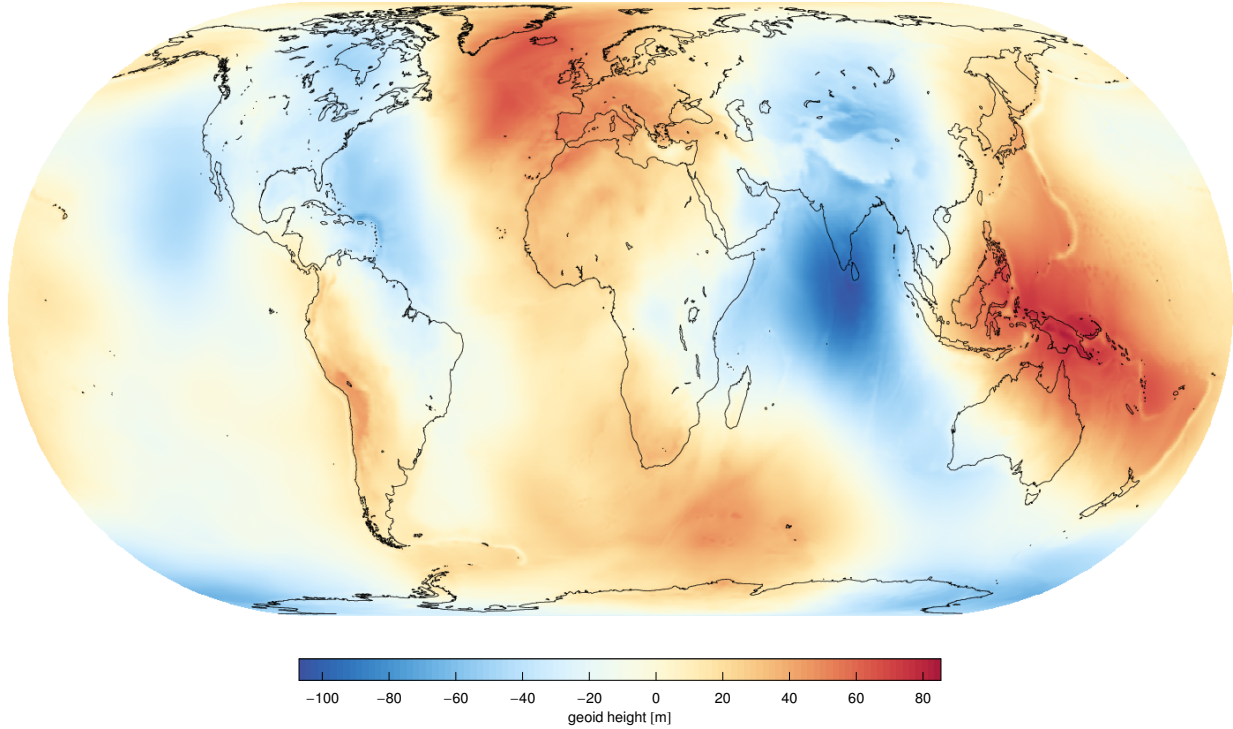


Figure 12: A diverging colour scheme: the middle of the legend is emphasized with light colours and low and high extremes are emphasized with dark colours that have contrasting hues. Distance between the WGS84 ellipsoid and the geoid calculated with the EGM96 gravity model.

with $0 \leq x \leq 1$ and error function erf. The smooth blue-yellow-red scheme in Fig. 8 is given by:

$$R/255 = 0.237 - 2.13x + 26.92x^2 - 65.5x^3 + 63.5x^4 - 22.36x^5, \quad (2a)$$

$$G/255 = \left(\frac{0.572 + 1.524x - 1.811x^2}{1 - 0.291x + 0.1574x^2} \right)^2, \quad (2b)$$

$$B/255 = 1 / (1.579 - 4.03x + 12.92x^2 - 31.4x^3 + 48.6x^4 - 23.36x^5). \quad (2c)$$

The quantitative (sequential and diverging) schemes in Fig. 7 and 8 were taken from the ColorBrewer website [4], where many others can be found. The qualitative schemes there do not have the characteristics of palettes I and II, which was the reason I designed these two.

4 Rainbow Schemes

Quantitative data should not be shown with a rainbow scheme, because the spectral order of visible light carries no inherent magnitude message. In addition, most rainbow schemes contain bands of almost constant hue with sharp transitions in-between, which are perceived as jumps in the data. Finally, colour-blind people have difficulty distinguishing some colours of the rainbow.

However, if you have tried schemes as discussed in the previous section and still want a rainbow, Fig. 13 shows such a scheme that is continuous and reasonably clear in colour-blind vision. The colours in each row are equidistant in normal vision using the CIEDE2000 colour difference [1] as a distance measure. The smooth

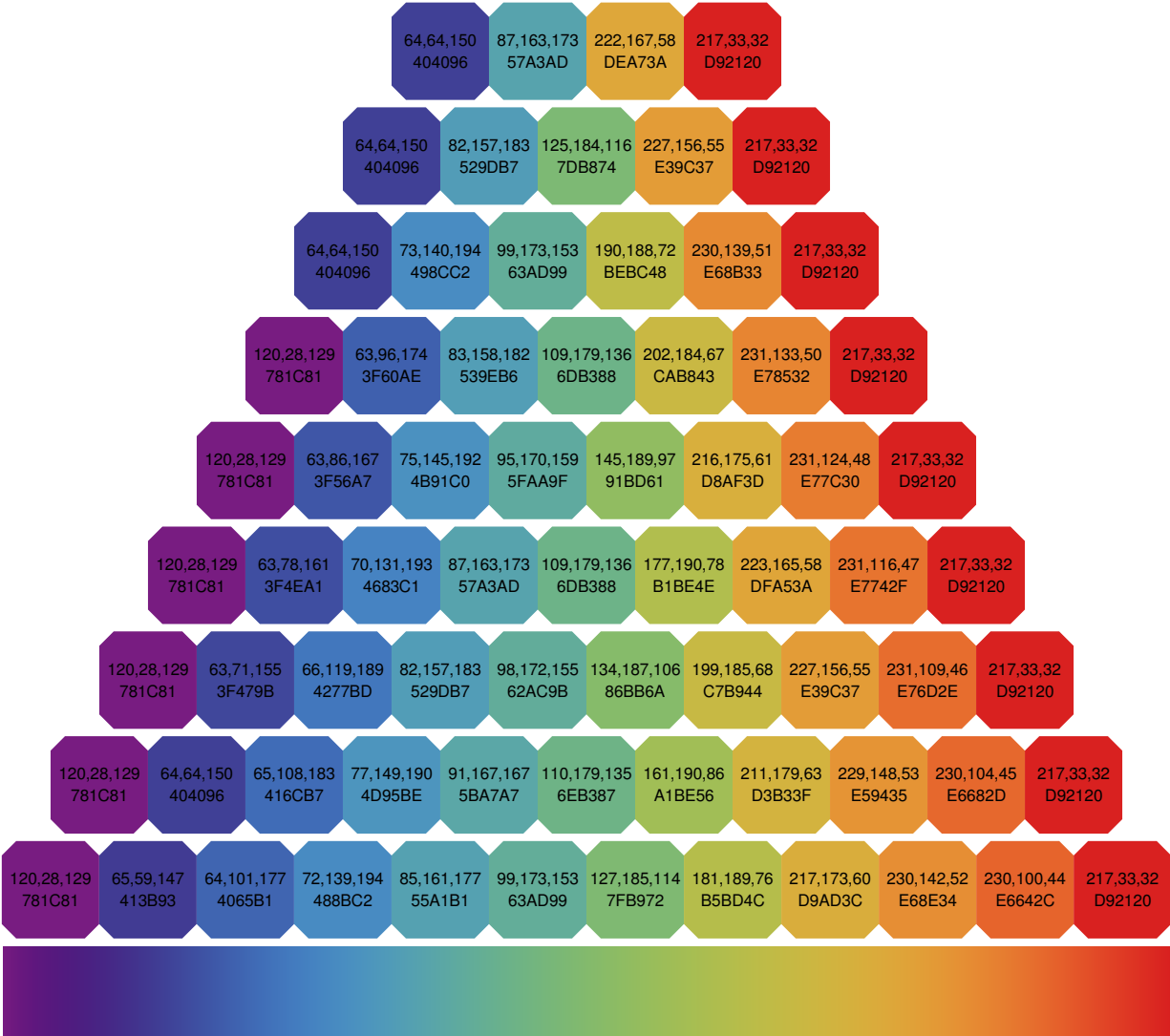


Figure 13: Continuous rainbow scheme. The smooth version at the bottom is produced with Eq. (3).

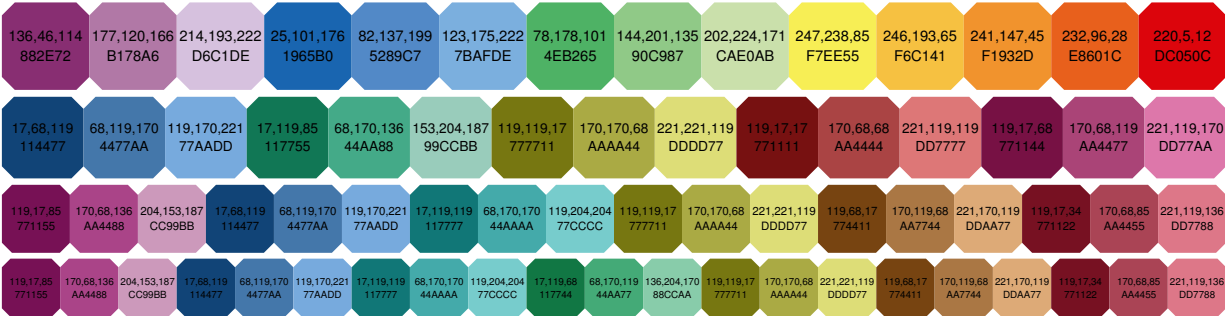


Figure 14: Banded rainbow schemes with a large number of steps. It is better to use all colours in a smaller scheme than to pick colours from a larger scheme.

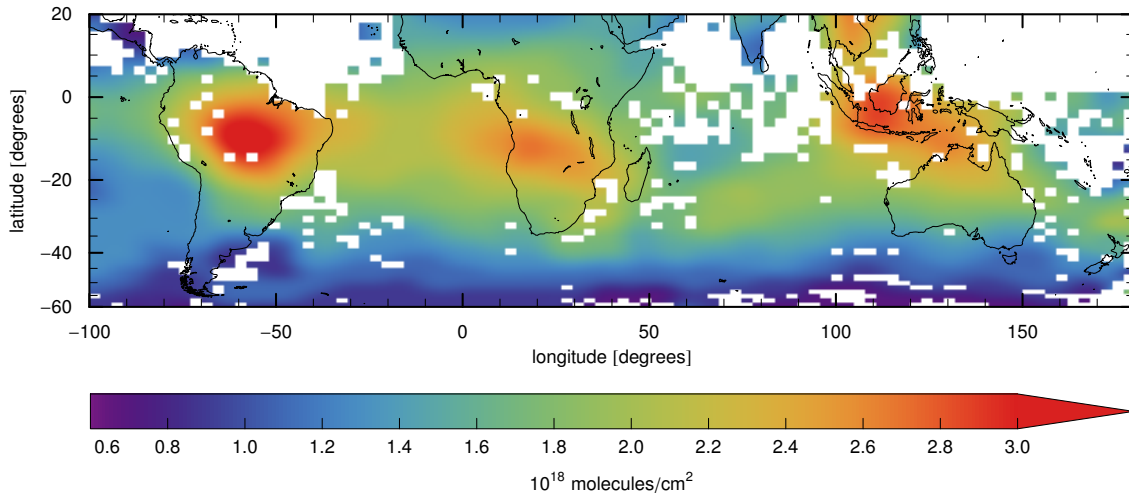


Figure 15: The smooth, continuous rainbow scheme from Fig. 13 used for sequential data. SCIAMACHY CO total column in October 2004 [5].

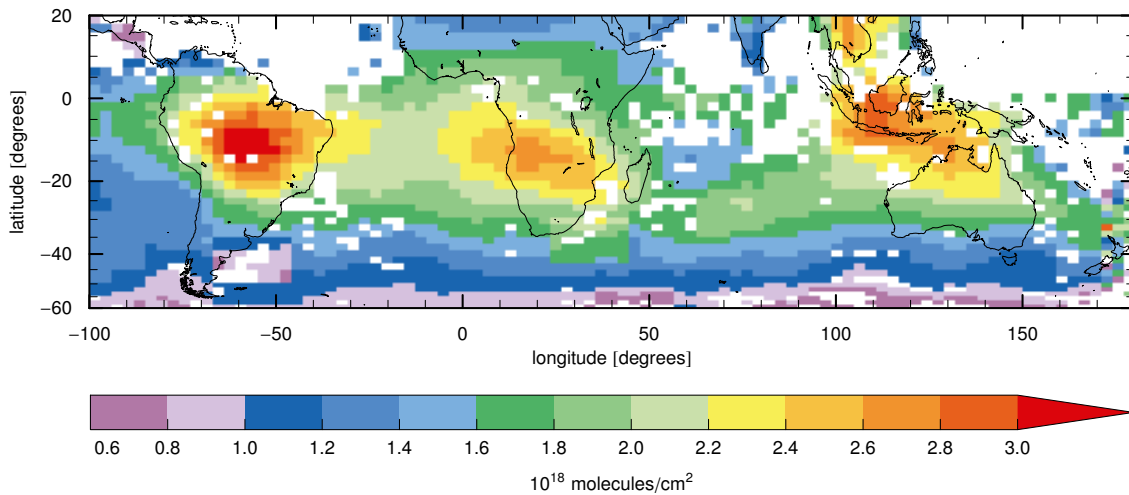


Figure 16: Top banded rainbow scheme from Fig. 14 used for the same sequential data as in Fig. 15.


version at the bottom is given by:

$$R/255 = \frac{0.472 - 0.567x + 4.05x^2}{1 + 8.72x - 19.17x^2 + 14.1x^3}, \quad (3a)$$

$$G/255 = 0.108932 - 1.22635x + 27.284x^2 - 98.577x^3 + 163.3x^4 - 131.395x^5 + 40.634x^6, \quad (3b)$$

$$B/255 = 1 / (1.97 + 3.54x - 68.5x^2 + 243x^3 - 297x^4 + 125x^5). \quad (3c)$$

If more than 10 steps are needed, the colours become difficult to discern. In that case consider using the smooth version or (part of) one of the banded schemes in Fig. 14. The top banded scheme is based on the temperature map of the weather forecast in newspaper *de Volkskrant*, tweaked to make the colours more distinct. The other banded schemes are based on distinct colour palette II and a reoptimization with 15 colours. Examples of all types are shown in Figs. 15, 16 and 17. Figure 15 shows an advantage of the continuous rainbow scheme over the earlier quantitative schemes when data is missing: because the whole range of colours is equally saturated, there is a clear distinction between data and non-data. The other schemes have pale colours at the low end or middle of the range. With a banded scheme as in Fig. 16, it is easier to determine the value at a particular location.

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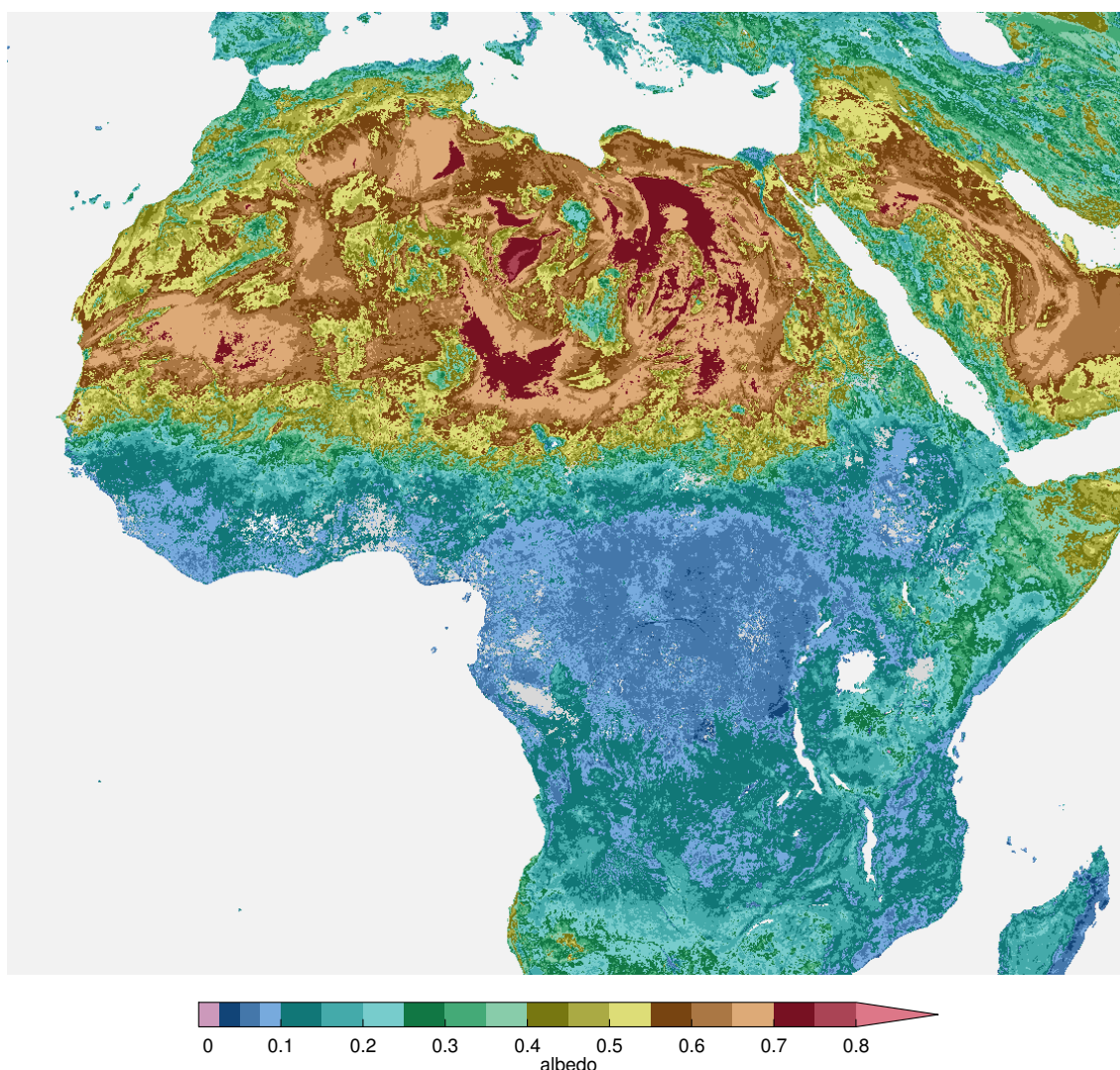


Figure 17: Bottom banded scheme from Fig. 14 used for sequential data. Albedo of snow- and cloud-free land at 2.1 μm at a resolution of 7.5 km, using MODIS data from 4–19 July 2007.

5 Colour-Scheme Robustness

Figure 18 shows most schemes defined in this document used in a variation of the diagnostic map used by the ColorBrewer website [4]. A scheme works if the following can be done without much effort:


- in the random section at the left, distinguish every colour;
- in each section with one main colour, find the outliers (one per colour) and distinguish them from each other.

All schemes are shown with nine colours; in cases where fewer colours are used, the data will be clearer.

6 Colour-Blindness

People usually find out at an early age whether they are colour-blind. However, there are subtle variants of colour-vision deficiency. The two main types are:

- Green-blindness – the cone cells in the retina that are sensitive to medium wavelengths are absent or have their response shifted to the red (6% of men, 0.4% of women);

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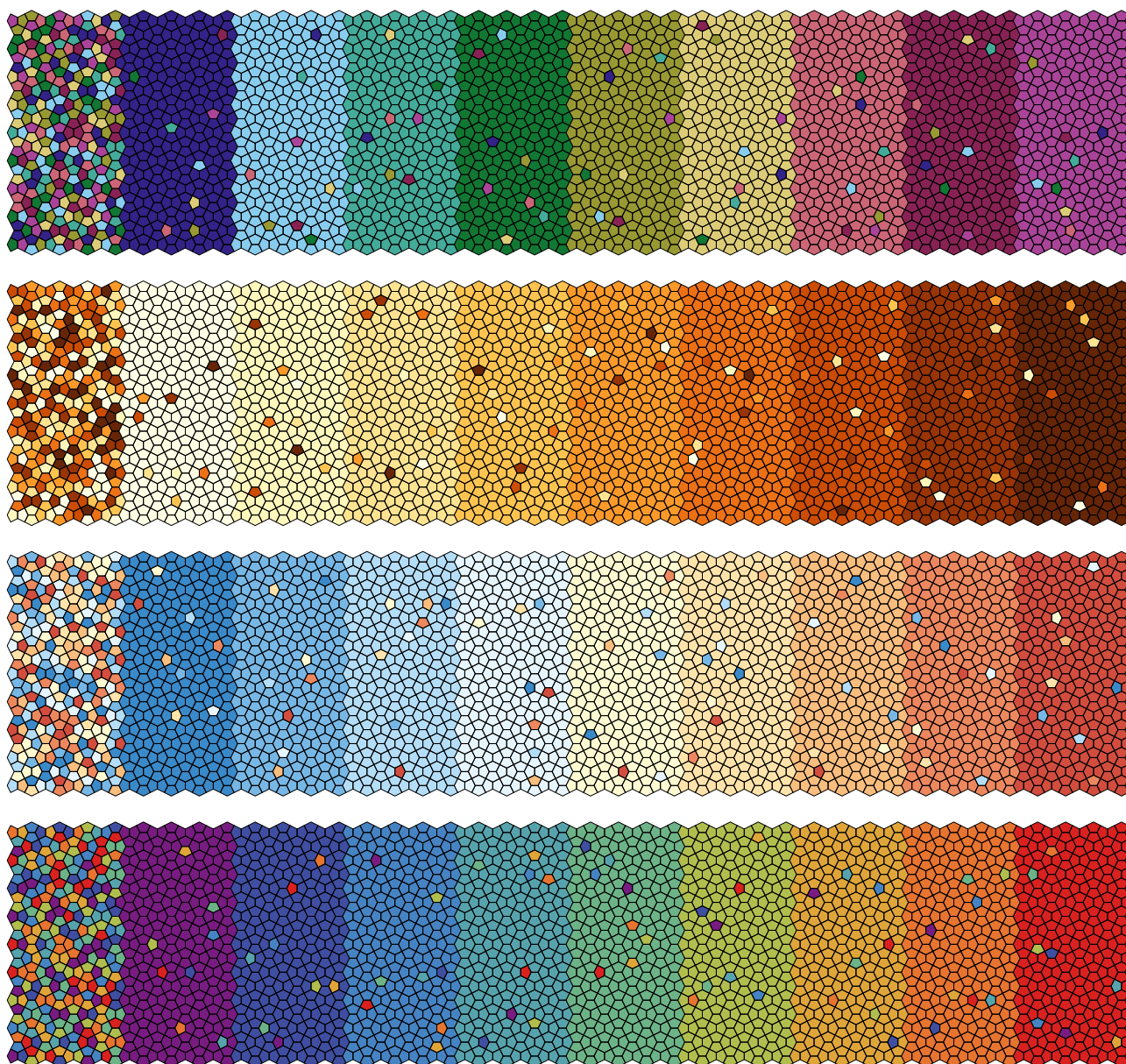



Figure 18: Check for colour-scheme robustness: can all colours be distinguished in a random pattern and when surrounded by another colour.

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EPS		

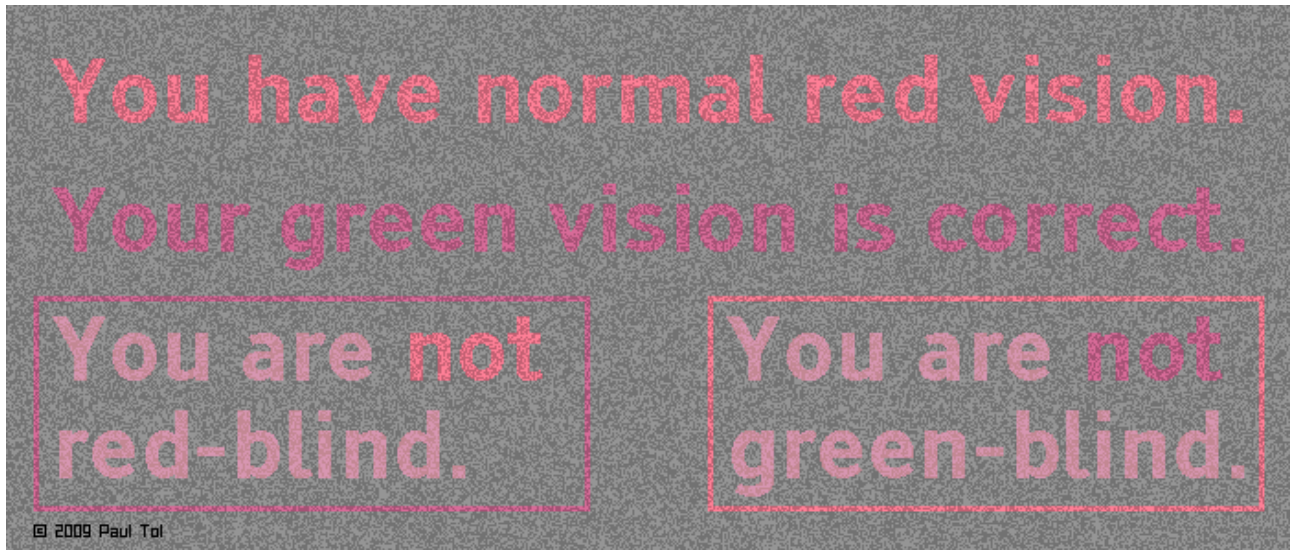


Figure 19: The readable text in this image is the colour-vision diagnosis of the reader. It is not a puzzle: there is no hidden message that requires much effort to see. The clarity of the text is not important, only whether it is readable at all. Please do not make life-changing decisions based only on this test.

- Red-blindness – the cone cells in the retina that are sensitive to long wavelengths are absent or have their response shifted to the green (2.5% of men).

Figure 19 is a test on these types. It works on a computer screen (when looking straight at it), projected with a beamer and sometimes even in unfaded print, although this will depend on the quality of the equipment.

To simulate green-blindness [6, 7], all RGB colours in an image are converted to R'G'B' colours with

$$R' = (4211 + 0.677G^{2.2} + 0.2802R^{2.2})^{1/2.2}, \quad (4a)$$

$$G' = (4211 + 0.677G^{2.2} + 0.2802R^{2.2})^{1/2.2}, \quad (4b)$$

$$B' = (4211 + 0.95724B^{2.2} + 0.02138G^{2.2} - 0.02138R^{2.2})^{1/2.2}, \quad (4c)$$

with parameters R , G and B in the range 0–255 and the output values rounded. To simulate red-blindness, colours are shifted as follows:

$$R' = (782.7 + 0.8806G^{2.2} + 0.1115R^{2.2})^{1/2.2}, \quad (5a)$$

$$G' = (782.7 + 0.8806G^{2.2} + 0.1115R^{2.2})^{1/2.2}, \quad (5b)$$

$$B' = (782.7 + 0.992052B^{2.2} - 0.003974G^{2.2} + 0.003974R^{2.2})^{1/2.2}. \quad (5c)$$

These conversions should be applied in sRGB colour space, i.e. they work on a standard video display, but not necessarily on paper. The conversion can be performed with the free software suite *ImageMagick*. The following two commands make green-blind and red-blind versions of original image `original.png`, respectively:¹

```
convert original.png \( +clone -channel RG -fx "(0.02138+0.6770*G^2.2+0.2802*R^2.2)^(1/2.2)" \) \
+swap -channel B -fx "(0.02138(1+v.G^2.2-v.R^2.2)+0.9572*v.B^2.2)^(1/2.2)" greenblind.png
```

```
convert original.png \( +clone -channel RG -fx "(0.003974+0.8806*G^2.2+0.1115*R^2.2)^(1/2.2)" \) \
+swap -channel B -fx "(0.003974(1-v.G^2.2+v.R^2.2)+0.9921*v.B^2.2)^(1/2.2)" redblind.png
```

Figure 20 shows the result when they are applied to a triangle of normal colours (top): the green-blind simulation is at bottom left, the red-blind simulation at bottom right. Contrary to popular belief, pure red and green

¹These are Unix-style commands, for Windows replace `\(` and `\)` by `(` and `)`, and use a caret (^) instead of a backslash to end the first line.

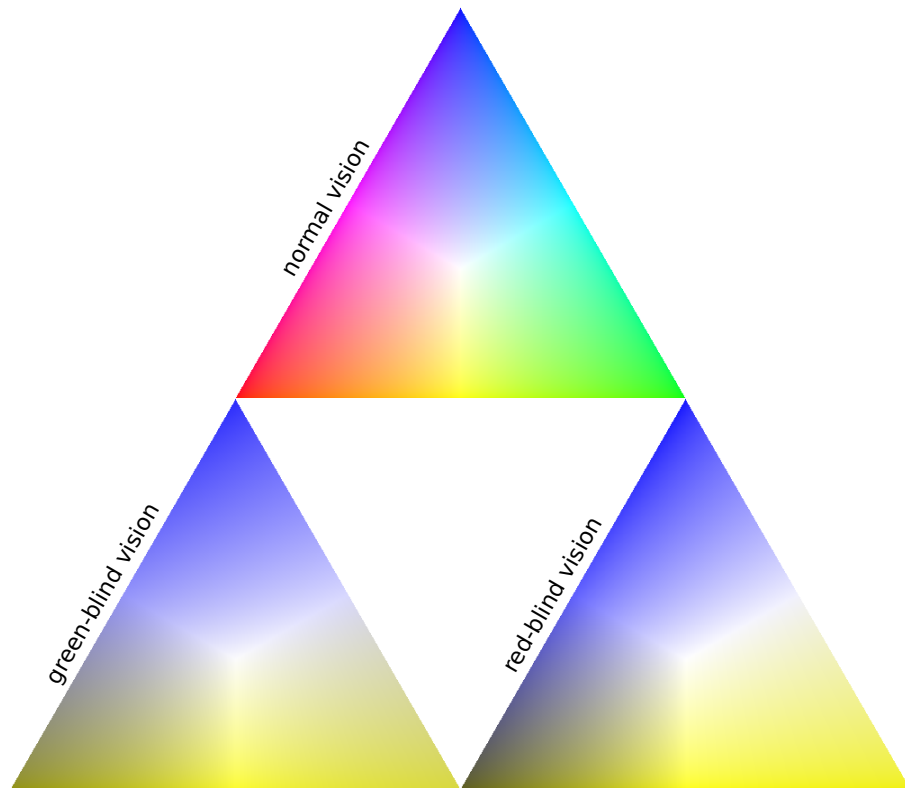



Figure 20: Colour scale in normal vision (top), green-blind vision (bottom left) and red-blind vision (bottom right). These conversions are only approximate and are designed for a computer screen.

Table 2: Colours in Fig. 1 as seen in normal and colour-blind vision.

Palette I in normal vision.	
Approximate green-blind simulation of palette I.	
Approximate red-blind simulation of palette I.	

can be distinguished. Instead, yellow/green and purple/blue combinations are problematic. However, there are more unexpected pairs of colours that look the same, as used in Fig. 19. Table 2 shows colour-blind vision simulations of distinct colour palette I.

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Reference Documents

- [1] Gaurav Sharma, Wencheng Wu, and Edul N. Dalal. The CIEDE2000 color-difference formula: implementation notes, supplementary test data, and mathematical observations. *Color Research and Application*, 30:21–30, 2005. <http://www.ece.rochester.edu/~gsharma/ciede2000/ciede2000noteCRNA.pdf>.
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