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ORGINIAL ARTICLE

Analytical and Empirical Evaluation of Color Schemes in Temperature Maps

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Abstract
The communication of weather and climate phenomena plays an important role in everyday life as well as in current debates. This article focuses on the representation of absolute temperatures in selected temperature maps from media and official sources. Its core objective is to analyze the usability of color schemes. An analytical and an empirical study were conducted to evaluate the usability of the color schemes. Specifically, the intuitive recognition of graphical sequence, association between values and meaning, differentiation of colors, and aesthetics were considered. Special emphasis was placed on users with color vision deficiencies. The studies identified several weaknesses in the color schemes—sometimes with contradictory findings, such as high subjective approval of readability versus poor effectiveness. These conclusions served as the basis for developing a new scheme to be proposed for future use.

Keywords Thematic Maps · Usability · Color vision deficiencies · Color differentiation · Color Association

Analytische und empirische Bewertung der Farbschemata in Temperaturkarten

Zusammenfassung
Die Kommunikation über das Wetter und Klimaphänomene spielt eine bedeutende Rolle im Alltag und in aktuellen Diskussionen. Der Schwerpunkt des vorliegenden Beitrags liegt auf der Darstellung absoluter Temperaturen in ausgewählten Temperaturkarten aus den Medien und offiziellen Quellen. Sein Hauptziel ist die Analyse der Benutzerfreundlichkeit von Farbschemata. Es wurden eine analytische und eine empirische Studie durchgeführt, um die Benutzerfreundlichkeit von Farbschemata zu bewerten. Insbesondere wurden dabei die intuitive Erkennung der graphischen Abfolge, Assoziationen zwischen Werten und Bedeutung, Unterscheidung der Farben und die Ästhetik betrachtet. Besondere Aufmerksamkeit erhielten Nutzer mit Farbsehschwächen. In den Studien wurden verschiedene Schwächen bei den Farbschemata erkannt – manchmal mit widersprüchlichen Ergebnissen, wie höhere subjektive Zustimmung vs. geringe Wirksamkeit. Diese Schlussfolgerungen dienten dann als Grundlage für die Entwicklung eines neuen Schemas als Vorschlag für die Verwendung in Zukunft.

1 Introduction

Weather forecast maps are one of the most common types of maps presented to the public. Communicating weather and climate phenomena plays an important role both in everyday life and in current debates about weather and climate phenomena—whether for the purpose of explaining them to the public or for exploring and analyzing very large amounts of data. As weather events such as heat waves, heavy rain, or thunder storms pose serious health and economic risks and can be potentially life-threatening, cartography plays

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a vital societal role in this overall context by communicating spatial patterns to users.

This article focuses on the representation of absolute temperatures as the most important weather parameter alongside precipitation and wind. Temperature maps are widely used in atlases and scientific reports, but above all in the media due to their widespread and frequent use. They could be considered a typical example of thematic maps; however, as will be shown below (including in the literature review, Sect. 2), there are a number of special characteristics that constitute the *problem setting*—focusing on temperature maps in the media presented to public users:

- There is no uniform, generally accepted, and standardized color scheme for temperature maps worldwide.
- There are also a number of prominent color schemes that violate basic cartographic rules (such as not following the red/blue metaphor).
- There are surprisingly few contributions dealing with analytical or empirical studies that examine the intuitive recognition of temperatures from maps.
- Temperatures vary greatly across regions; a uniform color scheme might not be efficient if only part of the temperature range is used.

The *objectives* of this paper are therefore:

- To analyze the characteristics and problems of color schemes in selected temperature maps from official and journalistic sources in an analytical manner
- To derive basic design recommendations from an empirical study on the intuitive perception of temperature information, with a particular focus on users with color vision deficiencies (CVDs)
- To promote a method for developing a new color scheme as a basis for discussion and investigation

The remainder of the paper is structured as follows: An overview of previous work (Sect. 2) will substantiate and elaborate on the aforementioned characteristics and problems of temperature maps. Section 3 describes the applied mixed methodology, which consists of an analytical and an empirical study. The results and discussion of these studies, which are based on typical criteria for evaluating thematic maps (e.g., separability of colors, comprehensibility of value sequences, or consideration of associations), follow in Sect. 4. Although there can be no uniform scheme, the procedure for developing a color scheme that can meet the usual criteria will be demonstrated using an example application (Sect. 5). The contribution is concluded by a summary and an outlook on current and future (Sect. 6).

2 Previous Work

There is broad consensus that maps are an important tool for communicating climate change. Fish (2020) identified eight typical design criteria that are responsible for clear visualization, including the use of colors that should correspond to common connotations. Johannsen et al. (2018) examined the influence of map complexity and intrinsic user motivation on the understanding of maps dealing with climate change. Retchless (2014) came to the conclusion that, compared to other forms of representation (text and spatial-analog mapping), maps can lead to different assessments of climate change at the local level.

There are several publications that deal with selected design elements in weather maps. Kolejkma and Svobodova (2020) developed a typology of printed weather forecast maps in newspapers, mainly focusing on background maps. Fairbairn and Jadidi (2013) introduced the concept of visual expression, which describes the basic elements of the map (such as background, borders, zoom and overview options) and their significance for map use. However, the use of colors, apart from distinguishing between foreground and background, is not discussed in detail here. Pappenberger et al. (2019) investigated the use of cartograms for the representation of extreme weather events, e.g., distortion to reproduce temperature anomalies. Ishikawa et al. (2005) concluded in their study on precipitation forecast maps that understanding probability categories is difficult. They recommend using colors instead of diagrams.

Ware and Plumlee (2013) pursued the goal of simultaneously visualizing several weather variables (e.g., temperature, air pressure, wind speed).

Of course, conventional knowledge about colors in maps has to be considered (e.g., Slocum et al. 2022; Brewer 1994). An explicit application with temperature maps was performed by Cuff (1973). A study showed that a sequential red color scheme was more effective in conveying temperature values than a blue or red–blue scheme. The author concluded that the warm–cold association with red–blue was less important for perception.

There are also further discussions about whether a sequential monochromatic, sequential, or spectral color scheme is better suited for recognizing patterns in maps (Borland and Taylor 2007; Ware 1988). The visually quick-to-grasp sequence, which is also present in the underlying (temperature) values, speaks in favor of using sequential schemes. On the other hand, the color differences in monochromatic scales are often not sufficient for the desired number of color classes. In addition, there are semantically intuitive associations such as blue for cold and red for hot, which argue against a monochromatic scheme. Finally, visual habits should not be ignored: Most temperature maps in the media use a spectral scheme.

3 Methodology

As temperature maps can be seen as a representative of any thematic map, we can also evaluate the color schemes according to these typical criteria:

- Consideration of value range
- Recognition of graphical sequence
- Association with meaning of values
- Differentiation of colors
- Consideration of CVDs
- Aesthetics

In order to describe and evaluate these criteria, we performed an analytical and an empirical study.

3.1 Sample Data

For the analytical study, eight color schemes were selected that are characterized by different geographical regions, different temperature intervals, and different areas of application (official, online, TV; Table 1). This selection was made in the knowledge that requirements may vary (e.g., fewer classes with larger value intervals for faster detection on TV maps) and, above all, that it was not necessarily intended to be a representative sample. In a previous step, we eliminated color schemes that were very similar, if not identical, to the final selected schemes with respect to the criteria under investigation. In this way we could keep the studies manageable and avoid redundancy.

In order to limit the time required for participants, only five of the aforementioned color schemes (Table 1) were used in this study: In addition to NOAA, SAWS, tagesschau, and ABC.net, our own development ("12Tempera"; see Sect. 5) was also integrated. The particular samples were chosen because they represent the biggest variety within the parameters listed in the analytical study, such as total temperature range (SAWS vs. NOAA), range per class (2–5 °C), usage of saturation (SAWS), color difference violations being present or not, etc.

Figure 1 shows the corresponding color schemes of the samples. The media almost exclusively use spectral schemes—this is also reflected in our selection. The graphic representation is based on corresponding temperatures and proportional reproduction of the class widths. Consequently, the same color tone does not appear below another in the vertical arrangement.

Table 1 Selected color schemes for analytical study

#	Publisher	URL
Weather services		
1	National Oceanic and Atmospheric Administration (NOAA)	https://www.noaa.gov/
2	South African Weather Service (SAWS)	https://www.weathersa.co.za/
3	Deutscher Wetterdienst (DWD)	https://www.dwd.de/
Media on Internet		
4	Tagesschau	https://www.tagesschau.de/
5	*Frankfurter Allgemeine Zeitung* (FAZ)	https://www.faz.net/
6	USA Today	https://eu.usatoday.com/
7	China Daily	https://www.chinadaily.com.cn/
8	ABC.net Australia	https://www.abc.net.au/

3.2 Analytical Study

This analytical study was part of the publication by Schiewe (2023). The fundamental measures and criteria can be summarized as follows:

- *Value range:* A rough distinction can be made between considering "all" conceivable temperature values and application-specific excerpts that are necessary for regions and seasons.
- *Graphical sequence*: Plotting of calculated lightness and saturation of used colors for detecting any monotonous increase or decrease.
- *Association*: Presence of semantically intuitive assignment to colors (in particular, red for hot, blue for cold).
- *Differentiation*: The color distance ΔE00 is used for the quantitative assessment of the distinguishability of neighboring color values—with a threshold value of ΔE00 = 10 for good separability; (Brychtová and Çötekin 2017).
- *Color vision deficiencies*: For this purpose, deuteranopia (red–green CVD) is simulated using the *ColorOracle* (2023) for evaluating any increase or decrease within color recognition.

The results of the analytical study are presented together with findings from the empirical study in Sect. 4.

3.3 Empirical Study

The empirical study aimed for a comparison of effectiveness and user experience of selected color schemes to obtain insights into the intuitive recognition of temperature values and patterns. For this purpose, participants were asked questions with different difficulties, in particular:

- To identify global temperature maxima and minima from a given selection
- To count local temperature maxima and minima on a given map
- To estimate temperature differences between two given points
- To rank the five color schemes according to their reading comfort

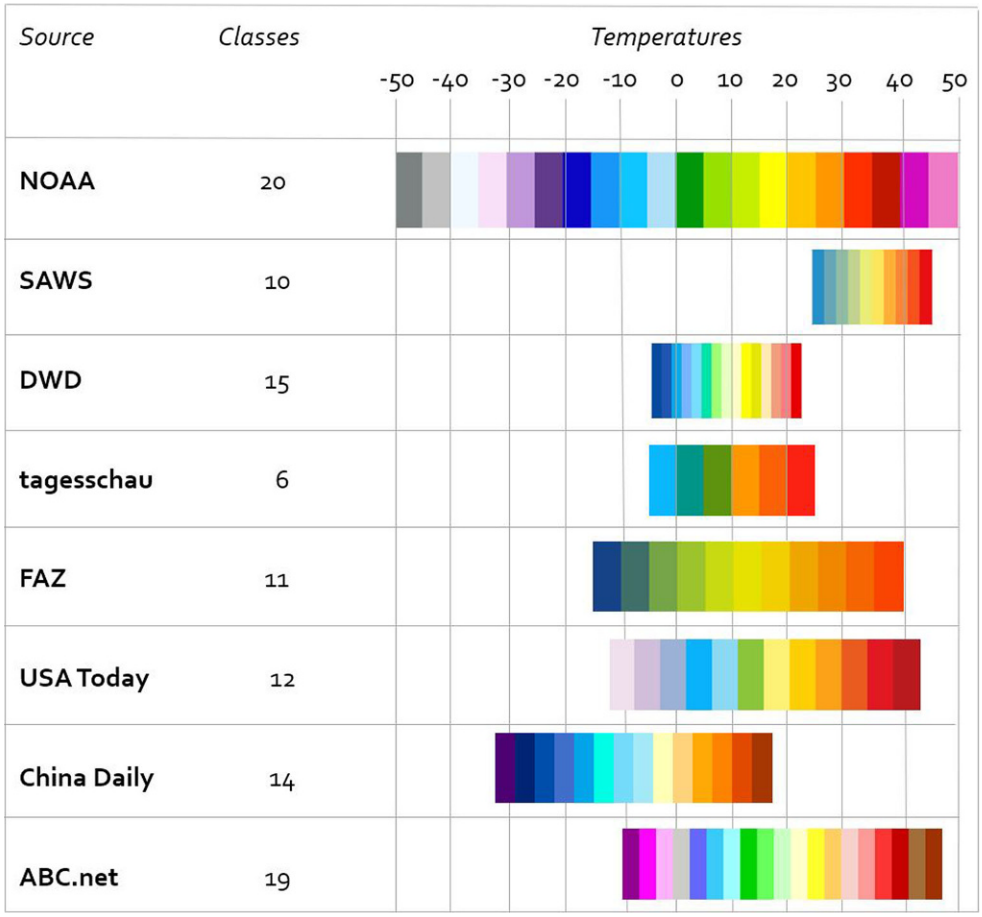


Fig. 1 Selected color schemes for analytical study. *DWD* Deutscher Wetterdienst, *FAZ Frankfurter Allgemeine Zeitung*, *NOAA* National Oceanic and Atmospheric Administration, *SAWS* South African Weather Service

Figure 2 shows an exemplary question for intuitively identifying the warmest temperature on the map, i.e., by deliberately omitting the legend. Each of the three points was marked with an arrow pointing to their exact position. The three points that participants could choose from were the global hot spot (point 2), i.e., the warmest temperature on the entire map and therefore the correct answer, another local hot spot (point 1), and a local cold spot (point 3).

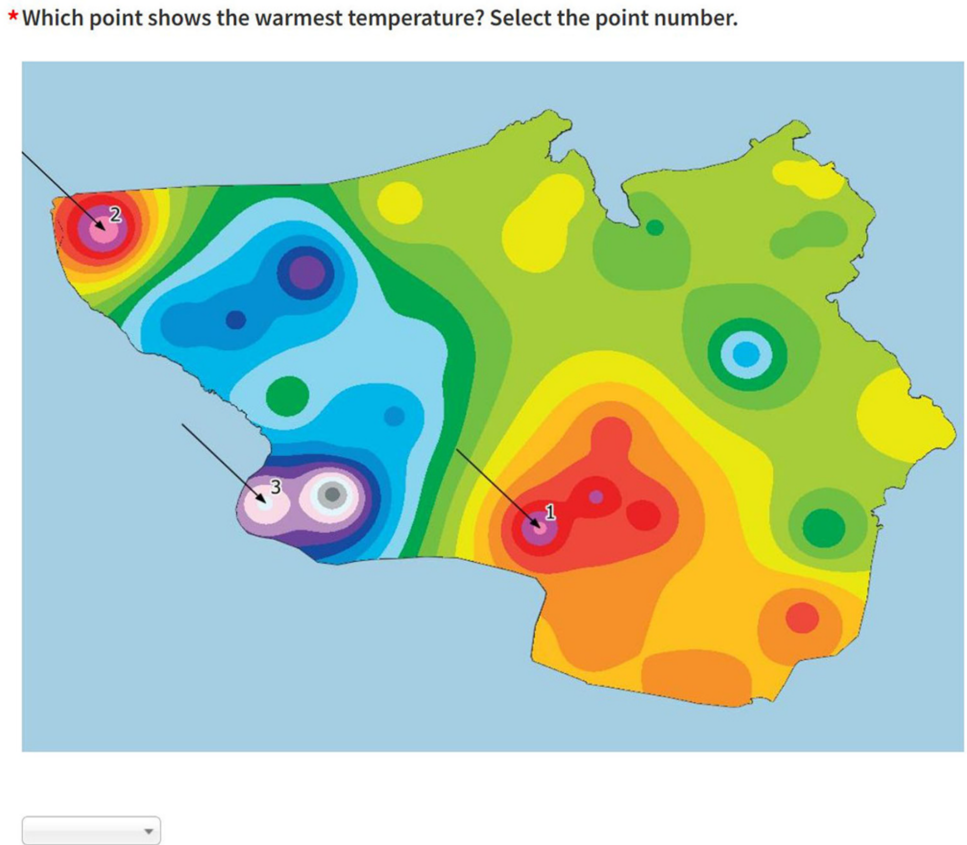
Considering the variety of accuracy in the results for the questions, we can state that some questions were easier to answer and others were more difficult to answer. For example, the questions regarding the counted cold and hot spots as well as the estimated temperature differences proved difficult.

To limit the time required for participants, only five of the aforementioned color schemes (Table 1) were used in this study: In addition to NOAA, SAWS, tagesschau, and ABC.net, our own development (12Tempera; see Sect. 5) was also integrated (Fig. 3).

The study was conducted as a Web-based format in a within-subjects design. Overall, 448 participants responded to the survey. Almost all of the participants were students from Slovenia, Germany, and the rest of Europe, and therefore younger than the average European population. Also, originating mainly from a temperate climate zone, they might show a subjective preference for temperature maps produced by mapmakers from the same climate zone (tagesschau, 12Tempera, NOAA) instead of those made by mapmakers from a different climate zone (SAWS, ABC.net). Among the 448 participants, 150 had attended courses or lectures that mentioned color schemes in choropleth maps. A total of 68 participants reported being affected by an unspecified type of CVD that was either protanopia/protanomaly, deuteranopia/deuteranomaly, tritanopia/tritanomaly, or monochromatic vision (Kolb et al. 1995). This high proportion of participants was a result of the distribution of the survey on *Reddit*, specifically on the *r/ColorBlind* subreddit (https://www.reddit.com/r/ColorBlind/?tl=de).

Details of this study are published in Hamann's master's thesis (2024). The full Smartphone version of the survey can be retrieved from https://www.1ka.si/a/ac3a5316 and the respective PC/Tablet Version from https://www.1ka.si/a/de321d52.

Fig. 2 Exemplary task in empirical user study



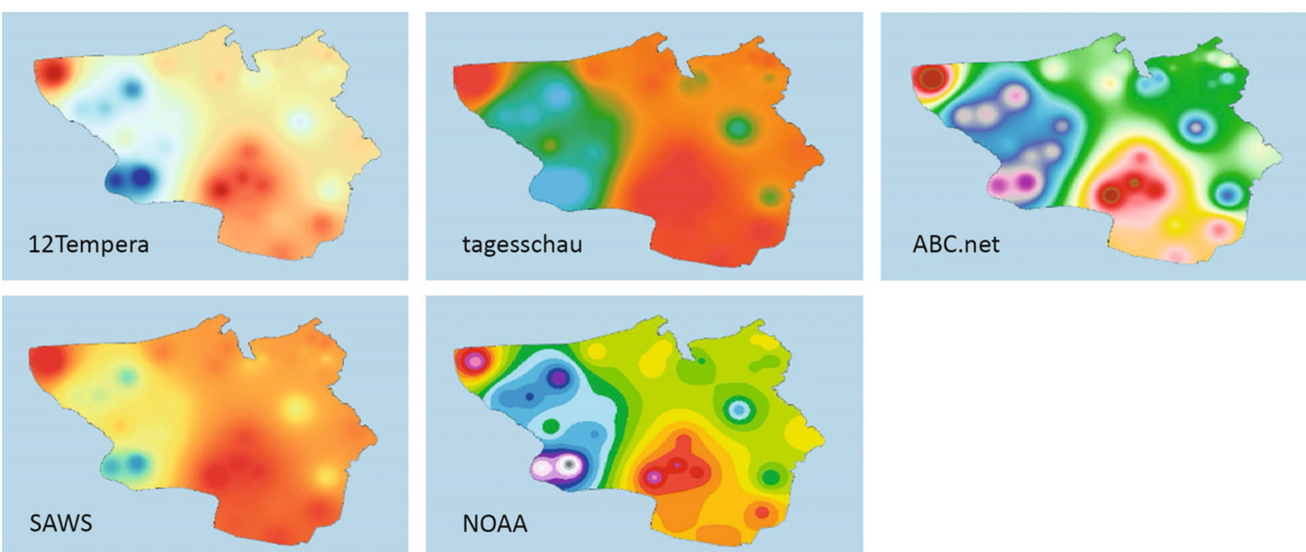


Fig. 3 Sample maps of five selected color schemes for the empirical study. *NOAA* National Oceanic and Atmospheric Administration, *SAWS* South African Weather Service

4 Results and Discussion

The aspects mentioned in Sect. 3 for evaluating color schemes for thematic maps are discussed separately here. The results of the analytical and empirical studies are summarized in each case to offer a more compact presentation.

4.1 Value Range

The range of values to be displayed depends on various specifications. In contrast to regional weather maps, weather services in particular may need to display the entire range of possible temperatures. In the examples selected

(Fig. 1), this can be seen for the NOAA scale (from –50 °C to +50 °C). It is obvious that such a large range of values necessarily entails an increased number of classes—and thus with the difficulty of finding an easy-to-understand color scheme (e.g., compare the schemes of NOAA and SAWS). All selected examples use an equidistant division. The predominant class width is 5 °C, in some cases 2 °C or 3 °C.

Furthermore, geographical differences in the actual temperatures play a role, leading to a shift in entire schemes (see, e.g., SAWS vs. DWD). Seasonal differences also have an influence. For example, the German TV news scheme tagesschau shifts the scheme to typical temperature value intervals depending on the season (Reisin and Siggelkow 2022; not shown in the figure).

4.2 Graphical Sequence

Taking into account the default setting for quantitative data, we see that sequential, single hue schemes are not used—which is meaningful because the typically large number of classes cannot be covered by such a scheme, and equally important, any color association with hot or cold temperatures is not given. Hence, spectral schemes have prevailed.

Only the NOAA and ABC.net scales, with their very high number of classes, are expanded with different shades of gray or brown, which contributes to confusion. Even though the spectral schemes have a physically based sequence, their fast interpretation is difficult for (lay) users due to the high number of classes (e.g., "Does yellow represent a higher value than green, or vice versa?").

As an important fact, the color schemes do not have clear sequences in terms of saturation or intensity values (Fig. 4: orange and gray curves), which could support intuitive ordering. Although there is often a rapid increase in saturation and/or intensity (as in the FAZ example), nearly identical and very high values around 100% are used for a very large number of entries. Only the SAWS scheme has a quasi-bipolar progression in terms of saturation (orange).

4.3 Association

Most of the color schemes under consideration follow the red/blue metaphor; however, there are exceptions (NOAA, ABC.net; see Sect. 4.2). It should also be noted that, depending on geographical or seasonal factors, red and blue tones are assigned to very different absolute temperature values. A "dark red" does not always correspond to temperatures around 30 °C (as one might assume in Central Europe, for example); instead, the examples shown use red tones for temperatures between 10 and 45 °C.

In contrast to the aforementioned study by Cuff (1973), our empirical study revealed significantly reduced comprehension for maps without the red/blue metaphor. As an example, for the task on detecting global hot spots as explained in Fig. 2, the following results were obtained (Fig. 5): The schemes 12Tempera and SAWS—both inher-

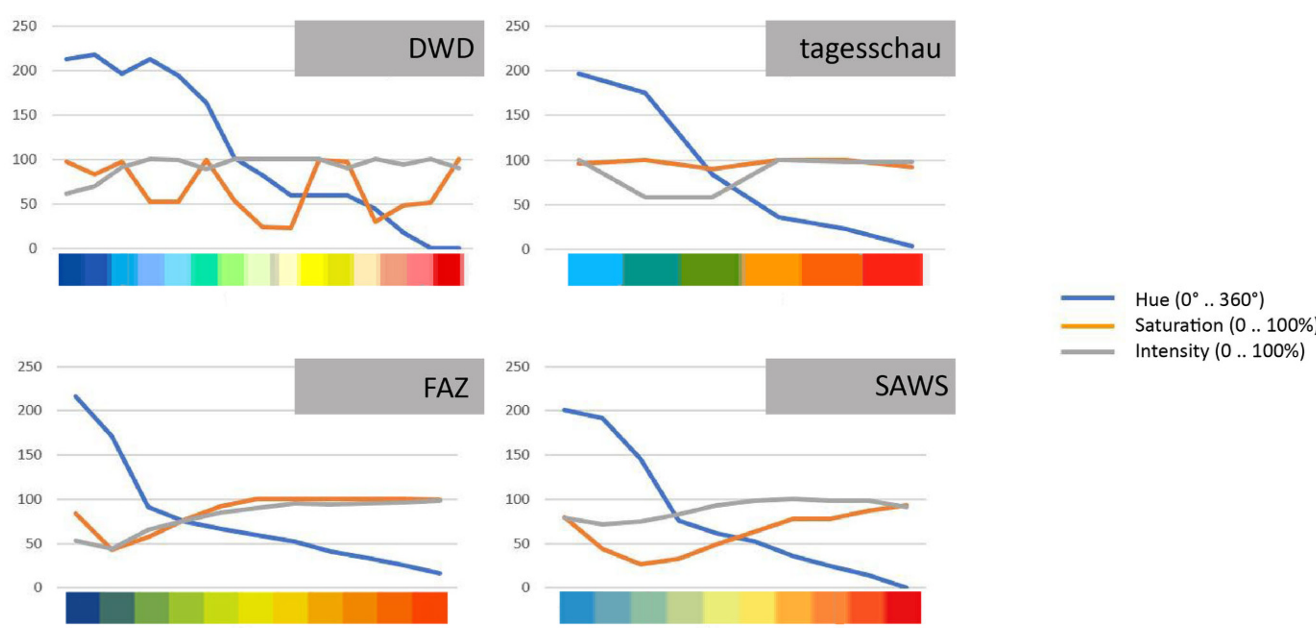


Fig. 4 Selected profiles of hue, saturation, and intensity for selected color schemes (note: upper axis uses different units according to hue, saturation, and intensity values). Strict monotonous increase/decrease is hardly visible. *DWD* Deutscher Wetterdienst, *FAZ Frankfurter Allgemeine Zeitung*, *SAWS* South African Weather Service

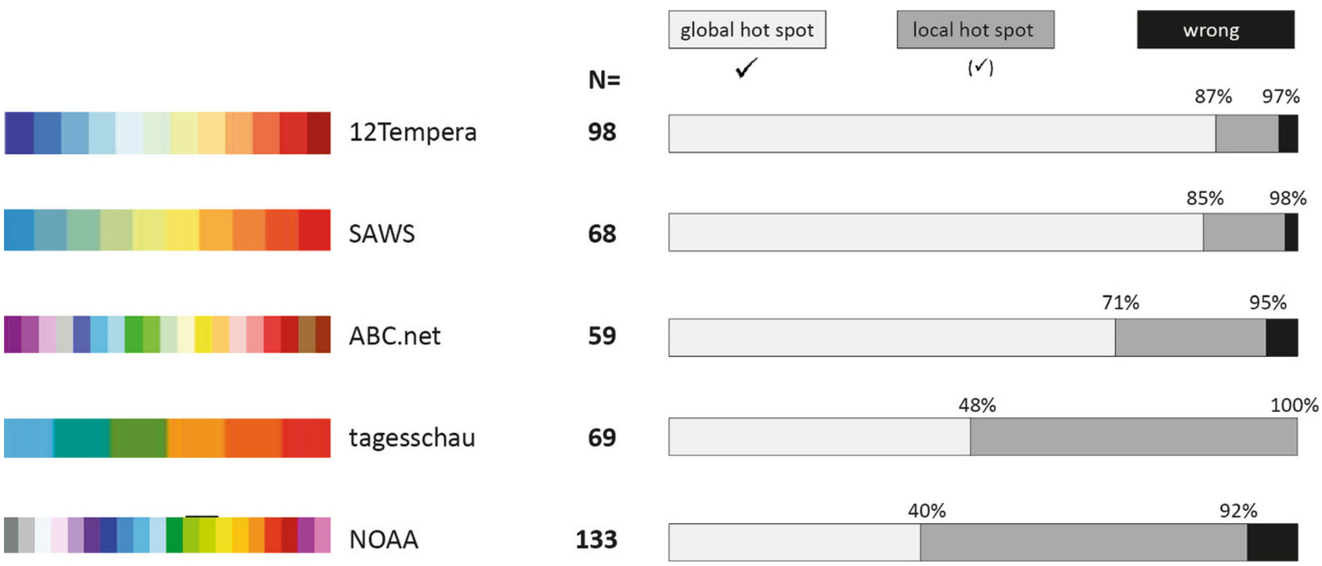


Fig. 5 Recognition rates for global hot spots (refer to task shown in Fig. 2—there, global hot spots are indicated by "2," local hot spots by "1," and wrong answers by "3"). *N* is the sample size, percentage numbers show cumulative values; thus, all bars represent 100%. *NOAA* National Oceanic and Atmospheric Administration, *SAWS* South African Weather Service

iting the red/blue metaphor—clearly show the best recognition rates for global hot spots (with 87% and 85%). On the other hand, NOAA (without the metaphor) shows the worst rates (40%).

However, it must also be taken into account that the distinction between "global" and "local" hot spots was too difficult for some test persons. If, theoretically, the detection of local hot spots is also added to the correct answers, values above 90% are obtained for all schemata. Here too, the schemata with the red/blue metaphor dominate, while NOAA performs the worst.

4.4 Differentiation

Due to the fact that a spectral, i.e., multi-color scheme is used, the problem of poor distinguishability between neighboring class colors is relatively rare. This is also evident from a quantitative analysis based on color distances ΔE00: Around 90% of class pairs are above the required threshold value of ΔE00 = 10 (Brychtová and Çötekin 2017). Figure 6 shows the pairs that do not meet this condition. However, the color distances also show quite large variances within all samples, as shown by the ratios of mean to minimum and maximum values.

The empirical study results have shown that even in those rare cases where two adjacent colors were below the color distance threshold of ΔE00 = 10, most of the participants could separate the colors. As an example, Fig. 7 (left) compares temperature estimation based on the "critical" neighboring greenish colors in the NOAA scheme with a ΔE00 below 10 (see Fig. 6) and a color pair with a ΔE00 clearly above 10. The estimation was better in the first case (no participant guessed a temperature difference of 0 °C, as expected). Also, the box plot for the first case with low ΔE00 is less scattered, which indicates a greater security. Altogether, this leads to the conclusion that the ΔE00 threshold of 10 seems to be rather pessimistic—in particular for spectral schemes for which the hue values seem to guide the differentiation.

The example in Fig. 6 (right) shows another interesting correlation—between color and the associated temperature difference: While small color differences between neighboring classes are also associated with the temperature difference between all classes (2 °C) (Fig. 6, left), larger color differences (still between neighboring classes) produce significantly higher estimates of the temperature difference (Fig. 6, right).

4.5 Color Deficiencies

The fact that spectral color schemes are used that also include red and green entries, and that no consistent, monotonous changes in saturation and/or intensity are apparent, inevitably leads to perception problems for people with most common types of CVDs. This is demonstrated in Fig. 8 for the red–green color deficiencies (deuteranopia). The simulation shows easily confused shades of green (in the middle of the schemes) and red (at the bottom) arranged in no comprehensible order. Only the SAWS scheme shows clearly recognizable gradations, but their mental transformation into sequences is made difficult by the bipolar arrangement.

Not surprisingly, in the empirical study we detected a reduced correctness of temperature spot comprehension

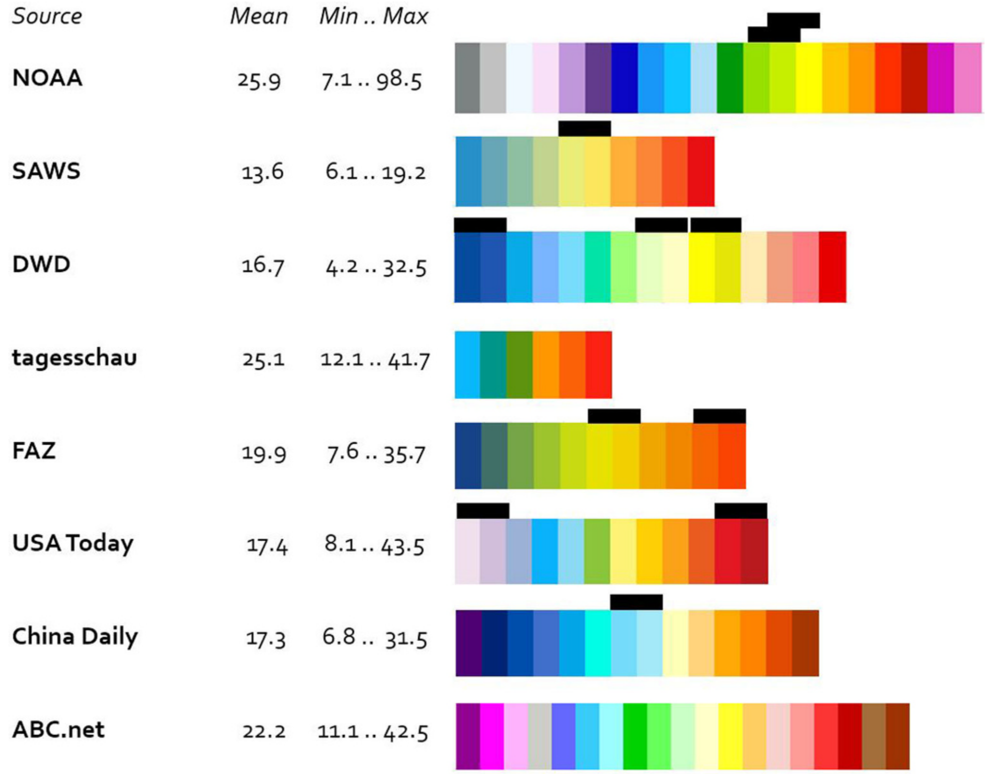


Fig. 6 Pairs of colors that do not fulfil color distance threshold of $\Delta E_{00} = 10$—marked with black bar. *DWD* Deutscher Wetterdienst, *FAZ Frankfurter Allgemeine Zeitung*, *NOAA* National Oceanic and Atmospheric Administration, *SAWS* South African Weather Service

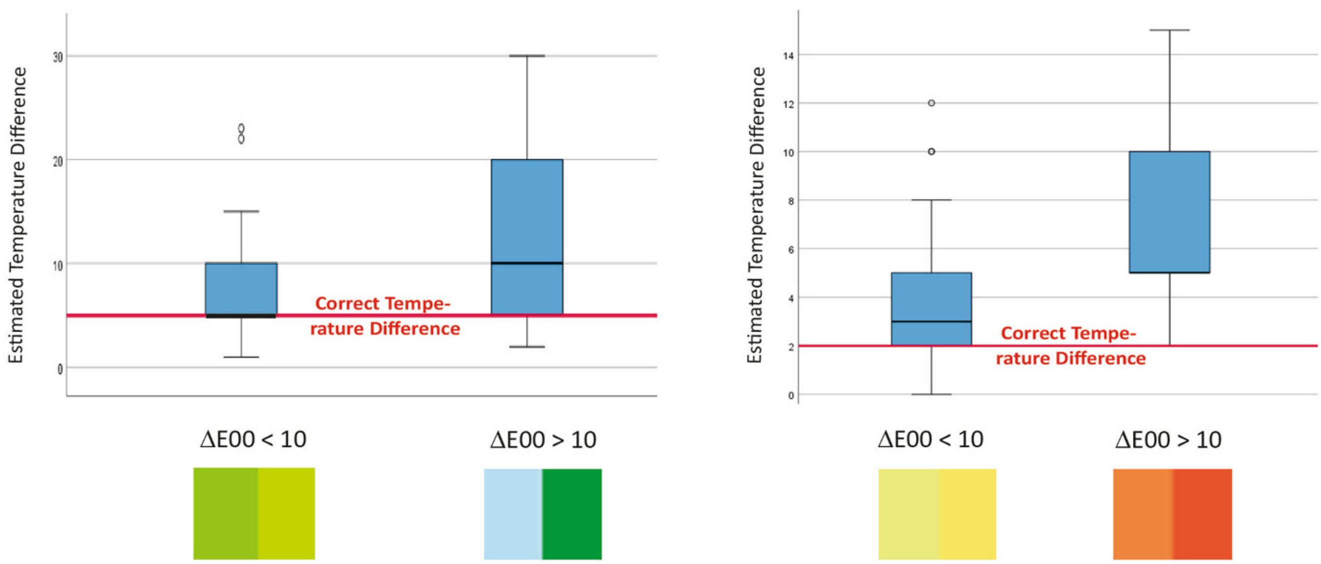


Fig. 7 Influence of color difference ΔE00 of two neighboring classes on temperature difference estimation with NOAA scheme (left) and SAWS scheme (right)—red line marks the correct difference value

among participants with CVD for schemes without any order: These three schemes (ABC.net, tagesschau, NOAA) on the left side of Fig. 9 show the largest deviations from the correct value (marked with red line).

Also, for hot spots, i.e., an agglomeration of high temperatures in a closed neighborhood, we detected a reduced effectiveness for CVD participants: Fig. 10 compares ABC.net (left, with difficult ordering of simulated colors, not following the blue/red metaphor) and SAWS (right, with well distinguishable and ordered simulated colors). This is not a surprise as we have several possible, typically extra color combinations in the left case that suggest a cluster with the same color impression although this color appears in different parts of the scheme.

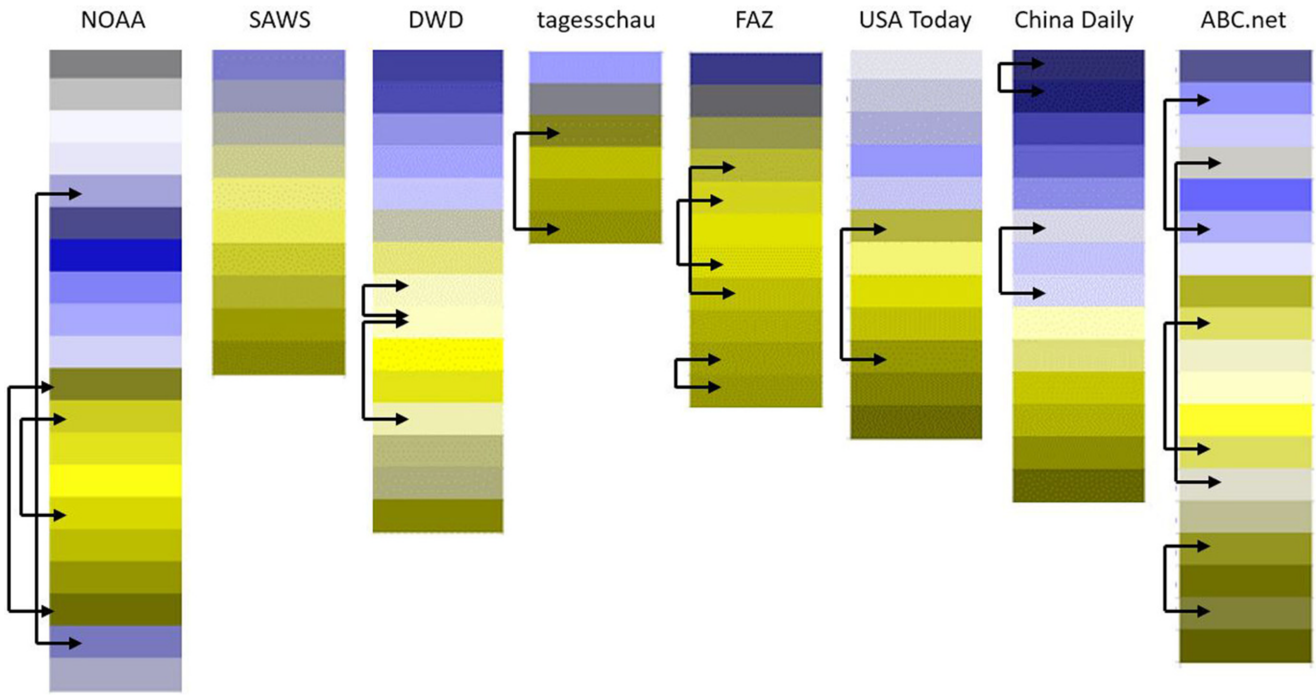
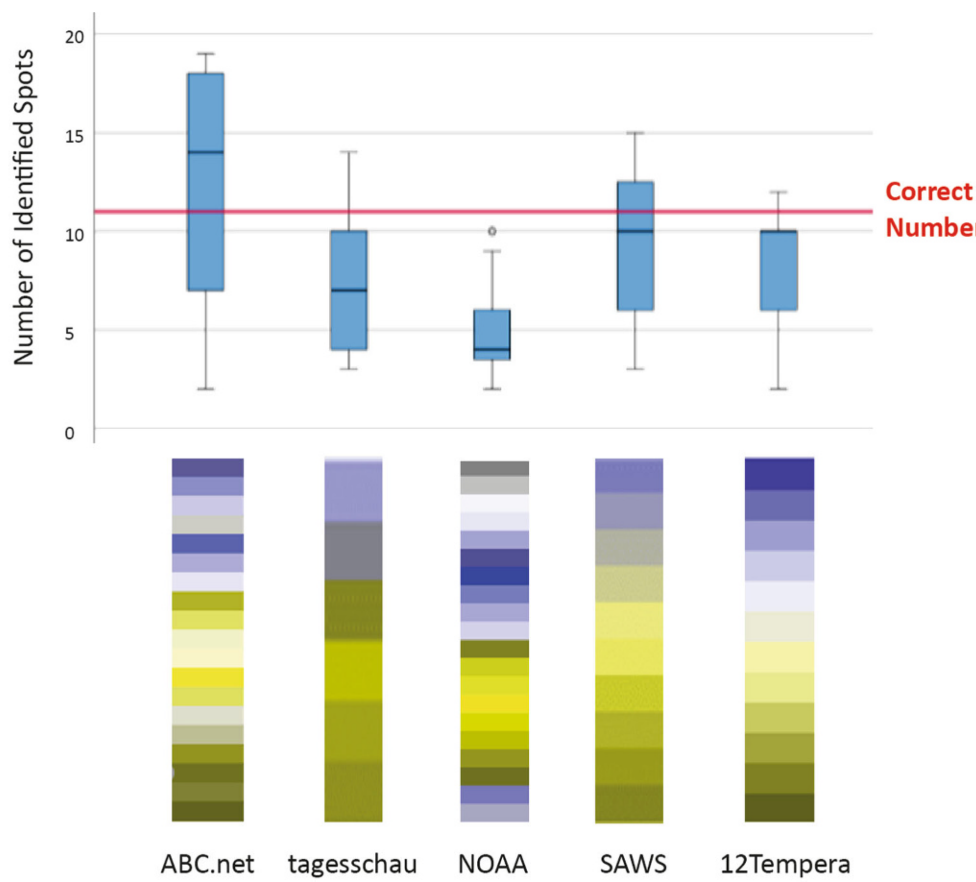


Fig. 8 Color schemes transformed to impression by persons with deuteranopia—arrows mark some of the color pairs that are hard to separate visually. *DWD* Deutscher Wetterdienst, *FAZ Frankfurter Allgemeine Zeitung*, *NOAA* National Oceanic and Atmospheric Administration, *SAWS* South African Weather Service

Fig. 9 Comparison of temperature spot comprehension depending on color scheme (red line marks the correct value). *NOAA* National Oceanic and Atmospheric Administration, *SAWS* South African Weather Service



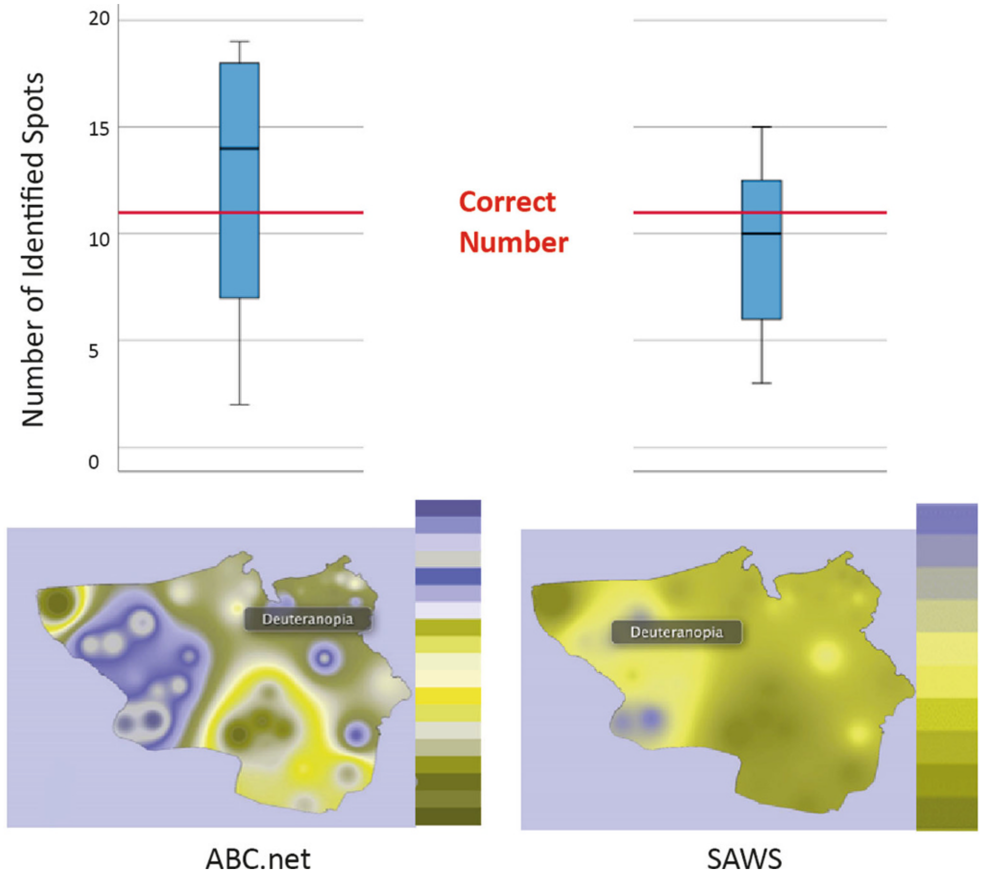


Fig. 10 Comparison of estimation of hot spots depending on color scheme (red line marks the correct value). *SAWS* South African Weather Service

4.6 Aesthetics

In addition to the measurable properties of color schemes, subjective impressions also play a role in their usage. In the empirical study, test participants were therefore also asked about the readability of the respective schemes (on a scale from 1 for "very good" to 5 for "very poor"). Figure 11 summarizes the results. Here, the color scheme 12Tempera is also considered—this is our own development, which will be described in Sect. 5.

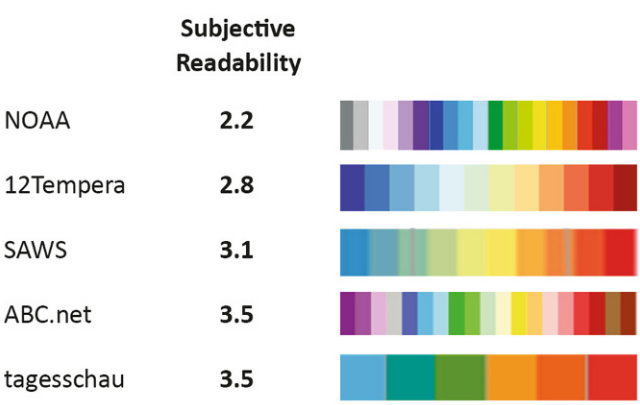


Fig. 11 Comparison of subjective impression depending on color schemes—subjective readability on a scale from 1 ("most readable") to 5 ("least readable"). *NOAA* National Oceanic and Atmospheric Administration, *SAWS* South African Weather Service

Surprisingly, the NOAA scheme scored the best—despite its poor effectiveness in the aforementioned criteria. Reasons for this may be the impressive "diversity" or wide range of temperatures displayed, the credibility of the source, or the simply the fact that people are used to such a (spectral) scheme. It should be noted that there was a large preference for NOAA among laypeople participants and only a small preference for NOAA over the 12Tempera scheme among the participants with higher cartographic experience. This contradiction between effectiveness and subjective impression has also been mentioned by Brewer et al. (1997).

In any case, there is a huge gap between emotional perception and analytical and empirical facts.

5 Proposal for New Color Scheme

5.1 Development of a Scheme

The above considerations show that there can be no optimal color scheme for use in temperature maps. Nevertheless, an

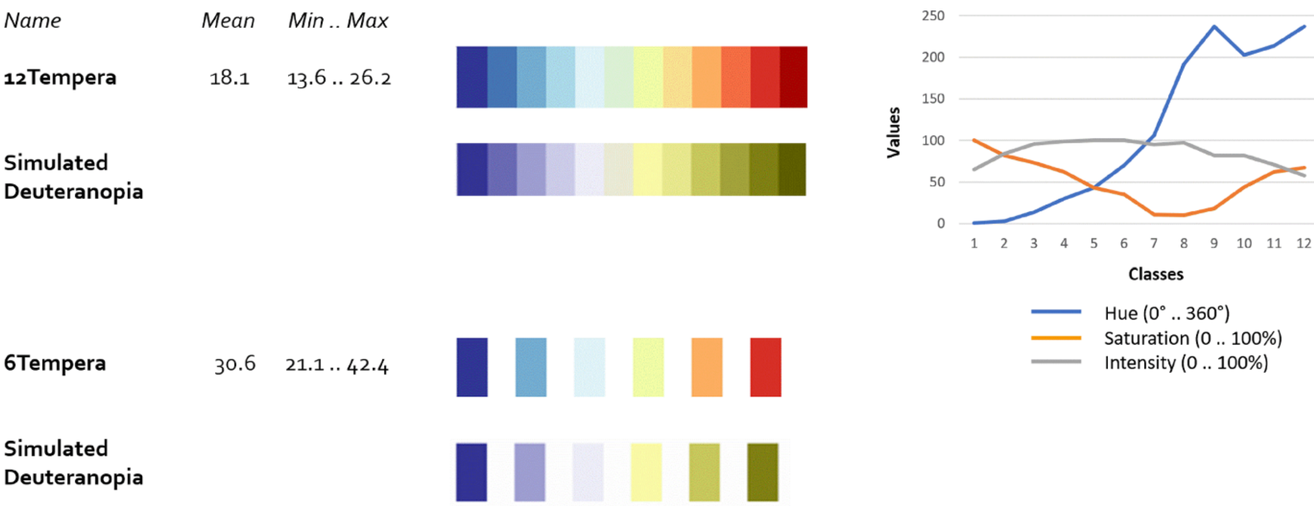


Fig. 12 Properties of new color schemes 12Tempera and 6Tempera (for diagram on the right, note: upper axis uses different units according to hue, saturation, and intensity values)

attempt should be made to find an approach that minimizes the weaknesses identified.

The established 10-class RdYeBl scheme from Color Brewer (2023) is used as a basis, as this follows well-known cartographic recommendations. This is a bipolar scheme that includes yellow tones in addition to red and blue tones. The proposed scheme (Fig. 12, 12Tempera) is created by the expansion to 12 classes through the insertion of two additional values in the greenish range. Several criteria were taken into account during fine-tuning, in particular adherence to color distances of ΔE00 > 10, avoidance of excessive ΔE00 variances between all color breaks, and an aesthetic appearance. To meet these criteria, the color, saturation, and intensity values were adjusted iteratively. Such a scheme also allows for an easy case-specific reduction to six classes (Fig. 12, lower part: 6Tempera).

5.2 Suitability of Scheme

The color scheme does not violate the ΔE00 rule and exhibits relatively low variance in ΔE00 values. The deuteranopia simulation (Fig. 12) also shows the reduced differentiation problems for people with CVDs.

In the empirical study, 12Tempera showed the highest recognition rate for global hot and cold spots among all participants with and without CVDs, as well as the second highest number of counted local hot spots (after SWS) and cold spots (after ABC). Regarding gradient line recognition, 12Tempera comes in third with a 70% recognition rate for CVD participants only (after SAWS with a 90% and ABC with an 80% recognition rate), but still showed a solid performance.

Furthermore, 12Tempera ranked second in the subjective ranking after NOAA (Fig. 10).

Overall, 12Tempera showed a good compromise between subjective impressions and special strengths on the extreme temperature visualization (which is key regarding the motivation behind this article) and the best graphical order.

6 Summary and Conclusions

Typically, sequential single-hue schemes are used for displaying data on a cardinal scale. In the case of temperature maps, however, the large number of classes cannot be covered by such a scheme, and equally important, any color association with hot or cold temperatures is not given. Hence, spectral schemes have prevailed.

The analytical and empirical analysis of selected color schemes in temperature maps revealed a variety of usability problems. In particular, it was shown that not applying the red and blue metaphor together with a diverging scheme leads to a decrease in effective usage. On the other hand, there is a surprising contradiction between effectiveness criteria and subjective impression.

The empirical study was conducted among students primarily from Germany and Slovenia. Consequently, it is not necessarily universally applicable. However, a holistic and statistically significant approach (with participants from a large number of countries) was and is not feasible for organizational reasons. We compared the subjective rankings between participants from the temperate climate zone of Central Europe (which includes both Germany and Slovenia) and participants from the subtropical climate zone (only 23 in total, mainly Erasmus students from Spain, Portugal, Italy, and Greece). Based on the number of hotspots counted and the estimated temperature differences, we were unable to identify any significant preference among participants from the temperate climate zone for color schemes developed by designers from the temperate climate zone (tagesschau, 12Tempera, NOAA) or among participants from the subtropical climate zone for subtropical color schemes (ABC, SAWS).

As mentioned, special emphasis was placed on users with protanopia/protanomaly, deuteranopia/deuteranomaly, tritanopia/tritanomaly, or monochromatic vision. On the one hand, no further distinction regarding these deficiencies was made (as the numbers of participants did not allow for statistically significant conclusions to be drawn). On the other hand, additional vision deficiencies based on eye diseases were not considered. Both aspects can be part of further research.

In some cases, color schemes are changed according to the seasons. For example, the tagesschau scheme actually has four "different" color scales, each covering only part of the value range. This means that 5 °C, for example, is shown in blue in summer and in yellow or orange in winter. This naturally makes comparisons between seasons more difficult and can lead to confusion among users. On the other hand, comparisons over several weeks or months are not a typical task when viewing television temperature maps. Future studies should examine possible confusion in more detail. In addition, it is necessary to investigate how to react best to the extending temperature color scales in response to rising temperature extremes (e.g., adding new colors such as purple or black).

It should be noted that it is not possible to design one universally "perfect" color scheme due to the different requirements concerning value range, temperature resolution, etc. It also seems difficult to improve the existing color schemes, as some framework conditions (such as temperature differences between classes, or overall value range) and the traditional "look and feel" are difficult to change. Nevertheless, possible partial adjustments (e.g., omitting greenish colors, or taking the red/blue metaphor into account) should also be considered here. On the other hand, the proposed 12Tempera scheme, with its now proven color vision deficiency-friendly color composition and versatile adaptability to varying temperature ranges, fulfills most of the conditions for practical perception—however, the aspect of user habit for sustainable use must also be taken into account.

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Conflict of interest J. Schiewe, K. Hamann and D. Petrovič declare that they have no competing interests.

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