Beyond choropleth maps: A review of techniques to visualize quantitative areal geodata

Alsino Skowronnek– *University of Applied Sciences Potsdam, Department of Design*

Abstract—Modern digital technologies and the ubiquity of spatial data around us have recently led to an increased output and visibility of geovisualizations and digital maps. Maps and »map-like« visualizations are virtually everywhere. While areal thematic geodata has traditionally often been represented as choropleth maps, a multitude of alternative techniques exist that address the shortcomings of choropleths. Advances of these alternative techniques derive both from the traditional domains of geography and cartography, as well as from more recent disciplines such as information visualization or even non-academic domains such as data journalism. This paper will review traditional and recent visualization techniques for quantitative areal geodata beyond choropleths and evaluate their potential and limitations in a comparative manner.

Index Terms—Choropleth Maps, Geovisualization, Cartograms, Grid Maps, Spatial Treemaps

1 Introduction

People have been fascinated with maps and geospatial representations of the world as long as we can think. This is not only due to maps' inherent potential for storytelling and identification with places, but also due to humans' excellent spatio-cognitive abilities, which allow us to easily navigate through geographic space and communicate spatial insights in meanigful ways (Card et al., 1999, Skupin, 2000).

Traditionally, cartographers and geographers have been at the fore of crafting these visual representations we call maps. Over the centuries they have developed and refined specific techniques to display environmental (physical) and socio-cultural and -economic (thematic) data on maps (MachEachren, 1979, Robinson, 1953). Cartography as a discipline has thus been highly influential to the domain of information visualization research, even though its traditions have often been all but ignored by the latter discipline (Skupin, 2000, Skupin/Fabrikant, 2003).

A particular branch of geovisualization techniques deals with the representation of quantitative thematic data. Thematic data describes socio-economic attributes such as population, income, crime rates or election results, which inform us about human activity in geographic space, opposed to topographical data such as land area, elevation or the like (Speckmann/Verbeek, 2010). Most often we are interested in the spatial distribution of a specific phenomenon (e.g. „In which city district are crime rates highest?") and thus would like to express this in a visual way. The most common technique to represent quantitative thematic areal geodata are choropleth maps. These maps highlight differences in geographically distributed data based on administrative units, often using color or patterns as principle visual variables. However, choropleths exhibit a number of shortcomings (i.e. support of specific data types and certain visual inadequacies) in different situations.

This paper will briefly review the literature on choropleth maps in the following part, before contrasting the technique with three alternative approaches, their main characteristics and implications for visualizing areal geodata in more general terms.

2 Related Work

2.1 Choropleth maps: The *de facto* standard

One of the most common techniques to represent areal thematic data in a spatial layout are choropleth maps. Choropleth maps are representations, which highlight differences in the geographical distribution of data by spatial unit, often using administrative boundaries such as countries, states or regions (Robinson, 1982). The body of cartographic research on choropleth maps is impressive as it spans more than seventy papers in more than forty-five years. An attempt to summarize this entire body of research at this point would fall short, but good overviews are offered by Brewer/Pickle (2002) and MachEachren (1979). Indeed, choropleth maps were one of the first types of thematic maps developed during the 18th century as general concern with social phenomena during the Enlightenment was also reflected in visual representations of societal trends (Meirelles, 2013 , Robinson, 1982). The first known choropleth map is a map by Frenchman Charles Dupin from 1826, which depicts the spatial variation of education levels in France by grey-shaded administrative areas (see Fig.1).

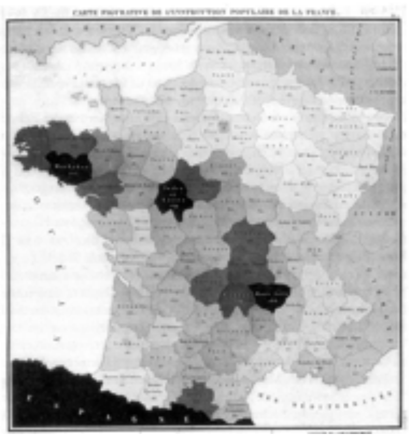


Fig. 1. Early choropleth map by Charles Dupin (1826)

Although choropleth maps are essentially the *de facto* standard for displaying areal attribute data, they suffer from a range of problems:

Area-size bias: Choropleth maps tend to overemphasize large administrative units by assigning them a stronger visual weight. A classic example of this phenomenon are bi-partisan election maps of the United States, where the larger area size of the Western and central states receives bigger visual weight than the smaller-sized Eastern states (see Fig. 2). This phenomenon has been widely discussed and is well-documented in the literature (see for example: Dent, 1999; Dorling, 1996, Speckmann/Verbeek, 2010).

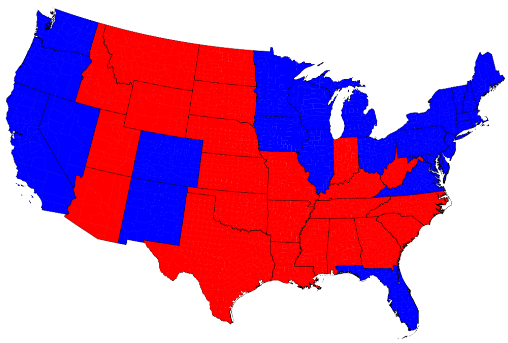


Fig. 2. Choropleth map of the 2012 US presidential election results; Democrats (blue) won over Republicans (red); note the area-size-bias towards red states

Intra-regional variation: Choropleths are usually not a very good at visualizing intra-regional variations of geodata by displaying data uniformly across the shape of the original geographic unit. This is especially relevant if agglomerations (e.g. big cities in otherwise less densely populated countries) account for the major share of the data values. Choropleths thus suggest uniformity of data across space, which rarely is the case.

Magnitudes vs. intensities: Choropleth maps are ill-suited to display magnitudes of a given phenomenon, but instead should only be used for intensities, i.e. absolute population figures of regions versus (normalized) population density of regions. This is the case because viewers unconsciously integrate over similarly-colored regions and thus usually perceive choropleths as representations of density (Monmonier, 1991, Speckmann/Verbeek, 2010).

Given these shortcomings of choropleth maps, there has been a vivid debate in the cartographic and geographic academic domains over the past decades on how to best address these issues and when to opt for alternative techniques. Today, this debate has spread beyond the realms of cartography and it is noteworthy that other disciplines, especially information visualization research and even non-academic disciplines such as data journalism are contributing to the further development of new approaches. These alternative techniques will be presented in the following sections.

2.2 Cartograms: Substituting space for data

One of the principle techniques to account for the area-size bias introduced by choropleth maps is the cartogram. Cartograms are geographic depictions of spatial phenomena (i.e. geovisualizations), which involve some degree of distortion of geographic space. Much cartographic work has been published on cartograms, dominated by the seminal works of Waldo Tobler (Dorling et al., 2006; Tobler, 2004). In contrast to a choropleth map, a cartogram will substitute a geographic area for some type of non-geographic information and display this accordingly. While this necessarily introduces spatial distortion, the visual representation may be more adequate for displaying data under certain conditions, i.e. if administrative areas have very different sizes (see Fig.3).

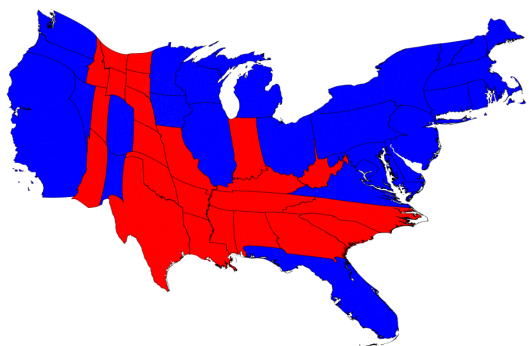


Fig. 3. Cartogram of the 2012 US presidential election results; Democrats (blue) won over Republicans (red)

For example, cartograms are often used to compare population data or trade flows on a country or subnational level (Dorling et al., 2006). Given these characteristics, cartograms are not “true” maps, even though they often look “map-like”, depending on the degree of spatial abstraction. Some cartographers have referred to cartograms as "diagrammatic maps" (Raisz, 1938) or "value-by-area maps" (Dent, 1999). The reason is that cartograms are depictions not of real geographic, but instead of partially *abstracted geographic space*. They could thus be situated somewhere on a spectrum between maps and geographic infographics. When representing non-geographic information in the form of spatial entities, an important distinction can be made concerning the trade-off between shape (geographic area) and topology (adjacency between connected areas). Based on this trade-off, one can roughly distinguish four different kinds of cartograms, based on the type of spatial distortion introduced:

- **Non-contigous cartograms:** Non-contigous cartograms are the simplest form of cartograms. This technique sacrifices topology between geographic neighbors (i.e. areas are no longer connected) in order to preserve the original geographic shape of spatial units. Because areas do not have to stay in place relative to their neighbours, they can grow and shrink according to their needs. Different algorithms for non-contigous cartograms have been suggested, some of them allowing area overlap, while others do not (Tobler, 2004, Fig. 4).

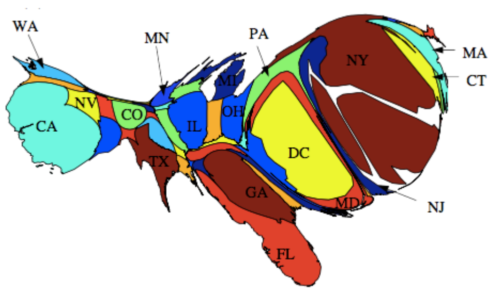


Fig. 5. Contigous cartogram of the United States; states are proportional to the frequency of their appearance in news stories (Gastner/ Newman, 2004)

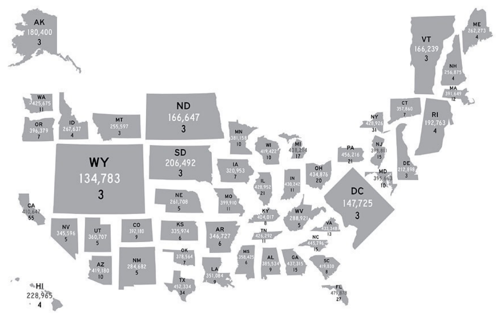


Fig. 4. Non-contigous cartogram of the United States showing each state resized in proportion to the relative influence of the individual voters who live there (NYT, 2008)

- **Contigous cartograms:** In contrast to the first type, contigous cartograms sacrifice geographic shape of spatial units in favor of the preservation of their topology (i.e. "connectedness"). These cartograms are thus usually more difficult to compute. The trade-off here consists in presenting a given data value adequately by area-size, while trying to preserve the "recognizability" or characteristic shape of a region. In fact, countless algorithms for computing contigous cartograms have been put forward over time (Dougenik et al. 1985; Gastner/ Newman, 2004; Keim et al. 2004; Tobler, 2004, Fig. 5) and a few applications have even gained popularity outside the academic sphere (see e.g. the Worldmapper project by Dorling et al., 2006).

- **Dorling cartograms:** In contrast to the previous two types, Dorling cartograms – named after their inventor Denny Dorling – are representations of geographic units through a higher degree of spatial abstraction. Administrative regions are shown as circles, which are positioned on each region's geographic centroid and by preventing overlap. Dorling cartograms' spatial abstraction of geographic shape is rather high while topology is partially preserved, depending on the type of layout algorithm used (Dorling, 1996, Fig. 6).

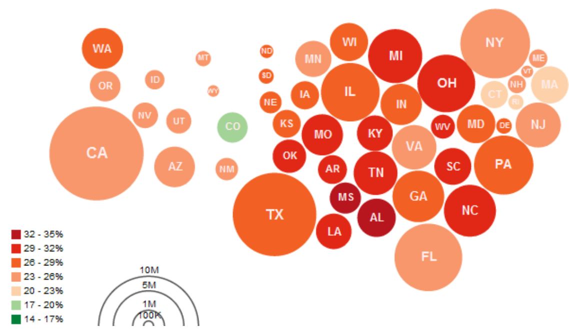


Fig. 6. Dorling cartogram of obesity levels in the United States, 2008

- **Demers cartograms:** A slight variation of Dorling cartograms are so-called Demers cartograms, which represent regions as squares instead of circles. While Dorling cartograms minimize distances between circles through gravitational forces, Demers cartograms allow for more flexibility in neighborhood arrangements to preserve original geographic adjacencies. They also use visual clues (e.g. water areas such as bays are excluded) to provide greater readability (Bortins et al. 2002). However, Demers cartograms do not preserve the original geographic position of regions, and only partially their topology.

2.3 Grid maps: Extending the cartogram

A slightly different type of geovisualization, which has recently gained much popularity, especially in the non-academic domain of data journalism and data science are so-called grid maps. Grid maps are essentially a particular type of cartogram, in which squared spatial units are snapped to a previously defined grid, instead of being assigning to random or algorithmically calculated adjacent positions. Grid maps have similar characteristics as cartograms, in that physical geographic shape is abstracted to simple geometric shapes. Most visualizations use circles or squares, but polygons (e.g. hexbins) are also gaining popularity, for their ability to allow for less distortion in neighborhood adjacency and recently even icons have been used to represent administrative areas (see Fig. 7). Grid maps differ from ordinary cartograms in that area sizes are usually uniform and data is encoded not via the size of the spatial container but through color or other visual variables within the container. In fact, grid maps have recently gained a great deal of popularity in data journalism, and their use for the depiction of spatial data versus other types of techniques has sparked a great deal of discussion. Some commentators have even referred to this debate as the „great grid map debate of 2015“ (Yau, 2015).

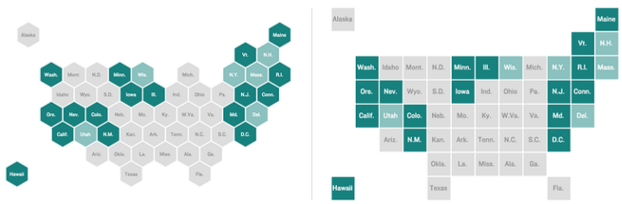


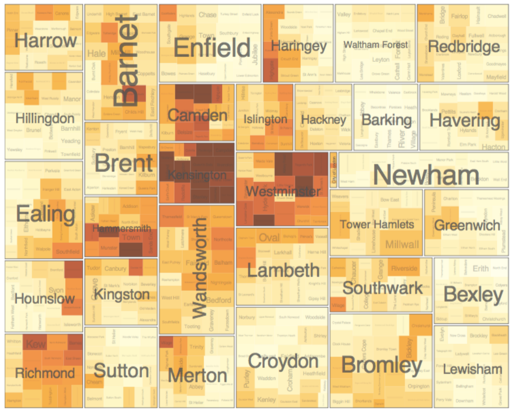
Fig. 7. Different grid map layouts: hexagon tile grid map (left), square tile grid map (right)

However, one should note that grid maps are not a new invention *per se*, but rather a variation and part of a toolbox of well-established cartographic techniques and principles, informed and nowadays re-interpreted by a cross-fertilization of different disciplines.

2.4 Spatial Treemaps: Coping with hierarchical data

A third technique for the representation of areal geodata are spatial treemaps. These are geographic derivates of ordinary treemaps - as suggested by Johnson/Shneiderman (1991) - a specific technique commonly applied to represent hierarchical data in a space-filling manner. Spatial treemaps can be used to represent spatially hierarchical data in a similar way. They differ from ordinary treemaps, however, in that node position and -order are not randomly assigned within a rectangular container, but rather based on their original geographic position (Buchin, 2011). They can be used to visualize data with higher levels of spatial depth, i.e. data with higher administrative granularity (e.g. country, state, county in the US). Smaller rectangles in spatial treemaps usually represent lower administrative units, which are nested within higher ranking ones (Fig. 8).

Fig. 8. Spatial treemap of property transactions in London 2000-2008; darker colors represent higher average prices



One of the advantages of spatial treemaps over choropleth maps is the ability to deal with variations in spatial data within a certain region and to infer spatial patterns, while retaining overview. One of the main challenges of spatial treemaps, however, is the preservation of geographic topology (position, direction) between nodes in order to maximize the level of "recognizability" of the depicted areas. Different algorithms and techniques have been proposed to tackle this problem. Among the more recent ones are Auber et al. (no year), Buchin et al. (2011) and Wood / Dykes (2008).

Spatial treemaps are essentially a geographical extension of ordinary treemaps. As such they have been developed by the academic disciplines of information visualization research and computer science. This is reflected in the at times "silo-esque" and self-referential literature. However, it is obvious that spatial treemaps are actually closely related to Demers cartograms. In fact, Buchin et al. (2011) refer to spatial treemaps as "hierarchical rectangular cartograms", pointing to the fact that the overlap between the academic disciplines of cartography and infovis research is becoming more commonly accepted.

3 Discussion

The previous part has laid out three common techniques to visualize geodata by area beyond choropleth maps. While much has been written about each single technique within the respective professional domain, less attention has ben given to the question how these different techniques relate to each other in terms of their spatial properties and under which conditions one technique is preferable over the other to meaningfully communicate the underlying data. The following part will make an effort to shed more light on a few selected issues.

3.1 The wonderful world of spatial transformation

Geovisualization and cartography are inherently about spatial transformations, take for example i) the common mathematical operations known as “projections” necessary to transform features of a three-dimensional sphere (geoid) onto a two-dimensional plane (map) or ii) different interpolation methods necessary to produce an isochrone map layer out of a collection of points. The famous cartographer Waldo Tobler has therefore called cartography a “transformational” science (Tobler, 1979). Thus, once we leave the realm of the choropleth map for alternative methods of geovisualizations, we are entering the fascinating world of spatial transformations. No matter whether we use cartograms, grid maps or spatial treemaps, they all have one thing in common: the transformation and distortion of “actual” geographic space in favor of some form of abstract geometric space. Spatial entities and administrative areas become abstract shapes such as squares, circles or polygons. A number of spatial characteristics are altered, including the overall geographic layout as well as the shape and topology of spatial entities (i.e. position, distance and direction) vis-à-vis each other.

The main issue here is that any type of spatial transformation inherently implies some form of *geometric trade-off*, because it is not possible to preserve all spatial attributes of an administrative area at the same time, when representing it through a “data lens”. For example, if we opt for the preservation of topology (e.g. France and Spain remain neighbors in a spatial treemap as they would in a map), we are not be able to preserve their shapes and vice versa. The ultimate goal is thus to choose an adequate technique that best suits the purpose of the portrayed data scenario or to find an optimal balance between the different spatial attributes. For each technique, different optimization procedures have been proposed to achieve this goal, mostly in the form of algorithmically optimized mathematical operations (see for example: *cartograms:* Dougenik et al., 1985; Gastner/ Newman, 2004; Keim et al., 2004; Tobler 2004, van Kreveld; Speckmann 2007; *grid maps:* Wongsuphasawat 2016; *spatial treemaps:* Buchin, 2011; Buchin et al., 2012; Ghoniem et al., 2015; Slingsby et al., 2009; Slingsby et al., 2010; Wood/ Dykes, 2008). However, the degree of spatial transformation varies between these different techniques. A simplification according to four different attributes is helpful for conceptual clarification:

- **Layout:** The general layout of spatial units is essential for the overall recognizability of any geovisualization. Both cartograms (contigous) and grid maps have a static layout according to a fixed reference system, i.e. cartograms are usually positioned according to the centroids of the spatial units they represent, while grid maps are fitted on a previously arranged grid. The position of units in spatial treemaps is however more randomly determined by a specific layout algorithm. Different approaches exist, such as the *spatially-ordered treemap algorithm* proposed by Wood and Dykes (2008) or the *adjacency preserving algorithm* by Buchin et al. (2011). In contrast to the other two techniques, spatial treemap layouts are by definition space-filling and thus efficiently handle high data volumes while consuming relatively little space.

- **Spatial abstraction:** The degree of overall spatial abstraction is both a *factual* as well as *perceived* attribute. The main research to date has, however, mostly focused on the former dimension, that is quantitative metrics to determine the extent to which a geovisualization differs from the underlying original map. However, the degree of spatial abstraction between these three different techniques could also be derived through observational studies, user testing and perceptional feedback: While cartograms (contigous) still closely resemble maps, the degree of abstraction for grid maps is relatively higher. The most abstract form of spatial representation among the three presented techniques are treemaps, which place spatial units into a square-shaped-container, while often exhibiting high information-density. The overall layout of spatial treemaps thus makes for more advanced visualizations, which are usually less readable than either cartograms or grid maps (see Fig. 9, Wood/Dykes, 2008).

Fig. 9. An information-dense spatial treemap

- **Shape of geographic units:** The level of spatial abstraction is determined by the distortion of the geographical units’ attributes. Shape is one of the principal attributes. While (contigous) cartograms preserve some form of geographic shape (even if highly distorted), grid maps and spatial treemaps use *geometric shapes* such as squares, polygons or even symbols to depict data values. While it may be desirable to represent areas as “same-sized” geometric shapes for comparative purposes, this technique may compromise readability through oversimplification. In contrast, readability can generally be enhanced through the facilitation of cognitive offloading on the viewer’s side, i.e. through the recognition of characteristic geographic shapes (e.g. the well-known “boot”-shape of Italy) (Ghoniem et al., 2015).

- **Topology of geographic units:** The major implication of a preservation of geographic shape is that it sacrifices topology (original adjacencies between neighboring regions) and vice-versa. Grid maps can reduce

	cartogram (continous)	grid map	spatial treemap
domain	geography/ cartography	data journalism/ design	computer science/ information visualization
visual reference	map	map/ infographic	treemap
layout	non-space-filling anchored/fixed	partially space-filling anchored/fixed	space-filling, variable/ random
spatial abstraction	low/ intermediate	intermediate	high
shape of geographic units	geographic	geometric (rect, hex)	rectangular
topology of geographic units	preserved	partially preserved	partially preserved
readability	intermediate-high	high	low-intermediate
allows spatial hierarchy	no	(yes)	yes

this

Table. 1 Overview of visualization techniques for areal geodata and their spatial transformation attributes (source: author)

effect through the application of different geometric shapes, i.e. hexagon tiles are more likely to preserve original adjacencies than squares because grids are more flexible. In contrast, square-tiled grid maps and spatial treemaps are usually not very good at preserving adjacencies. Depending on the purpose of the visualization and the degree of topological distortion, this may be a problem, especially if the viewer expects certain areas to be adjacent to each other, which are then not adjacent in the visualization. Table 1 above summarizes the different spatial transformation attributes of the three presented techniques. It also refers to their domain of origin and their visual references, which differ for each technique.

3.2 Spatial purpose and readability

Whenever we visualize geo-referenced data, there is an inherent objective or "purpose" that we would like to achieve by doing so. The type of geovisualization technique we use, should therefore be aligned with our main objective, be it a) general communication of a phenomenon through data, b) the exploration or analysis of data or c) advocacy for a certain cause through data. Of course, it could also be a mix of different objectives. Choropleth maps are quite versatile in their use as they are relatively easy to understand and well-known by novices and experts alike. The three more advanced techniques presented in this paper, however are less common and therefore it makes sense to distinguish the appropriateness of each technique for different purposes. After all, the objective should be that the viewer of the visualization derives some form of insight from the represented data.

The ultimate benchmark should thus be *readability*. Does the visualization transport its main objective through appropriate and clear design? How well can a viewer grasp the main message and context of the represented data? For the three presented examples, readability depends largely on the individual design of each visualization, so making broad statements across an entire category of techniques may be problematic.

However, it does not seem far-fetched that certain techniques lend themselves better for certain objectives. For example, both grid maps and cartograms tend to exhibit higher levels of readability than spatial treemaps, because of their overall similarity to geographic maps. These techniques thus work better in environments where the viewer is time-constrained and expects to derive directed and quick insights from a visualization. This is the case in journalism or public media.

In contrast, spatial treemaps may be better suited for exploratory purposes and playful discovery with less time-constraints, such as browsing collections or datasets with higher data depth. They also better support combination, transformation and the toggling views between geographic and other layout types. On the other hand, cartograms - especially the contigous type - may be better-suited for the communication of data in advocacy scenarios, because of their ability to clearly highlight spatial imbalances and contrasts (see Fig. 10). Of course these applications should be understood as suggestions and would require further verification, e.g. through user studies.

3.3 Advancing metrics: From »hard« to »soft« indicators

Given the multitude of different approaches to dealing with spatial transformations within each of the three presented techniques, it makes sense to assess the quality of the suggested visualizations in terms of their degree of deviation from an original geographic map and thus their overall readability. As mentioned above, a number of quantitative metrics exist to assess the fit of different layout algorithms, such as Ghoniem et al. (2015)'s and Wood and Dykes (2008)'s set of indicators for spatial treemaps or Wongsuphasawat (2016)'s suggested metrics for grid maps. Based on the aforementioned work, the following set of three metrics can be distilled:

- **Compactness:** A more compact layout with a low aspect ratio is generally easier to read and thus preferable. In a grid map, this could be calculated as *number of rows x number of columns*.
- **Accuracy of adjacency:** Regions that are neighbors on a geographic map should also be neighbors in a geovisualization; non-neighboring regions should not be placed adjacent in the visualization accordingly.
- **Accuracy of direction:** The relative positions of regions in the visualization should be as close to reality as possible. This could be computed as the degree variation between two lines: i) the line connecting the two geographic centroids of neighboring regions and ii) the line connecting the geometric centers of nodes or squares in a cartogram, grid map or spatial treemap.

While the presented indicators are helpful in determining to what extent a geovisualization differs from a "real" map, the question can also be approached from a "softer" angle. To what extent is the viewer able to recognize the depicted visualization as a spatial representation of reality? In how far can already familiar geographic shapes be recognized and used to understand the underlying data? Beyond algorithmically-optimized solutions, there still seems to be a lack of quantitative and qualitative studies that focus on the deeper perception of geovisualizations.

This is a research gap that could be addressed and informed by design and user experience research methods. An increased focus on general recognizability of the geovisualization for different target audiences and use cases could help to clarify the picture and support the development of softer metrics that inform better design strategies for such representations.

4 Conclusion

This paper has presented an overview of three advanced techniques for the visualization of areal geodata beyond choropleth maps. It has outlined the characteristics and ideosynchracies of cartograms, grid maps and spatial treemaps in a comparative manner. Given that these techniques hail from different academic disciplines and domains with different conceptual and methodological traditions (i.e. cartography, data journalism/design and information visualization), this comparative approach should be understood as a first attempt to integrate interdisciplinary knowledge about the characteristics of traditional and new types of areal geovisualizations.

By reducing complexity to a set of common characteristics, different spatial transformation attributes have been identified. These may help to inform specific use cases for which these techniques could be meaningfully applied with a clear "spatial purpose" in mind. The paper has also presented a number of common quantitative metrics in use to judge the quality of such representations. However, a potential need for "softer" indicators, focussing on *readability and perception* has been identified, which could be informed by the cross-fertilization of research methods from cartography, information visualization and other disciplines, especially design and user experience research.

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