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Assessment of the quality of colour scales: a case study "Landscape Atlas of Czech Republic"

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Abstract: The atlas, as a typical product of thematic cartography, is characterized by cohesive approaches in the procedures of atlas compilation. One of the results of these cohesive approaches is the uniform setting of colour scales in choropleth maps. The paper aims to evaluate the quality of colour scales in choropleth maps in an atlas from the point of view of systematic visualization, using the example of the electronic version of the Landscape Atlas of the Czech Republic. A total of 56 sequential and 6 divergent colour scales were selected from the Atlas. Seven hypotheses related to colours were formulated and then tested. The paper assumes that the colour scales in the atlas are not uniformly constructed. The authors hypothesise the approach by which the creators of the atlas chose these colours. In the CIELAB colour model, the colour distances between the colours of the intervals were measured, calculated, statistically evaluated and graphically expressed. The colour scales were also evaluated against the background of the map sheets. The results revealed the nature of the approach of the authors of the Atlas when compiling colour scales of choropleth maps. The aim of the paper was also to define the criteria for evaluating the quality of colour scales and to formulate recommendations for the compilation of colour scales. These recommendations should help map makers to create high-quality atlas maps and users to get more accurate and faster information from maps.

Keywords: colour scales, colour distance, atlas

1. Introduction

People prefer colour maps to black and white ones. Colour represents one of the key means of expression in cartography. It is a dominant visual variable that affects the readability of maps (Stigmar, 2010), expands the possibilities of the map language and can provide additional information about the object on the map (Bertin, 1967). The development of digital technologies in the visualization of spatial data required the compilation of colour models (sometimes referred to as colour systems) that would express colours numerically. However, there are a large number of pitfalls that electronic products have about to with concerning the user perceptions. For example, Brewer (2016) draws attention to perceptual colour systems and the influence of the background on colour scales. It is difficult to distinguish a colour on a map that is only in a small area surrounded by a large area of another colour. Çöltekin and Brychtova dealt with the influence of colour spacing and font size when reading maps (Brychtova, Coltekin, 2015).

The paper focuses on choropleth maps and tries to contribute to the correct creation of colour scale sets for atlas works (Vondrakova, Vozenilek, 2016).

2. Objectives

The aim of the paper is to evaluate the quality of colour scales of choropleth maps in the atlas from the point of view of systematic visualization using the example of the electronic version of the Landscape Atlas of the Czech Republic. Systematic visualization is a set of interrelated approaches for visualizing spatial information by various cartographical techniques with respect to the structure and behaviour of systems. The requirement for the solution was to use the measurement of colour distance in the CIELAB model and to reveal the approaches of the authors of the Atlas to the creation of colour scales of choropleth maps. An additional goal was to find out whether there is colour sinking in the Landscape Atlas of the Czech Republic and whether even the background colour can reveal this error. Colour sinking is a situation where the colour intensity of the subsequent interval is lower, while the value of the phenomenon is higher (and the colour intensity should correspond to it, i.e. be higher) (Fig. 1).

CIELAB is a device-independent colour model, which means that results are consistent regardless of where and how colours are imaged (Brychtova, 2016). The CIELAB model measures the colour distance between two colours using three values, which are expressed as numbers that fall within a range and can be easily compared to other values within the same model. CIELAB allows the differences between colours to be described in human visual perception, thus better matching the perception of colour differences and allowing for more accurate colour distance measurements.

The "Landscape Atlas of the Czech Republic" (Hrnčiarová, Mackovčin, Zvara, et. al., 2009) consists of a large set of traditional and newly composed landscape

maps, each in a digital form. The Atlas is the first comprehensive atlas of the environment of the Czech Republic and its population and characterizes the state of landscape and human society at the dawn of the 21st century.

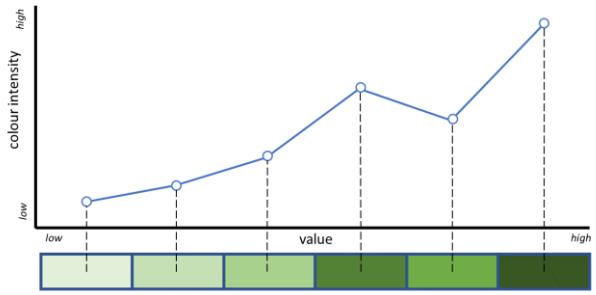

Figure 1 Colour drop in the sequential colour scale between the 4th and 5th interval, where the colour intensity of the subsequent interval is lower, while the value of the phenomenon is higher (and the colour intensity should correspond to it, i.e. be higher).

The Landscape Atlas of the Czech Republic is the up-to-date national atlas of Czechia in its concept and scope. Since its release it has had a very wide use and thanks to its easy accessibility the maps of the Atlas are often used without any modifications. It is a template for many choropleth maps. As the authors of this article are not the authors of the atlas maps evaluated, this is an external evaluation required by current Czech cartography.

The Atlas is a large-format publication 332 pages long and contains 906 maps and 767 pieces of additional material. Atlas is divided into 8 chapters and covers a variety of topics ranging from the location of the state territory in Central Europe, the history of Czech landscapes, contemporary natural conditions, socio-economic conditions, landscape as the heritage, present-day environmental problems, and Czech landscapes in art (paintings in oil on canvas). A majority of the maps in the Atlas present data on the county level (basic map scale 1: 500,000) but there are also large-scale maps and choropleth maps of selected landscapes, towns, and environmental problems. Many topics are presented for the first time (limits and potential of landscapes, stresses in landscapes, etc.). The book and its digital version are modern, colour, and include a variety of map styles and geodata visualization techniques. The Landscape Atlas of the Czech Republic has all the attributes of the national atlas.

3. Methods

3.1 Theoretical background

The concept of quality of colour scale wasn't so far unequivocally defined. In general, it can be deduced that the quality of the colour scale is a reflection of the number of intervals, choices of colour hue, and colour distances between intervals.

Colour distance is a quantity describing the difference between colours of two intervals. A principal approach to achieve the paper's objectives was the calculation of colour distances in the colour model CIELAB with colour parameters L* (brightness), a* (hue between red and green), and b* (hue between blue and yellow) (Brychtova, Coltekin, 2015). Calculation of colour distance ΔE_{00} was performed according to formula (1).

$$\Delta E_{00} = \sqrt{(L_2 - L_1)^2 + (a_2 - a_1)^2 + (b_2 - b_1)^2} \qquad (1)$$

Brewer (2016) describes the parameters of the colour scale, type, hue, and influence of the background. In her application "ColourBrewer 2.0" (https://colourbrewer2.org/), she manages a choice of colour scale of three to nine intervals. Brychtova (2016) evaluated colour distances in sequential scales from the application ColourBrewer 2.0 and found that colour distances between individual scales are not constant. This is despite the fact that ColorBrewer includes "learn more" tutorials to help users get their bearings, encourages them to test colour schemes as maps and legends, and provides output in five colour specification systems (Harrower, Brewer, 2003). That's why Brychtova created a tool for the compilation of colour scale "Sequential Colour Scheme Generator" (http://eyetracking.upol.cz/colour/), which allows the users choice colours of the first interval and colour, define what kind of direction colours of the subsequent intervals should proceed. The Sequential Colour Scheme Generator offers the possibility to set the number of intervals and colour distance between intervals.

Brewer (2016) does not recommend using pre-set colour scales in geographic information systems. User preferences for spectral and divergent maps were investigated by Brewer et al. (1977). They confirmed that the preference for colour scales is influenced by the level of clustering within the mapped distributions. Map users preferred spectral and violet-green hue combinations in divergent scales. Even Brychtova (2016) adds that graphic programs with colour management support are more suitable for colour selection, which ensures the reproducibility of colours. Both authors recommend their tools for creating colour scales.

The number of intervals in the colour scales has been solved by many authors, e.g. Dent et al. (2009), Beitlova et al. (2020), and . Mersey (1990) found, by testing scales with 3, 5, 7, and 9 intervals, that the effectiveness of the map decreases as the number of intervals increases, and that 9 intervals is a limiting number.

3.2 Procedure of processing

A total of 62 colour scales measured on screen (at calibrated monitor) from choropleth maps of the digital version of the atlas were selected from the Landscape Atlas of the Czech Republic for assessment. The selection included both sequential and divergent scales. If a group of maps with the same colour scale with the same number

of intervals occurred in the Atlas, the scale was considered only once. An inventory of selected scales was created, in which each scale was named according to the Atlas section and the order of the map in the section. In addition, the name of the map, the territory shown on the map, the map scale, the hue of the scale, the number of intervals in the scale, and the type of scale (sequential/divergent) were recorded.

As Vozenilek and Vondrakova (2017) considered, when reading maps, not only the colour distance from the white colour is essential, but also from the background colour (the colour of the map sheet). To determine the effect of the background colour on the colour scales, the colours of the intervals in the scales were compared with the background colours in all Atlas sections and at the same time with the white colour in the digital file.

An undesirable colour dipping was also found, where the intensity of the colour shade does not increase but decreases for adjacent intervals in the scale as the value increases. If the optical weight within the scale decreases, the foreground-background effect is disturbed and the map can easily be misinterpreted. This problem is also mentioned by Brewer (1996, 1997) in the context of simultaneous contrast when developing a quantitative model of simultaneous contrast (induction) to aid the selection of sets of easily identified map colours. Brewer found through user experiments that colour reading time was significantly slower and more erroneous for maps where colours were misinterpreted. Colour reading and error rates improved significantly when the colours were corrected on the map.

Therefore, hypotheses H1 and H2 were formulated, and to accept them, the colour distances between all intervals from the white colour (proving that the scale is correctly constructed) and from the background colour (proving that the placement of the scale on a coloured page does not spoil the readability of the scale) were calculated. The sequence of these values was recorded within the individual scales.

- H1: the colour distance of the colours of the intervals of the sequential scale with the intensity of the phenomenon from the white colour increases or decreases
- H2: the colour distance of the colours of the sequential scale intervals with the intensity of the phenomenon from the background colour increases or decreases

Hypotheses H3 and H4 were formulated to determine the colour distance between the colours of all intervals. According to Brychtova and Coltekin (2015), a value of $\Delta E_{00} = 2$ was chosen as the smallest discernible value for the user, and a value of $\Delta E_{00} = 24$, as the limit of the largest subjective perception of colour distance (Yang et al., 2012).

- H3: the colour distance between interval colours is greater than 2
- H4: the colour distance between interval colours is less than 24

For each section in the Atlas, the minimum and maximum colour distance between the colours of the intervals, as well as the geometric mean and the median of the colour distances between the colours of the intervals, were determined as the most important indicators for the characteristics of the Landscape Atlas of the Czech Republic.

Hypothesis H5 was formulated to determine the influence of the background colour to the first interval of sequential scales (the lightest).

- H5: the perception of the first interval colour of the sequential scales is influenced by the background colour

In confirming hypothesis H5, the colour distances of the first interval to white colour and to the background and the connection between the brightness of the first interval and the background brightness were compared.

When examining the colour distance between intervals by the number of intervals, the sequential and divergent colour scales were divided by the number of intervals. In the Landscape Atlas of the Czech Republic, 10 variants of the number of intervals were used. Two hypotheses were formulated:

- H6: the colour distance between the colours of all intervals in the sequential scales decreases as the number of intervals increases
- H7: the colour distance between the colours of interval in divergent scales decreases with the increasing number of intervals.

To prove the hypotheses, the value of the median colour distances between the colours of the intervals was calculated for each variant of the scale according to the number of intervals in sequential and divergent scales. Furthermore, the course of the median was determined with an increasing number of intervals in the scales.

4. Results

4.1 Quality of colour scale

Of the total number of 62 scales in the Atlas, 56 are sequential and 6 divergent, but the number of intervals differs for individual scales (Fig. 2). In sequential scales, there are 3 to 17 intervals, most often 5 intervals (33x), in divergent scales only 7, 8 and 14 intervals, most often 7 intervals (3x).

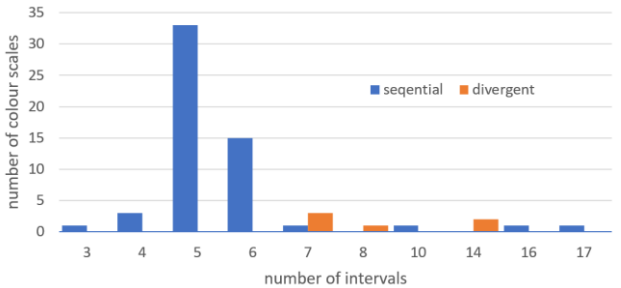

Figure 2 Frequency of sequential (blue) and divergent (orange) scales by the number of intervals

Sequential scales were divided by hue (Table 1) based on calculated hue angles from a* and b* values converted to a plane. Scales with an angle difference of up to 45 ° were classified as monochromatic scales, multichromatic scales with a hue difference of 45 ° to 180 ° and spectral scales with an angle difference greater than or equal to 180 ° were included. Divergent scales were distinguished into threshold-value scales and threshold-range scales.

sequential by hue	number	divergent by threshold	number
achromatic	0	threshold-value	5
monochromatic	39	threshold-range	1
multichromatic	15		
spectral	2		

Table 1 Types of sequential and divergent colour scales

Monochromatic and multichromatic sequential scales were categorised according to the predominant hue into 8 categories (red, red-yellow, yellow, yellow-green, green, green-blue, blue, and bluish-red (Fig. 3). Most monochromatic scales (Table 2) were compiled in yellow hues (12x), red-yellow (10x) and yellow-green (10x). Among multichromatic scales (tab. 3), the most numerous were the scales with a transition from yellow to a red-yellow tone (11x). Among divergent scales, the most numerous was a scale with a transition from blue to red (3x).

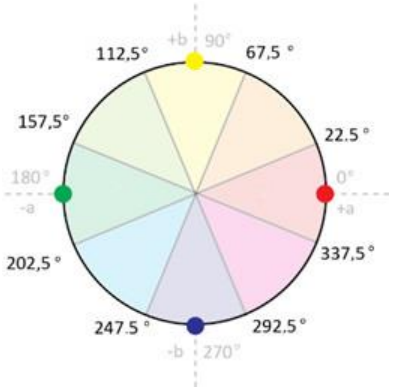

Figure 3 Distribution of hues in the a* b* plane according to the angle in the CIELAB colour model

Hue	hue angle	number
red	0 ° – 22.5 °; 337.5 ° – 360°	1
reddish yellow	22.5 ° – 67.5 °	10
yellow	67.5 ° – 112.5 °	12
yellow-green	112.5 ° – 157.5 °	10
green	157.5 ° – 202.5 °	3
greenish blue	202.5 ° – 247.5 °	1
blue	247.5 ° – 292.5 °	1
bluish-red	292.5 ° – 337.5 °	1

Table 2 Numbers of monochromatic sequential scales by hue

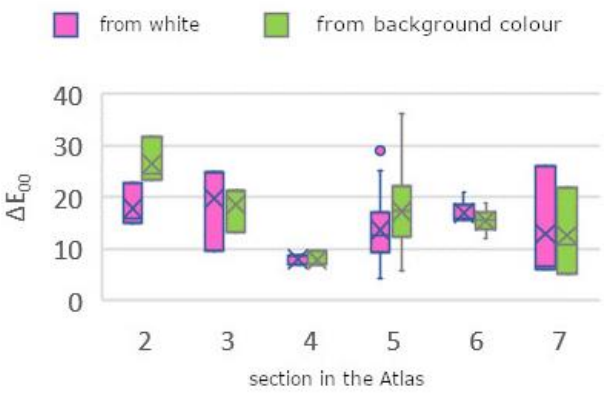

Figure 4 Colour distance of the first interval in the sections of the Landscape Atlas of the Czech Republic

For the sequential scales, the smallest colour distance of the first interval from white reached ΔE00 = 4.28, the median ΔE00 = 13.28, and the smallest colour distance ΔE00 = 5.05. The median colour distance from the background of the sequential scales is ΔE_{00} = 16.66. The background colour was not found to affect the colour of the first interval. The diversity of colour distances of the first interval in the sections is shown in the graph (Fig. 5).

Transition of hues	number
yellow to red-yellow	11
yellow-green to green	2
green-blue to blue	2

Table 3 Number of multichromatic sequential scales by hue

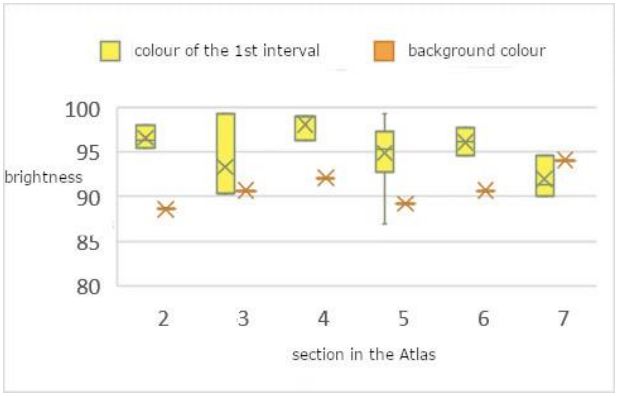

Figure 5 Brightness of the colour of the first interval and the background colour in the sections of the Landscape Atlas of the Czech Republic

In most cases, the brightness of the first interval is higher than the background brightness. For seven scales, the background brightness has a higher value. The correlation coefficient of the relationship between the brightness of the first interval and the background brightness (-0.09) refutes the linear dependence (hypothesis H5 not confirmed).

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4.2 Background

The number of selected scales in individual sections distinguished by background colour (colour of my sheet) is uneven. The highest number of selected scales is in the fifth section, Contemporary landscape, where there are many choropleth maps with demographic data. In the *A*tlas, each section has a different background (Table 4).

Section	background colour	hue	number of scales
1	90.7; 3; 8	yellow	0
2	88.6; 1.1; -7.7	blue	4
3	90.7; 6.2; 7.7	red yellow	4
4	92.1; -4.8; 5.2	yellow-green	3
5	89.2; 5.1; -4.6	bluish-red	46
6	90.7; -4.5; 1.1	green	2
7	94.1; 4; 8.4	red yellow	3
8	92.2; -0.8; 4.5	yellow	0

Table 4 Chapters and their background colours in CIELAB

The sinking in the colour intensity of the intervals of the sequential scales related to the white colour was found in the Atlas only rarely in 4 scales. The sinking is caused by a large number of intervals and an inappropriate change in colour intensity. For the other scales, it was shown that the value of the colour distance from the white colour increases, which confirms that there is no sinking of colours (hypothesis H1 confirmed). The colour distance from the background colour was determined for 15 sequential scales. The influence of the background colour on the colour distances of the scales for the three scales was not proven (hypothesis H2 not confirmed). The average range of colour distance values of the interval colours from the background colour is smaller than the range of colour distance values of the interval colours from the white colour in all sections.

4.3 Colour distances between interval colours

The determined values of the minimum and maximum colour distances between the colours of the intervals, the geometric mean and the median of the colour distances between the colours of the intervals (Table 5) prove that the colour distance $\Delta E_{00} < 2$ was not used in the Atlas (hypothesis H3 confirmed).

Characteristics of colour distance of intervals				
section	min	max	geometric mean	median
2	2.29	12.56	5.71	5.71
3	2.49	26.12	8.70	7.15
4	3.75	17.97	7.91	7.39
5	3.94	26.25	8.29	8.27
6	4.01	12.63	6.94	6.59
7	3.45	23.28	8.19	9.70

Table 5 Characteristics of the colour distances between the colours of the intervals in the sections

The smallest colour distance between intervals reached the value ($\Delta E_{00} = 2.29$) for a sequential scale with 14 intervals. Conversely, the highest measured distance ($\Delta E_{00} = 26.25$) was measured on a scale with 5 intervals. Colour distances $\Delta E_{00} > 24$ appear in the Atlas (hypothesis H4 not confirmed).

For sequential scales, the value of the median colour distances between intervals decreases from a three-interval scale to a seven-interval scale (Table 6). Sequential scales with the number of intervals 10, 16, and 17 have a more significant median value than scales with a lower number of intervals (hypothesis H5 not confirmed). For divergent scales, the value of the median colour distances between intervals is the highest for a scale with seven intervals, and subsequently, this value decreases (hypothesis H6 confirmed).

number of intervals	Sequential scales		Divergent scales	
	number of scales	median	number of scales	median
3	1	21.97	0	-
4	3	8.77	0	-
5	33	8.68	0	-
6	15	6.85	0	-
7	1	4.37	3	8.42
8	0	-	1	8.09
10	1	7.39	0	-
14	0	-	2	5.26
16	1	8.06	0	-
17	1	7.84	0	-

Table 6 Median of colour distances between colours of intervals by number of intervals in sequential and divergent scales

4.4 Evaluation of the Landscape Atlas of the Czech Republic

The Landscape Atlas of the Czech Republic is a crucial cartographic product applying various concepts in the completion of colour scales. Based on the statistical evaluation of the scales, the characteristics of the colour scales of the Landscape Atlas of the Czech Republic were compiled.

Sequential scales show the following characteristics in the Atlas:

- the scales have mostly 4, 5 or 6 intervals,
- in all colour scales, the colour distance between colours of intervals is greater than 2,
- the colour distance of the colours of the intervals from the white colour of the sequential scales increases or decreases with the intensity of the phenomenon,
- the colour distance of the interval colours from the background colour of the sequential scales varies.

In addition, the properties of the divergent scales were:

- the colour distance of the intervals of the divergent scale from the white colour is the lowest at the border interval or at intervals exceeding the border value.

It is necessary to consider all the properties of colour scales before starting to create scales. Additional adjustment of one parameter is not always possible (Popelka, Vozenilek, 2013). At the same time, it is advisable to compile scales on the colour of the background, as its influence on colour distances has been proven.

5. Conclusion

The characteristics of the colour scales from the Landscape Atlas of the Czech Republic were evaluated based on 7 hypotheses. After the statistical evaluation of the measured colour distances, 3 hypotheses were confirmed, and 4 hypotheses were not confirmed. Hypothesis H1 confirmed that the colours of the intervals do not sink in the scales and that they correspond to the intensity of the phenomenon. The value of the smallest colour distance between the colours of the intervals in the Landscape Atlas of the Czech Republic is confirmed by hypothesis H3. This means that all adjacent colours of the intervals in the scales are sufficiently different to be distinguishable by the human eye. By evaluating the hypotheses, it was proven that most of the colour scales in the Atlas are compiled more or less correctly and do not significantly violate the set cartographic rules.

The Landscape Atlas of the Czech Republic is a very diverse product in terms of colour scales. Four unconfirmed hypotheses document the authors' different approaches to creating scales. Nevertheless, it is necessary to point out that user testing can supplement the results (Ireinova, et al., 2021). The results cannot be applied to the printing of the Atlas, because the reproduction of colours in printed form is affected by many factors – the printer and its colour space, paper, lighting and others (Vozenilek, Vondrakova, 2018).

Based on all the findings, revised colour scales were created for three maps with adjustments to selected parameters. Analyses of colour scales resulted in compiling recommendations for creating colour scales of choropleth maps in 12 items.

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6. References

Beitlova, M., Popelka, S. and Vozenilek, V. (2020). Differences in Thematic Map Reading by Students and Their Geography Teacher. ISPRS International Journal of Geo-Information, 9(9), doi:10.3390/ijgi9090492

Bertin, J. (1967). Sémiologie graphique: Les diagrammes, les réseaux, les cartes. Paris: Gauthier-Villars.

Brewer, A. C. (2016). Designing better maps: a guide for GIS users. 2nd ed. Redlands, Calif.: ESRI Press.

Brewer, C.A. (1996). Prediction of Simultaneous Contrast between Map Colors with Hunt's Model of Color Appearance. Color Research and Application 21 (3):221-235.

Brewer, C.A. (1997). Evaluation of a Model for Predicting Simultaneous Contrast on Color Maps. The Professional Geographer 49 (3):280-294.

Brewer, C.A. et al. (1997): Mapping Mortality: Evaluating Color Schemes for Choropleth Maps. Annals of the Association of American Geographers, 87(3): 411-438.

Brychtova, A. (2016). Colour distance in cartography. Olomouc: Palacký University, Terra notitia.

Brychtova, A. and Coltekin, A. (2015). An Empirical User Study for Measuring the Influence of Colour Distance and Font Size in Map Reading Using Eye Tracking. The Cartographic Journal, Maney Publishing, doi: 10.1179/1743277414Y.0000000101

Dent B.D., Torguson, J. and Hodler, T. W. (2009). Cartography: thematic map design. 6th ed. Boston, Mass.: McGraw-Hill Higher Education,.

Harrower, M., Brewer, C.A. (2003). ColorBrewer.org: An online tool for selecting colour schemes for maps. Cartographic Journal 40 (1):27-37.

Hrnčiarová, T., Mackovčin, P. and Zvara, I. et. al. (2009). Landscape Atlas of the Czech Republic / Atlas krajiny České republiky. Praha, Ministerstvo životního prostředí České republiky, Průhonice: Výzkumný ústav Silva Taroucy pro krajinu a okrasné zahradnictví.

Ireinova, M., Vozenilek, V., Vondrakova, A. and Konicek, J. (2021). Mapping, synthesis and visualization of Czech dialects. International Journal of Cartography, doi: 10.1080/23729333.2021.1978039

Mersey, J.E. (1990). Colour and thematic map design. The Role of Colour Scheme and Map Complexity in Choropleth Map Communication. Cartographica, Toronto: University of Toronto Press.

Popelka, S. and Vozenilek, V. (2013). Specifying of Requirements for Spatio-Temporal Data in Map by Eye-Tracking and Space-Time-Cube. In: *Proc., International Conference on Graphic and Image Processing (ICGIP 2012), Proceedings of SPIE,* Vol. 8768, Article Number: 87684N, doi: 10.1117/12.2011438,

Stigmar, H. (2010). Making 21st Century Maps Legible - Methods for Measuring and Improving the Legibility and Usability of Real-Time Maps. Tryckeriet i E-huset, Lunds universitet.

Vondrakova, A. and Vozenilek, V. (2016). User issues in geovisualization. In: *Proc., 16th International Multidisciplinary Scientific Geoconference (SGEM 2016),* Albena, Bulgaria, Informatics, Geoinformatics and Remote Sensing Conference Proceedings, SGEM

2016, vol. III, Book Series: International Multidisciplinary Scientific GeoConference-SGEM.

Vozenilek, V. and Vondrakova, A. (2018). Proper use of colour schemes for image data visualization. In: *Proc., 9th International Conference on Graphic and Image Processing (ICGIP)*, Qingdao, China, Book Series: Proceedings of SPIE, Vol. 10615 , Article Number: UNSP 1061540

Vozenilek, V., Vondrakova, A. (2017). Systematic cartography in web atlas engineering. In: *Proc., International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM*, Albena, Bulgaria, 29 June 2017 - 5 July 2017, Vol. 17, Issue 23.

Yang et al. (2012). Color Image Quality Assessment Based on CIEDE2000. Advances in Multimedia, vol. 2012, Article ID 273723, doi:10.1155/2012/273723