



Empirical Studies on the Visual Perception of Spatial Patterns in Choropleth Maps

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Abstract

An essential purpose of choropleth maps is the visual perception of spatial patterns (such as the detection of hot spots or extreme values). This requires an effective and as intuitive as possible comparison of color values between different regions. Accordingly, a number of design requirements must be considered. Due to the lack of empirical evidence regarding some elementary design aspects, an online study with 260 participants was conducted. Three closely related effects were examined: the “dark-is-more bias” (i.e., the intuitive ranking of color lightness), the “area-size bias” (i.e., the neglect of small areas, since these are less dominant in perception than larger ones) and the “data-classification effect” (i.e., attention to data classification when interpreting spatial patterns). For each hypothesis, one or more maps in connection with single or multiple choice questions were presented. Users should detect extreme values, central tendencies or homogeneities of values as well as comment on their task solving certainty. In general, the hypotheses regarding the mentioned effects could be confirmed by statistical analysis. The results are used to derive conclusions and topics for future research. In particular, further comparative empirical studies are recommended to determine the best possible map types for given applications, also considering alternatives to choropleth maps.

Keywords Choropleth maps · Usability · Visual perception · Map design · Data classification

Empirische Untersuchungen zur visuellen Wahrnehmung räumlicher Muster in Choroplethenkarten

Zusammenfassung

Ein wesentlicher Zweck von Choroplethenkarten ist die visuelle Wahrnehmung von räumlichen Mustern (wie die Detektion von Hot Spots oder Extremwerten). Dies erfordert einen effektiven und möglichst intuitiven Vergleich von Farbwerten zwischen unterschiedlichen Regionen. Dementsprechend muss eine Reihe von Design-Anforderungen berücksichtigt werden. Aufgrund des bisherigen Mangels an empirischen Beweisen bezüglich einiger elementarer Design-Aspekte wurde eine Online-Studie mit 260 Teilnehmern durchgeführt. Diese untersuchte drei eng miteinander verwandte Effekte: Der „Dunkel-ist-mehr-Effekt“ (d.h., die intuitive Rangfolge der Farbhelligkeit), der „Flächengrößen-Effekt“ (d.h., die Vernachlässigung kleiner Flächen bei der Wahrnehmung, da diese im Vergleich weniger dominant wirken) und der „Datenklassifikations-Effekt“ (d.h., die Berücksichtigung der Datenklassifikation beim Vergleich von räumlichen Mustern). Für jede Hypothese wurden eine oder mehrere Karten mit single oder multiple choice-Fragen präsentiert. Die Nutzer sollten Extremwerte sowie zentrale Tendenzen und Homogenitäten der Werte erkennen und ihre Sicherheit bei der Aufgabenlösung bewerten. Im Allgemeinen konnten die Hypothesen bezüglich der genannten Effekte durch statistische Analysen bestätigt werden. Aus den Ergebnissen werden Schlussfolgerungen und Themen für die zukünftige Forschungsarbeiten abgeleitet. Insbesondere werden weitere

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vergleichende empirische Studien empfohlen, um bestmögliche Visualisierungsformen für gegebene Anwendungsfälle zu bestimmen, dies berücksichtigt auch Alternativen zu Choroplethenkarten.

Schlüsselwörter Choroplethenkarten · Gebrauchstauglichkeit · visuelle Wahrnehmung · Kartengestaltung · Datenklassifikation

1 Introduction

Choropleth maps are used to visualize area-related, standardized data on a cardinal or ordinal scale with different colors or hatching (Slocum et al. 2009). While it is also possible to determine numerical values or value intervals at particular locations, the main objective of choropleth maps is the visual communication of spatial distributions (Monmonier 1974; Mersey 1990)—this includes

- detection of global or local extreme values,
- comparison of values of two or more regions,
- estimation of hot/cold spots,
- assessment of global or local homogeneity or heterogeneity,
- estimation of central tendency (according to mean value),
- estimation of global patterns (e.g., north–south divide), or
- comparison of patterns in two maps.

Regardless of the specific task, one can distinguish between questions that require quantitative processing and outputs (e.g., “What is the maximum population density value?”), and those that require qualitative outputs on the basis of the visual perception only (e.g., “Which federal state has a higher population density—Hamburg or Bavaria?”). Visual perception is here understood as the organization, identification and interpretation of sensory information (Ward et al. 2015: 73).

For the visual perception based on maps, many applications (such as watching media maps) demand for as little usage of legends as possible. Instead, together with the imagination of spatial properties such as spatial homogeneity or hot spots, the tasks are primarily solved by comparing colors between given enumeration units. Accordingly, a couple of design requirements have to be taken into account to support these operations. Because the aspect of differentiation of colors—including the consideration of color vision deficiencies or the effect of lightness contrast—has been thoroughly investigated in previous work (see also Sect. 2), it is not in the scope of this study. Instead, the following research questions will be examined:

- Is there an intuitive ranking or association of color lightness with attribute values (so-called “dark-is-more bias”)?

- How strong is the effect of neglecting small areas because those are visually less dominant compared to larger areas or are simply overseen (so-called “area-size bias”)?
- Is there a sufficient consideration of data classification during the comparison of spatial patterns (so-called “data-classification bias”)?

For answering these questions, an online study with 260 participants was conducted together with the German news agency dpa infografik and the news website SPIEGEL ONLINE (Sect. 3). Statistical testing is applied to verify the underlying hypotheses and to evaluate possible correlations with user groups. Finally, the results of the study will lead to general design and application recommendations for the overall goal of this research, which is concerned with an effective and efficient visual perception of spatial and thematic information in choropleth maps by focusing on the aforementioned biases (Sect. 4).

2 Previous Work

The overall idea of this article is to contribute to effective and efficient task solutions with the help of choropleth maps. Many years ago, several authors already defined necessary task classifications and catalogs (e.g., Monmonier 1974; Robinson et al. 1984). Mersey (1990) defined three types of choropleth map use functions—extracting values at locations, conveying an impression of spatial distribution, and comparing patterns between two or more maps. A more operational view was proposed in our own work (Schiewe 2016), which was based on a general scheme of tasks defined by Andrienko and Andrienko (2006) and decomposed the processes into necessary inputs, detailed operations and outputs. The remainder of this paper does not focus on specific map use tasks, but deals with design issues that support the underlying visual perception.

A key design issue is the choice of a suitable color scheme—with the focus on the distinctiveness of colors (hatching is neglected in the following because of its decreasing importance). There are some rules and recommendations in the literature that mainly depend on the type of data to be displayed (e.g., Brewer 1994; Slocum et al. 2009). For example, for unipolar data, it is recommended to use a sequential color scheme (one hue, varying lightness or saturation) to reflect a value order. There are tools such

as ColorBrewer (Harrower and Brewer 2003) that support map makers with corresponding pre-defined color schemes.

In addition, there are other aspects such as esthetics, color associations, color vision problems or intended use for choosing an appropriate scheme (Slocum et al. 2009). With respect to the last item, Mersey (1990) compared color schemes for direct acquisition versus recall or recognition tasks, or Brewer et al. (1997) for sequential versus divergent attribute value displays. However, these and other studies show some inconsistent results. On the other hand, Brychtova and Coltekin (2015), based on eye tracking analysis, confirmed the hypothesis that large color differences increase the reading accuracy. For a good differentiability of six or more classes, a distance of $\Delta E_{00} = 10$ or more was recommended (ΔE_{00} being the Euclidian color distance in the color space CIEDE 2000 of the International Commission of Illumination, CIE).

Closely related to the distinctiveness of colors, the intuitive ranking of colors is required for visual comparison purposes in choropleth maps. This is normally achieved by varying the intensity or saturation (single- or multi-hued). In textbooks (such as Robinson et al. 1984), the assignment of light colors to small values and dark colors to high values was recommended (so-called dark-is-more bias). However, there is little or outdated empirical work on this recommendation. For example, McGranaghan (1996) confirmed this bias using monochrome displays only. Because the intuitive dark-is-more bias is crucial for further interpretation tasks, it will be treated in this article.

Some studies also addressed the influence of background, contrast and opacity (e.g., McGranaghan 1989; Schloss et al. 2019), which may lead to a reduction of the dark-is-more bias. But again, studies could not reveal unique or transferable results. One step further, an adjustment of color distances to value differences is hardly considered (Weninger 2015). This may be of particular interest if a strong deviation from equidistant data classification occurs, which is then not translated into non-linear color value distances.

Choropleth maps have the problem that larger regions receive a higher visual weight than smaller regions (so-called area-size bias). This overemphasis is mentioned in the literature (e.g., Dent 1999; Speckmann and Verbeek 2010), in most cases with identifying alternatives to avoid this effect. For example, equal-area cartograms as grid or hexagon tile maps, either as single- or multi-element approximations, can be applied (Slocum et al. 2009). However, this leads to shape and topology distortions that are counterproductive to visually perceiving spatial patterns (see also Sect. 4). Thus, Wood and Dykes (2008) suggested equal-area cartograms that can interactively be switched forth and back (and eventually also morphed) with choropleth maps to display correct geographical and topological relationships.

However, this approach is not feasible for a quick and easy perception in static (and for example, media) maps.

Alternatively to the idea of area equalization, areas can be resized according to the attribute values that they represent (area-by-value cartograms; Dent 1999)—examples are the well-known Worldmapper maps (Dorling et al. 2006). But again, localization is hampered and spatial patterns are disturbed. Roth et al. (2010) favored value-by-alpha maps that use translucency for visual equalization of each enumeration unit. Other ideas, like necklace maps that use additional symbols that surrounds the map regions (Speckmann and Verbeek 2010), avoid the area-size bias; however, localization occurs only in an indirect manner and spatial patterns are difficult to derive. To compare the different properties of cartograms, Johnson (2008) introduced the cube representation Cartogram³ that places map types along the axes topology preservation, shape preservation and visual equalization.

The topic of data classification is comprehensively treated in literature—here reference is made to the reviews by Cromley and Cromley (1996) or Coulsen (1987). Several empirical studies were also concerned with the comparison of such methods for answering typical map use tasks (e.g., Goldsberry and Battersby 2009; Brewer and Pickle 2002). A couple of non-spatial measures (such as within-class homogeneity or between-class heterogeneity) were defined to describe the resulting statistical uncertainty due to the classification process (Jenks and Caspall 1971; Dent 1999; Schiewe 2018). On the other hand, the influence of different classification methods and results on the visual perception is hardly investigated. Schiewe (2018) proposed some measures (global visual balance, within-class visual imbalance) for this purpose. However, empirical linkage of such measures to actual visual perception is still missing.

3 Empirical Study

3.1 Hypotheses

The first block of the study dealt with the dark-is-more bias, i.e., the intuitive association of color lightness with attribute values. To test the intuitiveness, maps were first shown without legends. The following hypotheses were under investigation:

- (H1.1): Even without a legend, the darkest color hue is associated with the largest data value (and lightest hue with smallest value).
- (H1.2): Providing a legend, the correct association of dark (light) color values to large (small) data values is further improved.

The second block was concerned with the area-size bias (also “Russia–Andorra effect”), i.e., the neglect of small areas in extreme value detection:

- (H2.1): Without a legend very small areas with global extreme values are often missed.
- (H2.2): Providing a legend very small areas with global extreme values are still (but less frequently) missed.

Finally, the data-classification bias was investigated, i.e., the consideration of data classification along with the comparison of spatial patterns:

- (H3.1): Without a legend, spatial patterns (here: central tendency, homogeneity) are primarily classified according to the related color intensities—without questioning the underlying data classification.
- (H3.2): Even with a legend, spatial patterns are primarily classified according to the related color intensities—without questioning the underlying data classification.

3.2 General Organization

To receive statistically reliable quantitative results, the study was designed as online study (created with Google Forms). It was advertised through the general communication channels of our project partners dpa infografik and SPIEGEL ONLINE, including calls for participation placed directly at the bottom of news maps on SPIEGEL ONLINE. The survey was online for about 8 weeks. The study was in German language only. In total, 260 participants took part.

3.3 Materials

3.3.1 Framework

After a short introduction into the survey, some questions related to cartographic skills (distinction of expert, school knowledge, layman), role (designer only, user only, both), and used display device (desktop monitor, smartphone, tablet, others) were asked.

For each hypothesis, one or more maps in connection with single or multiple choice questions were presented. In total, 14 maps were used, all of them having the States of the United States of America as geographical reference. On purpose, the map topics were not mentioned. The default data classification used six classes as a typical application case. Different color schemes with specific color hues (red, green, blue) were used for different tasks, all designed according to ColorBrewer scheme (Harrower and Brewer 2003). To avoid learning effects, all maps without legends were displayed first (referring to hypotheses x.1), followed by all maps with legends (hypotheses x.2).

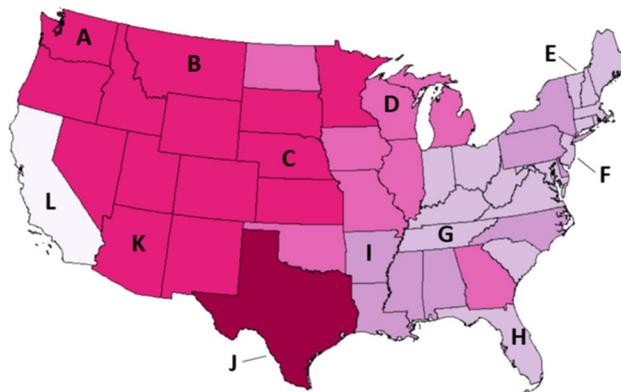


Fig. 1 Hypothesis (H1.1)—in this example the task was to detect the maximum value without a given legend (correct answer: “J”)

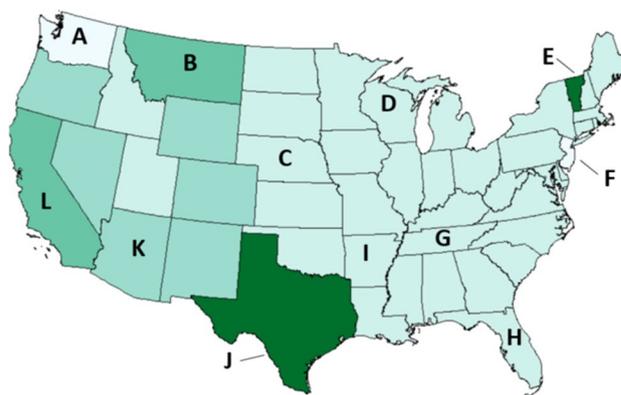


Fig. 2 Hypothesis (H2.1)—in this example, the task was to detect the minimum values without a given legend (correct answers: “A” and “F”)

After each block of hypotheses, the users were asked how safe they felt with their answers (single choice question, 5 classes).

3.3.2 Tasks Related to Hypotheses

For the first block, dealing with the dark-is-more bias, the task was to intuitively detect the minimum value in one, and the maximum value in another map (Fig. 1). The correct answers are based on common cartographic understanding that largest values are displayed with darkest color. In the first round, maps did not inherit a legend, in the second round they did.

With respect to the area-size bias, the task was to intuitively detect two minimum values in one map (Fig. 2), and two maximum values in another one. In both cases, the correct units were characterized by very different area sizes. Again, first round maps did not show any legend, while second round maps did. To consider the influence of the number

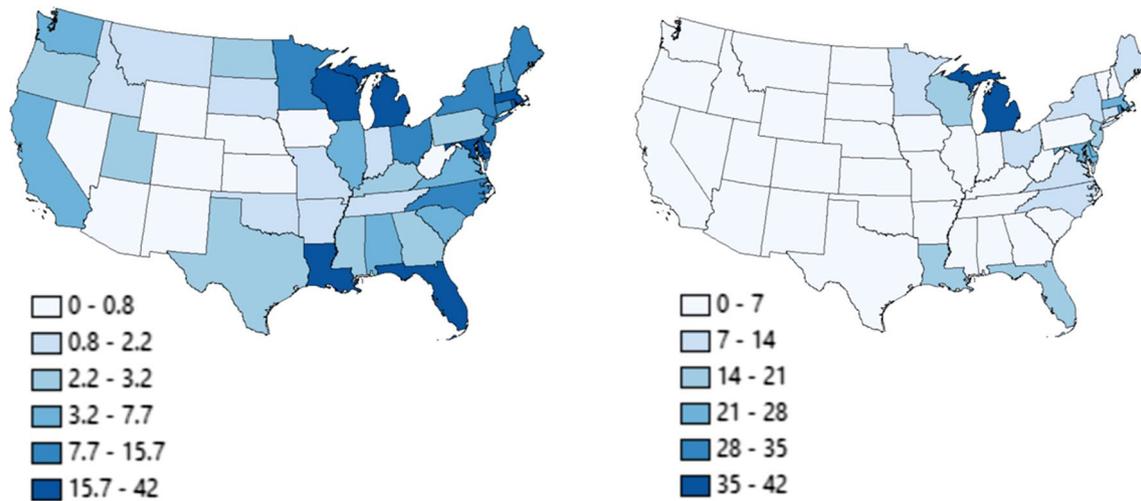


Fig. 3 Hypothesis (H3.2)—in this example the task was to compare central tendency (global mean) with given legends (showing different class limits)

of classes, different variations (4, 6, and 10 classes) were also used for the “with legend” case.

Concerning the data-classification bias in the realm of comparing spatial patterns, the tasks were to intuitively compare central tendency and homogeneity of data values in two side-by-side maps. For the case of a missing legend, the strict answer was not possible due to missing information about the underlying data classification. For the case of a given legend (Fig. 3), the example showed different class limits for the two maps so that an (at least fast and efficient) comparison was also not possible. If one would assume the same classification for both maps, one would have found larger central tendency (average) for the left and larger homogeneity of values for the right map in Fig. 3 due to the overall lightness impressions. Again, three different variations (4, 6, and 10 classes) were used to investigate the influence of the number of classes.

3.4 Analysis Method

In a first step, the answers were counted—in total, but also in subgroups by taking the user and usage characteristics (cartographic skills, roles, display devices) into account. Because in all cases the type of answers were either at nominal or ordinal scale, χ^2 or Fisher tests (depending on the number of entries in the contingency tables) were conducted to evaluate differences between tasks or groups. A level of significance of $\alpha=5\%$ is applied. In addition, the overall degree of certainty was calculated as weighted mean of the five options (with 1 = “very certain”, etc.).

3.5 Results

3.5.1 User Data

With respect to cartographic skills, the majority of participants grouped themselves into the class of school knowledge (52%), followed by experts (43%) and laymen (5%).

Most of the participants saw themselves in the role of a user (69%), 7% as a producer only and the remaining 24% as producer and user.

Nearly half of the participants used a desktop monitor as display device (49%), followed by smartphones (37%), tablets (12%), and others (2%).

3.5.2 Test of Hypotheses

Detailed results of the study are documented in the “Appendix”. In the following, a summarized view is given for each hypothesis.

3.5.2.1 Dark-Is-More Bias As Fig. 4 indicates, 92.6% correct answers were given for the first task (identification of maximum value), and 85.4% for the second one (minimum value)—in both cases without showing a legend. Surprisingly, a significant difference between these tasks occurred with the group of experts ($p=0.006/\chi^2$), having the worst rate of 82.9% for the second task. It seems that many persons in this group were just too fast—smallest values in the eastern part were detected, while the absolute minimum in the west was missed quite often. Another reason for this could be a too optimistic self-assessment of “experts”. For all other combinations of groups and tasks, no significant differences could be observed.

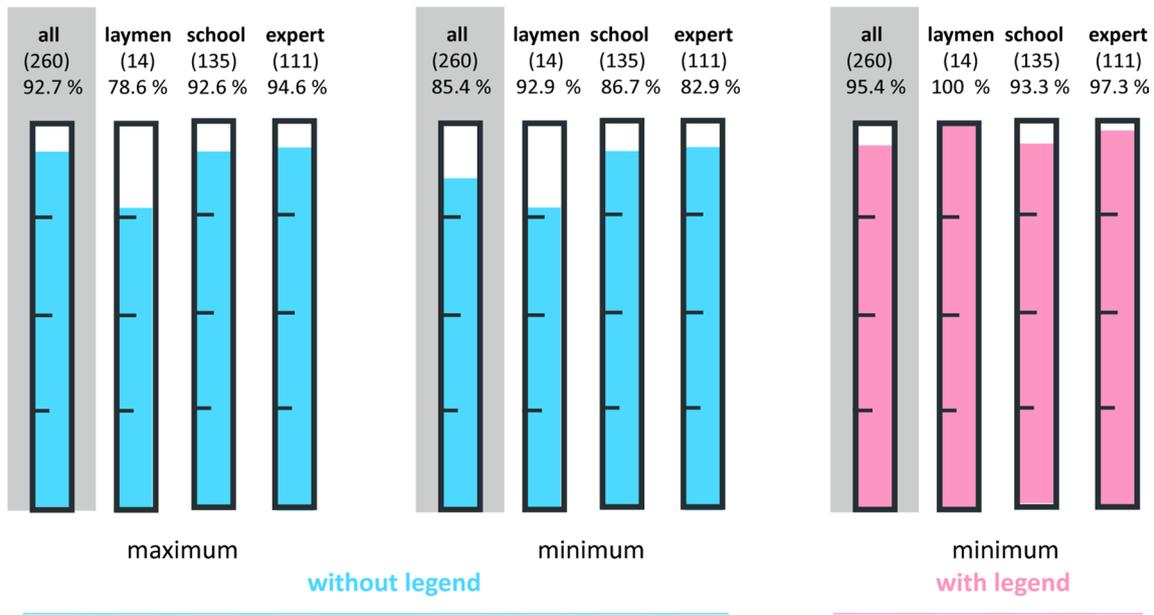


Fig. 4 Detection rates in the context of dark-is-more bias: differentiation between cartographic skills (“all”, etc.), with number of participants in brackets; percentage values represent correct answers; further

differentiation between tasks (maximum or minimum detection, with or without legend)

The overall grade of certainty was 1.92 (close to 2 = “certain”). Only 7.7% of all participants were either not certain or very uncertain with their answers—this corresponds very well to the overall error rate. Here, layman showed the largest rate (3/14); however, due to the small number of people

in this group, this is not statistically significant compared to the rest of the participants.

All in all, (H1.1) can be verified based on the rate of correct answers of about 90%.

Introducing a legend improved the level of correctness for finding the minimum value to 95.4%. Compared to the

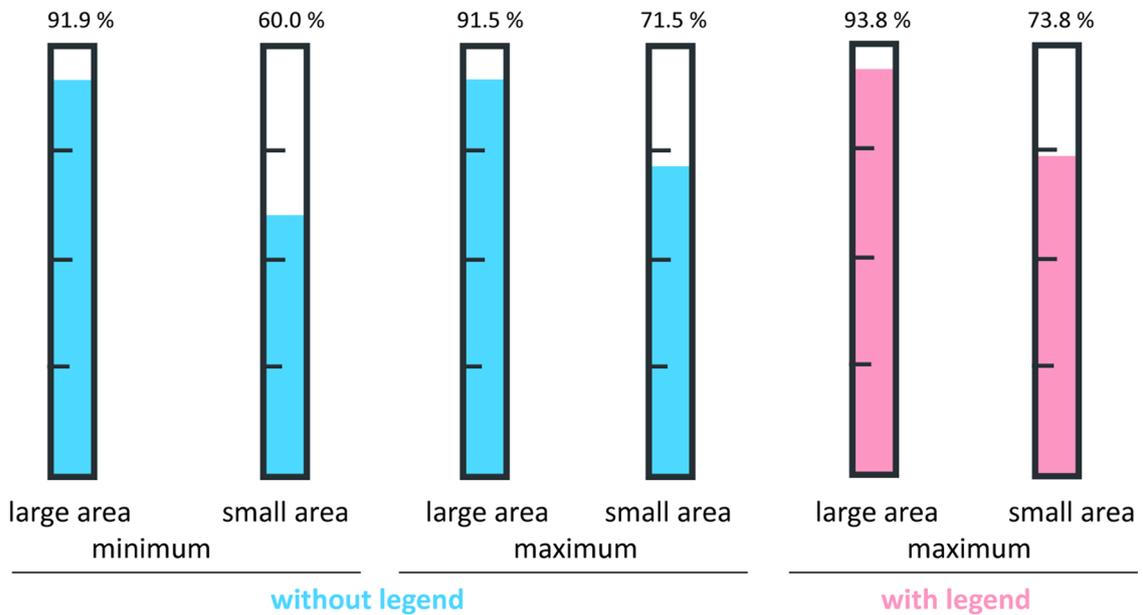


Fig. 5 Detection rates in the context of area-size bias: all users; percentage value represent correct answers; differentiation between detection of large and small areas within one example

same scenario without legend (85.4%), this corresponds to a significant difference ($p < 0.001/\chi^2$). Laymen showed the best rate (100%); however, significant differences to the other two groups could not be detected. The overall grade of certainty increased from 1.92 to 1.33 (with only 1.5% being not certain or very uncertain)

Even if a certain learning effect is taken into consideration, (H1.2) can be verified based on these results.

3.5.2.2 Area-Size Bias Correct answers for the detection of multiple extreme values—without legends—were 66.5% (for finding maximum values) and 55.8% (for minimum values; Fig. 5). As with the detection of just one extreme value before, the detection of minimum values was again worse than that of maximum values (with $p = 0.011/\chi^2$). In both cases, the large areas with extreme values were well detected—with success rates of 91.5% (maximum values) and 91.9% (minimum)—this is comparable to the rates observed before with the dark-is-more bias. On the other

hand, the smaller areas had detection rates of only 71.5% (maximum) and 60.0% (minimum)—which in both cases is significantly different to the large areas ($p < 0.001/\chi^2$). Surprisingly, the overall certainty rate of users slightly improved from 1.92 (H1.1) to 1.89. Now only 5.4% of the persons were either “uncertain” or “very uncertain”.

With that, (H2.1)—the area-size bias—could be verified: small areas were missed by approximately 30–40% of map users, which is definitively too much.

Providing a legend led to an increase in the detection rate of extreme values within small areas (Fig. 5). However, in all cases, there was still a significant difference in large area detection ($p < 0.001/\chi^2$). It seems that there was a learning effect: Table 1 shows the chronological sequence of experiments, with an increase in the small area detection from 66.5 to 81.9%.

On the other hand, variations within the large area detection rates based on legends were getting slightly worse as the number of classes increased from 4 over 6 to 10 (96.2%, 93.8%, and 92.7%). However, this effect is statistically not strongly significant (change from 4 to 10 classes: $p = 0.085/\chi^2$).

The overall level of subjective certainty increased from 1.89 (H2.1) to 1.46 (H2.2).

Summarizing these results, one can verify (H2.2): there was an increase in the detection of small areas; however this error around 15% to 25% was probably also due to a learning effect and was still clearly larger than the one for large areas (5–10%).

Table 1 Detection rates (correct answers in %) of maximum values (all users, in chronological order of tests)

Legend	No. of classes	Detection of large area (%)	Detection of small area (%)	Total detection (%)
Without	6	91.5	71.5	66.5
With	6	93.8	73.8	71.2
With	4	96.2	78.8	76.5
With	10	92.7	86.1	81.9

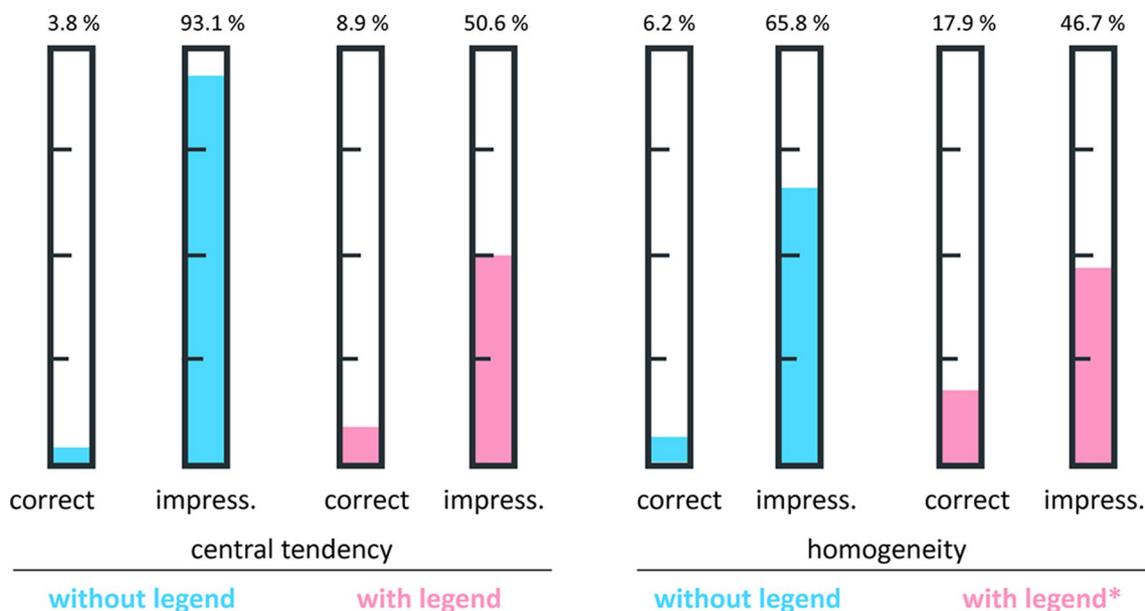


Fig. 6 Detection rates in the context of data-classification bias: all users; percentage value represent either strictly correct answers (“correct”) or answers based on lightness impression (“impression”); case (*) with 10 classes, all others with 6 classes

3.5.2.3 Data-Classification Bias For comparing the central tendency (“identify map with larger values on average”), first no legends were given. Taking the theoretical case of different classifications into account, the correct answer should be “don’t know”. However, only 3.8% took this choice. The majority (93.1%) selected that map that showed an overall darker appearance (Fig. 6). Also for comparing the homogeneity (“identify map with more homogeneous values”), the strict correct answer should be “don’t know”. Only 6.2% chose this option, while 65.8% took the one according to the more homogeneous color impression.

The overall certainty index of 2.22 (with only 8.9% in the “not certain” or “very uncertain” group) confirms that pattern interpretation is a more challenging task compared to the ones before.

Hypothesis (H3.1) could be confirmed. The underlying, actual data classification is not questioned by about 95% of the participants. If one neglects this aspect (and assumes identical class limits), the interpretation of central tendency based on the global distribution of related color intensities was performed mainly correct. However, error rates for homogeneity detection were significantly worse.

In the case of providing a legend, it has to be considered that different classifications were used for the left and right map. Consequently, a comparison of central tendency is hardly possible. For the three examples (with 4, 6, and 10 classes), only 15.2%, 8.9%, and 16.7% of the participants selected the strictly correct answer “don’t know”. The majority (43.6%, 50.6%, 47.9%) still relied on the dominant color lightness, neglecting the different class limits.

A similar result was obtained for the homogeneity comparison (10 classes): only 17.9% voted for “don’t know”, while 46.7% made their choice according to the perception of homogeneous lightness. Experts realized the problem of different class limits more often than the other groups.

Obviously, these pattern interpretation tasks were the most difficult ones, including the additional (and eventually also confusing) effect of different class limits. Accordingly, the overall certainty level was only 2.79.

All in all, hypothesis (H3.2) could be verified. The majority of the map readers (including experts) ignored the data-classification bias and relied on the color lightness distribution only.

3.5.3 Free Comments

Most of the free comments were concerned with the missing legend for some of the tasks (which actually were left out by purpose) and the choice of colors. 5 out of the 260 users mentioned that the used color differences were not well detectable on their display devices. Consequently, a multi-hue instead of the single-hue color scheme was explicitly requested by two participants.

4 Discussion and Conclusions

4.1 Dark-Is-More Bias

Concerning the dark-is-more bias, a high intuitive and successful interpretation of extreme values for approximately 90% of all cases could be observed. With that the underlying hypotheses (H1.1) and (H1.2)—high values are associated with dark colors—could be verified. Surprisingly, maximum detection was significantly better than minimum detection—this effect might be due to the fact the maximum detection is required more often; however, this should be further investigated.

Despite this high success rates, a legend is still recommended for further optimization, even if an exact value determination is not required. To improve color distinctiveness, multi-hue schemes are helpful; however, it is expected that the intuitive ranking based on the overall lightness becomes more difficult. It is worth examining this aspect in more detail.

4.2 Area-Size Bias

Concerning the area-size bias, it was observed that the detection of small areas with global extreme values is significantly worse than those of large areas. Providing a legend improved these results; however, an unacceptable error rate of 15% to 25% remained. With that, hypotheses (H2.1) and (H2.2) could be verified.

As pointed out in Sect. 2, in the past a couple of alternatives to choropleth maps have been discussed to tackle this bias (e.g., equal-area, area-by-value, or value-by-alpha cartograms). However, from a theoretical point of view, there is no “perfect” solution as localization is hampered and/or topology and/or shape are disturbed so that spatial patterns cannot be determined with necessary accuracy (Fig. 7).

Much more comparative empirical research is needed to find (sub-)optimal solutions. Independent variables will be, aside from alternative map types, different base map geometries (such as number of islands, number of polygons, or interval of areas sizes), and different class numbers. Dependent variables are the effectiveness and efficiency for typical tasks such as localization of spatial units and detection of spatial patterns.

At this point, another dilemma occurs: on the one hand, empirical research can lead to the determination of a case-dependent optimum and on the other hand this flexibility does not increase intuition (for layman user in particular), because repetitive learning and experience are not supported through recurring map type displays.

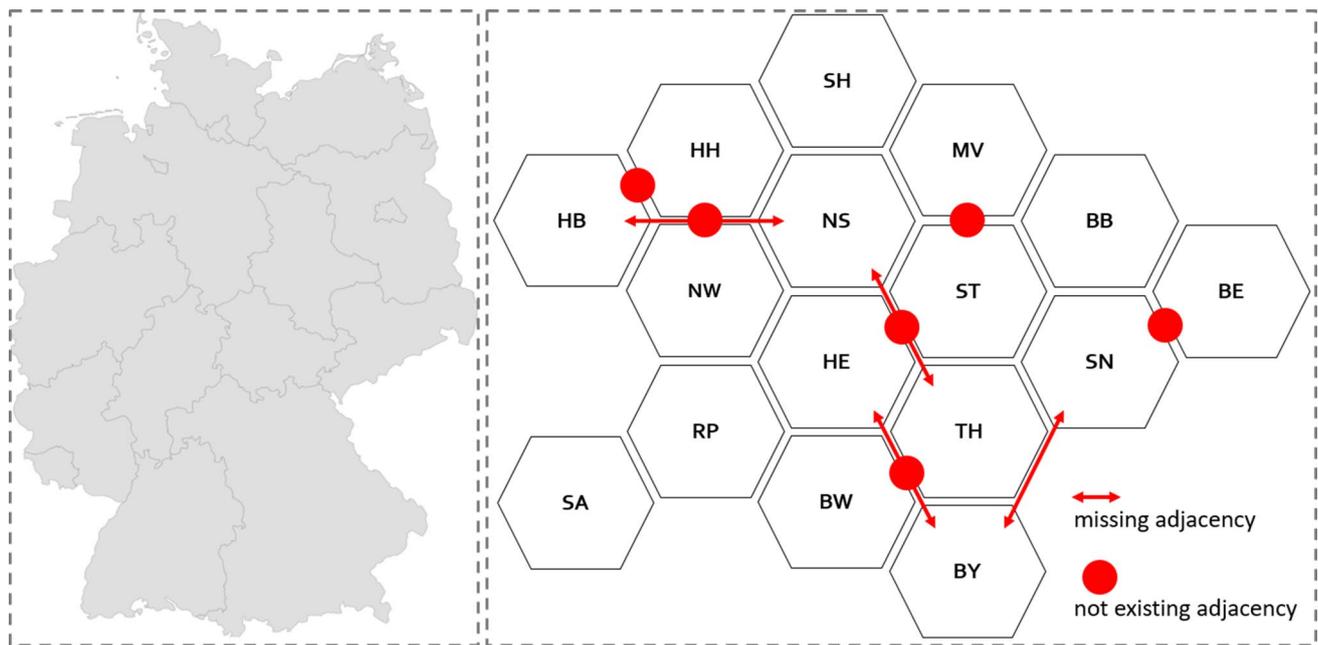


Fig. 7 Equal-area cartogram map of Germany (right) produces topological errors (red circles and arrows) and shape distortion (indicated by dashed overall outline, in comparison to “correct” geometry, left)

4.3 Data-Classification Bias

Also the data-classification bias could be confirmed: while there is a good intuition during the global interpretation based on lightness differences, this takes place without questioning the underlying data classification by more than 90% of users (without legend) and 80% (with legend). Interpreting global homogeneity based on lightness impression only was obviously a much more challenging task compared to evaluating central tendency.

The data-classification bias is closely linked to an appropriate visualization, in particular, the distinctiveness of color intensities. As there are still problems for certain display devices, the number of classes should be kept as small as possible, in particular when (small) monitor displays are used. Defining a universal upper limit (e.g., 5 or 6 classes) is of course rather difficult due to the variety and huge number of available displays.

The perception of spatial distributions assumes that respective patterns such as local extreme values, large values differences between polygons, or hot spots are not disturbed through the data classification step. However, conventional classification methods do not consider spatial properties and do not guarantee their preservation. Hence, it is recommended to apply advanced methods that explicitly consider spatial context and show improved preservation rates (Chang and Schiewe 2018).

4.4 Overall Evaluation

All in all, the central hypotheses could be verified with this empirical study. Interestingly, in nearly all tasks, there was no significance for the groups with different cartographic skills. Of course, the within-subjects design of the survey together with no random task order facilitated some learning effects. However, the given sequence avoided confusion about the different tasks. Although some learning effects are assumed (in particular, when varying the number of classes), this did not disturb the overall trend of the results.

Although no major surprises occurred, the study now delivered a so far missing empirical evidence for key aspects in the context of visual perception of spatial distributions in choropleth maps. A couple of detailed study topics as mentioned earlier are still needed to further optimize the respective design. In addition, also the impact of different class numbers on successfully detecting spatial patterns needs to be further investigated.

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Appendix

Numerical Results of Empirical Study

Hypothesis (H1.1): Dark-is-more bias—without legend (6 classes)

Group	Detection of one maximum value			Detection of one minimum value		
	Correct (abs.)	Wrong (abs.)	Correct (%)	Correct (abs.)	Wrong (abs.)	Correct (%)
Laymen	11	3	78.6	13	1	92.9
School knowledge	125	10	92.6	117	18	86.7
Expert	105	6	94.6	92	19	82.9
Designer	17	1	94.4	15	3	83.3
User	166	14	92.2	155	25	86.1
Both	58	4	93.5	52	10	83.9
Desktop	120	6	95.2	112	14	88.9
Tablet	30	2	93.8	27	5	84.4
Smartphone	85	10	89.5	77	18	81.1
Etc.	6	1	85.7	6	1	85.7
Total	241	19	92.7	222	38	85.4

Decision	Very certain	Certain	Medium	Uncertain	Very uncertain	Overall grade
Total	101	105	34	14	6	1.92

Hypothesis (H1.2): Dark-is-more bias—with legend (6 classes)

Group	Detection of one minimum value		
	Correct (abs.)	Wrong (abs.)	Correct (%)
Laymen	14	0	100.0
School knowledge	126	9	93.3
Expert	108	3	97.3
Designer	18	0	100.0
User	169	11	93.9
Both	61	1	98.4
Desktop	126	0	100.0
Tablet	27	5	84.4
Smartphone	89	6	93.7
Etc.	6	1	85.7
Total	248	12	95.4

Decision	Very certain	Certain	Medium	Uncertain	Very uncertain	Overall grade
Total	192	55	9	3	1	1.33

Hypothesis (H2.1)—Area-size bias—without legend (6 classes)

Group	Detection of two maximum values			Detection of two minimum values		
	Correct (abs.)	Wrong (abs.)	Correct (%)	Correct (abs.)	Wrong (abs.)	Correct (%)
Laymen	8	6	57.1	8	6	57.1
School knowledge	89	46	65.9	69	66	51.1
Expert	76	35	68.5	68	43	61.3
Designer	12	6	66.7	8	10	44.4
User	118	62	65.6	95	85	52.8
Both	43	19	69.4	42	20	67.7
Desktop	89	37	70.6	76	50	60.3
Tablet	19	13	59.4	14	18	43.8
Smartphone	60	35	63.2	50	45	52.6
Etc.	5	2	71.4	5	2	71.4
Total	173	87	66.5	145	115	55.8

Decision	Very certain	Certain	Medium	Uncertain	Very uncertain	Overall grade
Total	98	113	35	8	6	1.89

Hypotheses (H2.2)—Area-size bias—with legend (varying number of classes)

Group	Detection of two maximum values of 6 classes			Detection of two maximum values of 4 classes			Detection of two maximum values of 10 classes		
	Correct (abs.)	Wrong (abs.)	Correct (%)	Correct (abs.)	Wrong (abs.)	Correct (%)	Correct (abs.)	Wrong (abs.)	Correct (%)
Laymen	7	7	50.0	7	7	50.0	11	3	78.6
School knowledge	96	39	71.1	103	32	76.3	108	27	80.0
Expert	82	29	73.9	89	22	80.2	94	17	84.7
Designer	12	6	66.7	12	6	66.7	12	6	66.7
User	124	56	68.9	140	40	77.8	149	31	82.8
Both	49	13	79.0	47	15	75.8	52	10	83.9
Desktop	88	38	69.8	97	29	77.0	107	19	84.9
Tablet	22	10	68.8	22	10	68.8	24	8	75.0

Group	Detection of two maximum values of 6 classes			Detection of two maximum values of 4 classes			Detection of two maximum values of 10 classes		
	Cor- rect (abs.)	Wrong (abs.)	Cor- rect (%)	Cor- rect (abs.)	Wrong (abs.)	Cor- rect (%)	Cor- rect (abs.)	Wrong (abs.)	Cor- rect (%)
Smart- phone	69	26	72.6	73	22	76.8	76	19	80.0
Etc.	6	1	85.7	7	0	100.0	6	1	85.7
Total	185	75	71.2	199	61	76.5	213	47	81.9

Group	Detection of central tendency				Overall grade	
	Very certain	Certain	Medium	Uncer- tain	Very uncertain	Overall grade
Total	167	69	20	2	1	1.46

Hypothesis (H3.1)—Data classification bias—without legend (6 classes)

“correct” = strictly correct (“don’t know”), “impression only” = neglecting classification, using lightness only (but correctly)

Group	Detection of central tendency		Detection of homo- geneity		Overall grade
	Correct (%)	Impres- sion only (%)	Correct (%)	Impres- sion only (%)	
Laymen	0.0	92.9	0.0	42.9	
School knowl- edge	1.5	95.6	4.4	76.3	
Expert	7.2	90.1	9.0	55.9	
Designer	11.1	88.9	22.2	55.6	
User	1.7	96.1	4.4	72.8	
Both	8.1	85.5	6.5	48.4	
Desktop	4.0	92.1	7.9	59.5	
Tablet	6.3	87.5	6.3	68.8	
Smartphone	3.2	95.8	4.2	72.6	
Etc.	0.0	100.0	0.0	71.4	
Total	3.8	93.1	6.2	65.8	

Group	Detection of central tendency				Overall grade	
	Very certain	Certain	Medium	Uncer- tain	Very uncertain	Overall grade
Total	59	115	63	17	6	2.22

Hypothesis (H3.2)—Data classification bias—with legend (varying number of classes)

“correct” = strictly correct (“don’t know”), “impression only” = neglecting classification, using lightness only (but correctly)

Group	Detection of central tendency of 6 classes		Detection of central tendency of 4 classes		Detection of central tendency of 10 classes		Detection of homogeneity of 10 classes	
	Cor- rect (%)	Impres- sion only (%)	Cor- rect (%)	Impres- sion only (%)	Cor- rect (%)	Impres- sion only (%)	Cor- rect (%)	Impres- sion only (%)
Laymen	14.3	64.3	14.3	57.1	14.3	64.3	7.1	57.1
School knowl- edge	6.0	57.9	12.7	49.3	16.3	51.1	15.6	45.9
Expert	11.8	40.0	18.3	34.9	17.1	40.5	21.6	45.0
Designer	22.2	44.4	22.2	50.0	22.2	55.6	16.7	55.6
User	7.3	54.7	13.9	48.3	16.7	51.7	17.2	47.2
Both	10.0	40.0	16.9	27.1	15.3	33.9	20.3	42.4
Desktop	12.2	44.7	15.4	41.5	18.7	42.3	21.1	43.9
Tablet	3.1	59.4	12.5	31.3	9.4	46.9	9.4	43.8
Smart- phone	6.3	54.7	14.7	50.5	16.8	55.8	16.8	50.5
Etc.	14.3	57.1	28.6	42.9	14.3	42.9	14.3	57.1
Total	8.9	50.6	15.2	43.6	16.7	47.9	17.9	46.7

Group	Very certain		Certain		Medium		Uncer- tain		Very uncertain		Overall grade
	Correct (%)	Impres- sion only (%)	Correct (%)	Impres- sion only (%)	Correct (%)	Impres- sion only (%)	Correct (%)	Impres- sion only (%)	Correct (%)	Impres- sion only (%)	
Total	32	75	84	54	15	2.79					

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