Cartogram Mapping and its Application to Cancer Data Visualization

Stephanie Kobakian, Jessie Roberts and Dianne Cook

Contents

1 Introduction **2**

2 Map displays for disease data **3**

3 Cancer atlases **3**
3.1 Overview of publicly available atlases . . . 6
3.1.1 The Environment and Health Atlas of England and Wales . . . 6
3.1.2 Globocan 2012: Estimated Cancer Incidence, Mortality and Prevalence Worldwide . . . 6
3.1.3 Atlas of Cancer in Queensland . . . 6
3.1.4 Bowel Cancer Australia Atlas . . . 6
3.1.5 United States Cancer Statistics: An Interactive Cancer Statistics Website . . . 6
3.1.6 Map of Cancer Mortality Rates in Spain . . . 7
3.1.7 Atlas of Childhood Cancer in Ontario . . . 7
3.2 Common statistics displayed . . . 7
3.2.1 Geographic hierarchies . . . 7
3.2.2 Population distribution . . . 7
3.2.3 Statistical uncertainty . . . 8
3.2.4 Demographics . . . 8
3.2.5 Socio-economic indicators . . . 8

4 Alternative to choropleths **9**
4.1 Micromaps . . . 9
4.2 Cartograms . . . 9
4.2.1 Contiguous . . . 12
4.2.2 Non-Contiguous . . . 15
4.2.3 Dorling . . . 15
4.3 Tile map . . . 16
4.4 Geofaceting . . . 16
4.5 Multivariate displays . . . 16

5 Comparison of maps and cartograms **18**

6 User interactions with maps **19**
6.1 Interaction and animation in publicly available atlases . . . 20
6.2 Under-utilised techniques . . . 22

7 Conclusions **22**

8 Acknowledgements **23**

9 References **23**

Abstract

Choropleth maps are widely used in cancer atlases, and traditionally communicate cancer statistics over geographic domains. The type of statistic displayed varies immensely, and effective choices can assist in the understanding of impact of cancer on a population. Atlases have moved from print media to web format, and the availability of graphical user interfaces, and user interaction and animation, greatly enhance the ability to communicate more information and positively engage readers. More use of alternatives to choropleth maps, such as cartograms, could be employed in online atlases, to better representation of spatial distributions, and show statistics on small areas. This is especially true for the geography of Australia, where the population is concentrated is small areas along the coastlines.

1 Introduction

Cancer statistics are usually delivered as an aggregated value for a geopolitical area. Presenting these statistics requires transforming individual observations into aggregations of communities as geographical units, in large part for privacy protection or political and policy purposes. The information could be as simple as counts per area (e.g. state, province, local government area, post/zip code). Counts alone are not sufficient to compare areas, because the populations of areas are all different. In this case, the counts data needs to be merged with population data to appropriately calibrate it to incidence, for example, rate per 100000 people. This type of data is collected on a routine basis for public health purposes, and may be made available to the general public as a service to the community. The task, then, is to examine what are the usual ways to communicate cancer statistics, to the public, are there alternative approaches, and what are the pros and cons of these choices.

A common approach to communicate cancer statistics, is to display statistics on a map. Using a choropleth map: the statistic is mapped to color and the geographic region is filled with this color. The viewer would then be able to examine the spatial distribution of the disease incidence, where there is a trend in longitude or latitude, or rural vs urban, or coastal vs inland, or even specific hot spots of the disease. Visualizing diseases on maps is often the first step in exploratory spatial data analysis and effectively helps in the formulation of hypotheses [1]. Disease maps help to present geographic patterns that may be overlooked in a table, obscuring the geospatially related statistics [2]. By providing a visual representation of cancer outcomes, geographic patterns of disease may be identified and effectively addressed with public health policy and actions. [3] recognizes one of the key challenges with mapping spatial patterns of disease is the design of visualizations. This paper addresses the visualization techniques and their applications to cancer statistics. Highlighting the differences and historic use of these displays.

The paper is organized as follows. The next section describes the choropleth map which is the common approach to disease maps. Section 3 surveys atlases in use today. Section 4 describes an alternative display, the cartogram what may be useful for countries that have heterogeneously sized geographic units. The pros and cons of these approaches is discussed in Section 5. Disease maps are more useful when made interactive, and common options are described in Section 6, along with a discussion of benefits and disadvantages. The last section summarizes the paper and discusses future directions.

2 Map displays for disease data

A choropleth map is used to display differences in the geographical distribution of data by spatial unit by shading areas of a map. The geography is faithfully rendered, and the color rendering is designed to reveal spatial patterns among data values. A choropleth is constructed by drawing the geographic or political boundaries, and filling the shapes with colors to represent values of a measured variable [4]. Figure 2 shows a choropleth of age-adjusted rate (per 100,000 people) of new cases of lung and bronchus in the USA, averaged over 2012 through 2016. The data was extracted from the official federal statistics by [5] on cancer incidence and deaths, produced by the Centers for Disease Control and Prevention (CDC) and the National Cancer Institute (NCI).

Early versions of choropleth maps used symbols or patterns instead of color. [6] discuss the use of choropleths to visualize cancer data, and [7] gives an overview of the development of these maps for displaying disease data.

Utilizing the state boundaries can make a map familiar to read [8], and allows viewers to visually infer the spatial relationships in the data. The familiarity of the geography is a worthy consideration when presenting results of spatial analysis. Just as geographers are no longer the only creators of maps, [6] suggests the audiences of spatial health data analysis have extended beyond researchers to the public, policymakers and the media.

Identifying and explaining spatial structures, patterns, and processes involves considering the individuals in communities and organizing communities into representable units [2]. In Figure 2, a west to east spatial trend of increasing rates, can be seen. There is also a spatial outlier – Utah has a noticeably lower rate that its neighbors. Also Kentucky has a noticeably high rate, and Maine also has a higher rate than its neighbors. There is something of a cluster of higher rates around the tobacco states.

While the areas are recognizable shapes, they are often politically driven boundaries with individual areas being of non-uniform size, containing different population densities and subject to change over time. The different population and geographical sizes of administrative areas can attract attention to the shades of the underpopulated but large areas [4], Skowronnek [9] calls this an area-size bias. Choropleths can inhibit visual inference when presenting human related statistics as the display may draw attention away from the 'potentially more important results in the more populous communities' that are geographically smaller [3].

3 Cancer atlases

Choropleth maps can be useful devices for communicating information to public on a familiar map base. A cancer atlas is a choropleth map, or collection of maps, representing cancer incidence and mortality for a country, or group of countries. In epidemiology, choropleths are often used as a tool to study the spatial distribution of cancer incidence and mortality. The data collection methods of cancer mortality rates across regions, and the administrative control within regions lends itself to choropleth visualization. [10] provides the definition of a cancer atlas, beginning with Haviland's

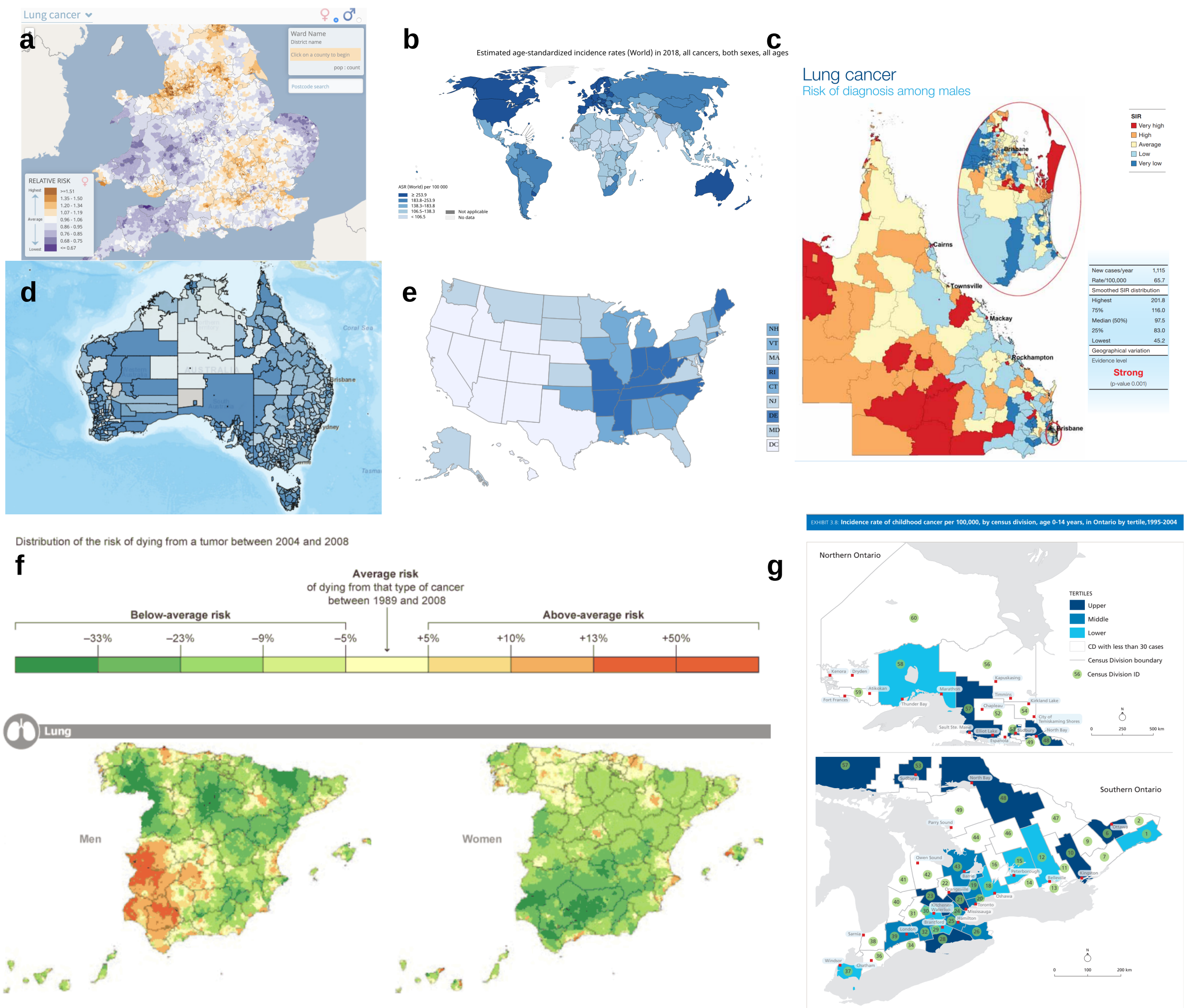

Figure 1: Publicly available choropleth cancer maps published between 2010 and 2015.

maps in 1875, they attribute UK cancer atlases to Howe (1963), and early work in US cancer atlases can be attributed to Burbank (1971). The increasing development and use of disease maps can be attributed to the availability of geographic information system software [3]. The choropleth maps presented levels via hatching or dots on a black and white scale. These atlases were key to developing hypotheses regarding areas with unusually high rates, geographic correlations, work related exposures, and high risk diets [10].

The presentation of cancer statistics has changed over time with greater access to computational power. Mortality rates are now often presented as relative rates of risk across the population, and age adjusted to correct for the higher prevalence of cancers in older populations. Howe [11] describes Stock's development of the standardized mortality ratios through the 1930s. Table 1 summarizes the measures presented in published cancer atlases, and provides a definition of each measure.

Table 1: Common statistics for reporting cancer information.

Measure	Details
1. Count	Crude cancer counts
2. Rate per 100,000	Cancer incidence per 100,000 population
3. New cancer cases per 100,000	Specific methods could not be found
4. IR (Incidence Ratio)	$(IR)_i = \frac{(Incidence\ Rate)_i}{Average\ Incidence\ Rate}$, Cancer incidence rate in region i over the average cancer incidence rate for the total region
5. Age Adjusted Rate per 100,000	Standardized by age structure or region
6. Age Adjusted Relative Risk	RR standardized by age structure in each region i
7. SIR (Standardized Incidence Ratio)	IR standardized by age structure in each region i
8. Below or above Expected	Alternative expression of the SIR
9. RER (Relative Excess Risk)	$RER = \frac{(Cancer\ related\ mortality)_i}{Average\ cancer\ related\ mortality}$ Represents the estimate of cancer related mortality within five years of diagnosis Also referred to as 'excess hazard ratio'

Cancer maps are effective tools for communicating to wide range of audiences, including the general public and others not trained in statistical analyses. These visualizations enable non-expert audiences to interpret the outputs of sophisticated statistical analyses. Cruickshank (1947) as cited by [7], discusses using visuals as a 'formal statistical assessment of the spatial pattern'. Overwhelmingly, cancer maps utilized to communicate to the public and other non-expert audiences are choropleths. These atlases provided Incidence, Survival and Mortality rates to the public on areal map bases.

The Atlas of Cancer in Queensland [12] focused on highlighting the difference in experience for those living in rural and disadvantaged areas, the Standardized Incidence Ratios (SIR) were modeled via Bayesian methods. The presentation of these rates considers not only the shapes of the areas, but also appropriate choices of color blind friendly color schemes, and categories of the values to highlight significantly different areas.

3.1 Overview of publicly available atlases

[13] identified 33 publicly available cancer atlases, published between January 2010 and November 2015. All of these use choropleth maps. All but one of these were published by non-commercial organizations, including not-for-profits, government, research organizations, advocacy groups or government funded partnerships. The use of choropleths within the public domain mirrors the heavy use of choropleth maps within the research literature, discussed above. The cancer atlases identified by [13] covered geographies from all around the world, most focused on single nations. Figure 1 displays a global (b), national (a, d, e, f) and state (c, g) choropleths. The sections below provide details on each of the maps within Figure 1.

3.1.1 The Environment and Health Atlas of England and Wales

Figure 1a contains an image from *The Environmental and Health Atlas of England and Wales* [14]. This map shows the relative risk for women developing lung cancer in England and Wales in 2010. The cancer data used to generate this map came from Office for National Statistics (ONS) (England) and from the Welsh Cancer Intelligence and Surveillance Unit (WCISU).

3.1.2 Globocan 2012: Estimated Cancer Incidence, Mortality and Prevalence Worldwide

The map seen in Figure 1b is from the *Globocan 2012: Estimated Cancer Incidence, Mortality and Prevalence* [15]. This global map shows age standardized incidence rates (per 100,000) for all invasive cancers for both men and women, aggregated at a national level for 2018. This map is published by the World Health Organization's International Agency for Research on Cancer. Data was sourced from cancer registries in each country, contributing registries can be seen in the supplementary material on the cancer atlas website.

3.1.3 Atlas of Cancer in Queensland

Figure 1c shows an extract from *The Atlas of Cancer in QLD* [16]. This map was published by the Queensland Cancer Council and shows the relative incidence ratio of lung cancer in males in the state of QLD within Australia based on data from 1998 to 2007. Data to generate this map was sourced from the *Queensland Cancer Registry.*

3.1.4 Bowel Cancer Australia Atlas

Figure 1d shows the *Bowel Cancer Australia Atlas* [17]. Published by *Bowel Cancer Australia* (Australia). This map shows the percentage of Australian males between 50 - 54 years of age that diagnosed with bowel cancer in 2016 in Australia. The source of the data is not provided.

3.1.5 United States Cancer Statistics: An Interactive Cancer Statistics Website

The *United States Cancer Statistics: An Interactive Cancer Statistics Website* [5] can be seen in Figure 1e. This map contains the incidence rate per 100,000, of all cancer types for men and women in the United States in 2016, aggregated at the state level. The map was published by the *Centers for Disease Control and Prevention.* Incidence data seen in this map were compiled from cancer registries meeting U.S. Cancer Statistics data quality criteria covering 100% of the U.S. population.

3.1.6 Map of Cancer Mortality Rates in Spain

The *Map of Cancer Mortality Rates in Spain* [18] can be seen in Figure 1f. The side by side maps show relative risk of lung cancer for men vs women based on data from 2004 to 2008. The source of the data and statistical methods are unknown.

3.1.7 Atlas of Childhood Cancer in Ontario

Figure 1g shows an extract from the Atlas of Childhood Cancer in Ontario and specifically displays the *incidence rate of childhood cancers* [19] per 100,000 (by census division) for children aged 0-14, in Ontario from 1995 to 2004.

3.2 Common statistics displayed

Cancer maps are powerful visualizations that summarize complex statistical analyses, however the statistics represented in these maps cannot tell the entire story. Supplementary graphs and plots are often included to add more depth and information to the map. [6] suggests additional materials such as tables, graphs, and text explanations support understanding and inference derived from maps, ensuring the message communicated will be consistent across a range of viewers. There are many visualizations used for displays of statistical summaries, these may be dot plots, bar plots, box plots, times series plots, cumulative distribution plots, scatter plots, Q-Q plots. These additional displays of the cancer distribution can provide alternative views of the cancer statistics, as well as the supporting statistics including error, confidence intervals, distributions, sample or population sizes, standard deviation and other measures. When presenting cancer maps, [10] believes the intuition derived from maps must be 'validated by rigorous statistical analyses', the supplementary statistics help for this validation.

3.2.1 Geographic hierarchies

While atlases are often used to describe differences between areas, statistics may be displayed at different levels of aggregation. Global health statistics can be aggregated to administrative and arbitrarily defined regions, such as those used by the World Health Organization and the United Nations [20]. World atlases can allow for displays of data aggregated into continents, countries, states, provinces and congressional districts [5].

3.2.2 Population distribution

It is extremely likely that each population area will have a different number of people. The distribution of the population residing in all areas may also be communicated in a table or histogram display [21]. Atlases can connect the population to the land available to them by communicating population density. Atlases can also connect the population to the land available to them by communicating population density.

3.2.3 Statistical uncertainty

Additional statistics that accompany an atlas often include a measure of the statistical uncertainty surrounding the statistics presented in a choropleth. In the review of atlases in the public domain, atlases were considered to report uncertainty to the non-expert user if they included a measure of statistical uncertainty either within or alongside the map [13]. The maps considered used standard and well-known measures including credible intervals and standard deviation, statistical significance, box plots and distributions. Other methods involve providing adjacent maps or overlapping maps with symbols [22]. The maps employing uncertainty ranged from static documents or infographics, to interactive online visualizations. Communicating the statistical uncertainty associated with the estimates occurs using confidence intervals (CI), credible intervals (CrI), statistical significance levels, box plots, distribution plots, and reporting sample size and standard deviations. Close to half of the atlases identified (42%, n=14) included some measure of uncertainty. The most common measure used to represent uncertainty were credible or confidence intervals (CIs).

3.2.4 Demographics

Demographics include information regarding the age and sex distribution of the areas presented. Sex is an important cofactor for cancer atlases. As some cancers are sex specific, and others may be found in both males and females, atlases often specify the relevant sex as part of the visual output in the displays. Digital atlases allow for users to interact with the controls of the displays, they can select males, females or both depending on the type of cancers explored.

3.2.5 Socio-economic indicators

Socio-economic indicators can explain how the experience of cancer prevalence varies for various members of a society. These indicators include unemployment rates, poverty rates, remoteness, and education levels achieved though, only a few atlases also explored the impact of rurality on cancer rates. These rates may also be explored as percentages above or below the mean or median value for the set of spatial areas. The Human Development Index can be used to understand the socio-economic experience of a community, as well as Income levels which can be sourced from the World Bank list of economies [20]. The areas are often ranked and allocated to quintiles; each quintile can be presented as categories describing the ranking.

One of the concerns of adding too much information to a map is the fear of cognitive overload [23] in which the user reaches an information threshold, beyond which will not be able to make sense of the information. These concerns are not unfounded, complexity and density of representation methods appear to overwhelm novice decision makers, while experts are able to use the detail more readily when making-decisions [24]. Interactivity is a design feature within modern mapping methods that can be used to incorporate additional information and complexity without overloading the user.

Interactivity enables supplementary information to be incorporated into online atlases without cluttering the display. Interactive design features found in online cancer maps include tool tip features, drop down menus, data selection, zooming and panning allow users to explore the map as they want more information and allow flexibility in the display [25]. The use of these supports were found in various online cancer maps identified by [13]. The controls for basic interactive features are often placed outside of the plot space [26], thus the map image is updated/replaced as the user interacts with the controls. For example, changing the population age or other demographic variables. Some more advanced interactions include direct interactions with the plot via the use of overlaid tool tip features, very few cancer atlases involve these more complex selection tools.

Additionally, interactivity allows the user to toggle between different variables, map views or multiple realizations of possible future scenarios [27]. Thus providing additional mechanisms for the users comprehension as well as the uncertainty of the available information ([28]; [29]).

These interactive features provide an opportunity for users to explore the additional information available. This helps users to understand and interpret the spatial distribution presented, as well as validate, explain or explore the presented statistics and their relationships to each other and/or their underlying spatial distribution. This allows relationships between spatial areas and diseases to be explored with sophistication in non-traditional but still 'cognitively accessible' ways [30]. The interactive features of the publicly available maps identified by [13] allow the exploration of geographic hierarchies, population distribution, statistical uncertainty, demographics and socio-economic indicators. [30] suggested LM plots as a solution to linking cartography and statistical graphics.

4 Alternative to choropleths

4.1 Micromaps

Choropleths are uni-variate displays, they do not inherently support multi-dimensionality. This makes it difficult to pair demographic, environmental and other factors with spatial distributions.

4.2 Cartograms

Choropleths imply uniformity of data across the geographic space however population densities are extremely unlikely to be uniform [9]. A cartogram displays abstracted geographic space, with the intention of improving the presentation of the statistic of interest. For a single variable of interest, each map area is changed to emphasize the distribution by representing the corresponding value, in comparison to the value of the other areas [31]. Changes in the map base are implemented by altering the boundaries, and therefore shapes, of individual areas.

Australia presents an extreme case of an urban rural divide. The land mass occupied by urban electoral districts is only 10% of Australia, yet 90% of the population live in these urban areas. To present election results on a choropleth map should be 'unthinkable', as it means diminishing the visual impact of majority of the electorates. A 1966 cartogram presented an alternative where boundary lines were largely straight line, and the result looked very little like the geographical shape of Australia. This issue is felt in any nation which experiences a spatially heterogeneous population distribution. As this feature of population distributions continues to intensify, the need for cartograms as an alternative to a choropleth map should only increase.

Choropleths may be considered true topological maps, however, if the land mass displayed covers enough of the globe, there must be a transformation or distortion to display the land in 2D [25]. The

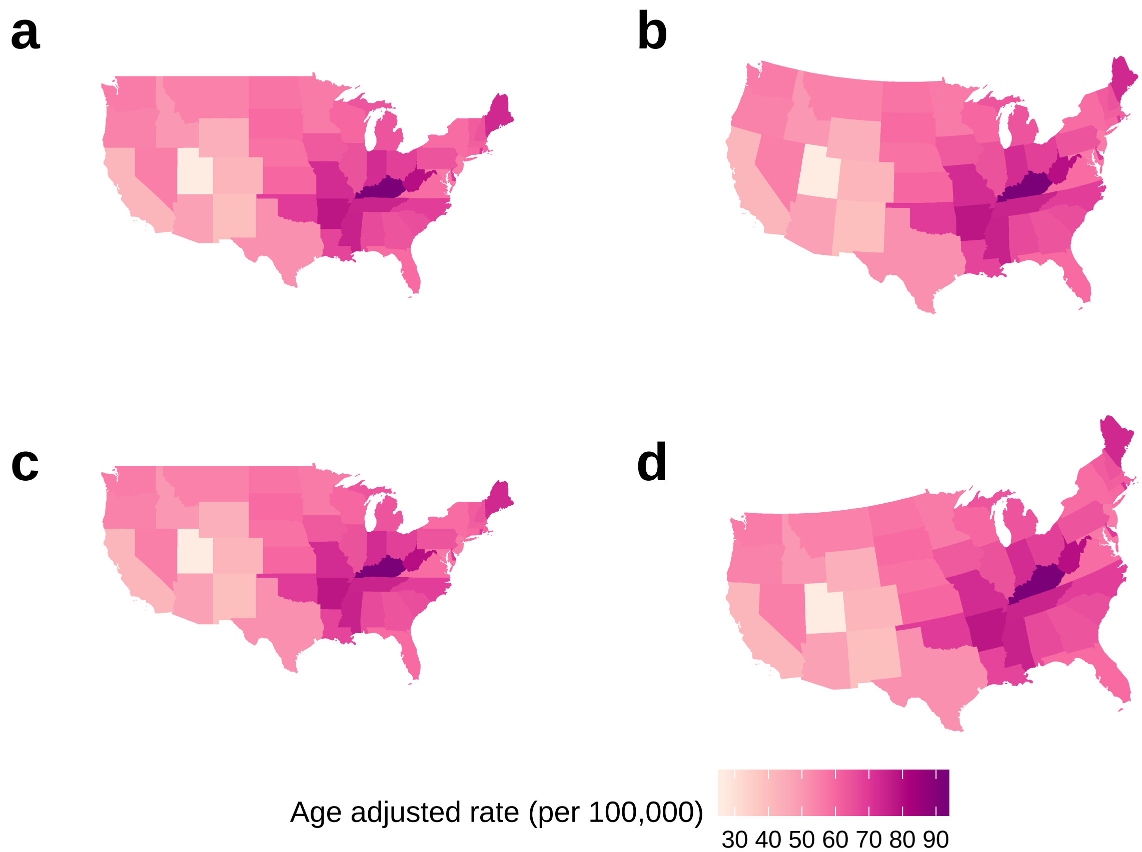

Figure 2: Four choropleth maps of the United States of America using various coordinate reference systems. Each state has been colored according to the average age-adjusted rate of incidence for lung and bronchus for females and males in the United States 2012-2016. The map projections alter the shapes and angles of the boundaries of each state. Maps a and b are similar in their straight edges, unlike maps c and d which curve on the northern United States border.

amount of distortion is related to the distance covered by the landmass displayed [32]. World map projections reflect the frequent perspectives used to view the earth. Choropleth maps will always be distorted if they cover enough of the globe, just like photographs of the globe from space. Choropleth creation requires choosing a map projection that shows a favorable distortion of the geography for presenting the set of spatial information. Selecting a display can prevent misinterpretation of global statistics, as global maps face the challenge of equitable displays of land mass on maps [33]. If the statistic presented on the map base relies on physical distance and is influenced by the topology there is no transformation needed, beyond choosing a reasonable projection.

Event cartograms change the area of regions on a map depending on the amount of disease related events, but this does not consider the effects of land area and population [22]. The purposeful distortion of the map space, transformed according to population density, is beneficial when a uniform density of the map base is desired. Population then becomes a uniformly distributed background for the statistic presented [34]. [35] suggests ‘population distribution is often extremely uneven in former British colonies’, this makes the distortion necessary [36]. When implementing a distortion of the geographical shape according to population, the resulting display is an area cartogram [37], or population-by-area cartogram [38].

Cartograms provide an alternative visualization method for statistical and geographical information. The key difference between a choropleth and a cartogram is the desirable augmentation of the size, shape or distance of geographical areas [35]. [25] suggests that white lies may be employed to create useful displays and map creators have the ability to draw lines that may distort the geometry and suppress features and it is easy for the average person to disregard the impact of transformations used to create cartograms. Cartograms may be seen as an extension of map transformations and projections. The favorable distortion is proportional to a value other other than actual earth size area [37]. A disadvantage of the conventional map is that sparsely populated rural areas may be emphasized, whereas the areas representing cities are very small, making interpretation of spatial patterns very difficult. The distortion of a cartogram accounts for the population density, preventing it from obscuring the spatial patterns [38]. The spatial transformation of map regions relative to the data emphasizes the data distribution instead of land size [39]. When visualizing population statistics, [35] considers this equitable representation design 'more socially just', or honest [40], giving due attention to all members of the population and reducing the visual impact of large areas with small populations [7]. [11] suggests that 'cancer occurs in people, not in geographical areas' and [36] believe that spatial socio-economic data, like cancer rates, are best presented on a cartogram for urban areas as the population map base avoids allocating 'undue prominence' to rural areas. [1] encourage the use of cartograms to highlight small areas and uncover local-level inequalities.

The creation of cartograms was historically in the hands of professional cartographers [41]. Early approaches including John Hunter and Jonathan Young (1968) and Durham's wooden tile method, Skoda and Robertson's (1972) steel ball bearing approach and Tobler's (1973) computer programs [35]. Geographical information systems allowed map users, and researchers to implement their own cartograms, but these systems are utilized depending on 'the effectiveness, efficiency, and satisfaction of the map products (Nielsen 1994), [41]. [11] discusses the impact of electronic computer-assisted techniques.

There are many alternatives to consider, the intended audience of the map, and its purpose are key points in cartogram use and creation. [35] reiterates: 'There is no "best" cartogram or method of creating cartograms just as there is no "best" map' (Monmonier and Schnell, 1988). [42] provided a framework to investigate implementations of the many algorithms presented, and the "statistical accuracy, geographical accuracy, and topological accuracy".

Table 2: Maps used to present statistics for the United States of America. Each state has been colored according to the average age-adjusted rate of incidence for lung and bronchus for females and males in the United States 2012-2016.

Map display	Details
a. contiguous cartogram	Each stated shape has been distorted according to the population of the state in 2015. The state of California has become much larger due to it's large population density. This draws attention to the densely populated North East region, and detracts from the less populated Mid West.

Map display	Details
b. Non - Contiguous	The geographic shape of the states has been maintained, but the size has altered according to the population of the state in 2015. The state of California has remained closer to it's original size than it's surrounding states. The North East states have remained closer to their geographical size, in the case of Massachusetts and Connecticut. This draws attention to the densely populated North East region, and the sparse Mid West.
c. Dorling	The states have been represented by a circle, but the size was determined by the population of the state in 2015. The North East states remain closer to their neighbors, and may be displaced from their geographic location. The sparsity of the population in the Mid West is highlight by the distance between the circles, located at the geographic centroids.
d. Hexagon Tessellation	Each state is represented by a hexagon of equal size. The neighbouring states are easily contrasted, however the north east regions has been displaced from their geographic location. The sparsity of the population in the Mid West is highlight by the light yellow color, the age adjusted rate in Kentucky is the darkest and its neighbors are similar.

4.2.1 Contiguous

A contiguous cartogram maintains connectivity of the map regions while areas are altered according to a statistic. This transformation often occurs at the expense of the shape of areas [39]. From a computer graphics perspective, [43] explain the application of 'map deformation' to account for the value assigned to each area, they provide three methods for creating value-by-area cartograms. Examples include Tobler's Pseudo-Cartogram Method, Dorling's Cellular Automaton Method [35], Radial Expansion Method of Selvin et al., Rubber Sheet Method of Dougenik et al., Gusein-Zade and Tikunov's Line Integral Method, Constraint-Based Method (Kocmoud and House) [39].

An intentional goal when creating the 1966 Census population cartogram for Canada was to maintain contiguity, while attempting to keep the actual shape of places. The end result was a 'very accurate isodemo-graphic map of Canada'. This intentional design goal coincided with the rising interest in urban geography and presentation of social statistics. Figure 3 a shows a population contiguous cartogram of the United States. All states are visible and the shape of the United States overall is still recognizable. In contrast, Figure 4 a shows an Australian contiguous cartogram also based on population. The south east is completely distorted, areas with low population are still large very the map, as their initial area was used to determine the area allocated in the contiguous cartogram.

To be able to recognise the significant changes, a reader will usually have to know the initial geography to find the differences in the new cartogram layout [37]. Tobler's Conformal mapping means to preserve angles locally so that the shapes of small areas on a traditional map and a cartogram would be similar. [39] presents this issue as conflicting tasks or aims, to adjust region sizes and retain region shapes.

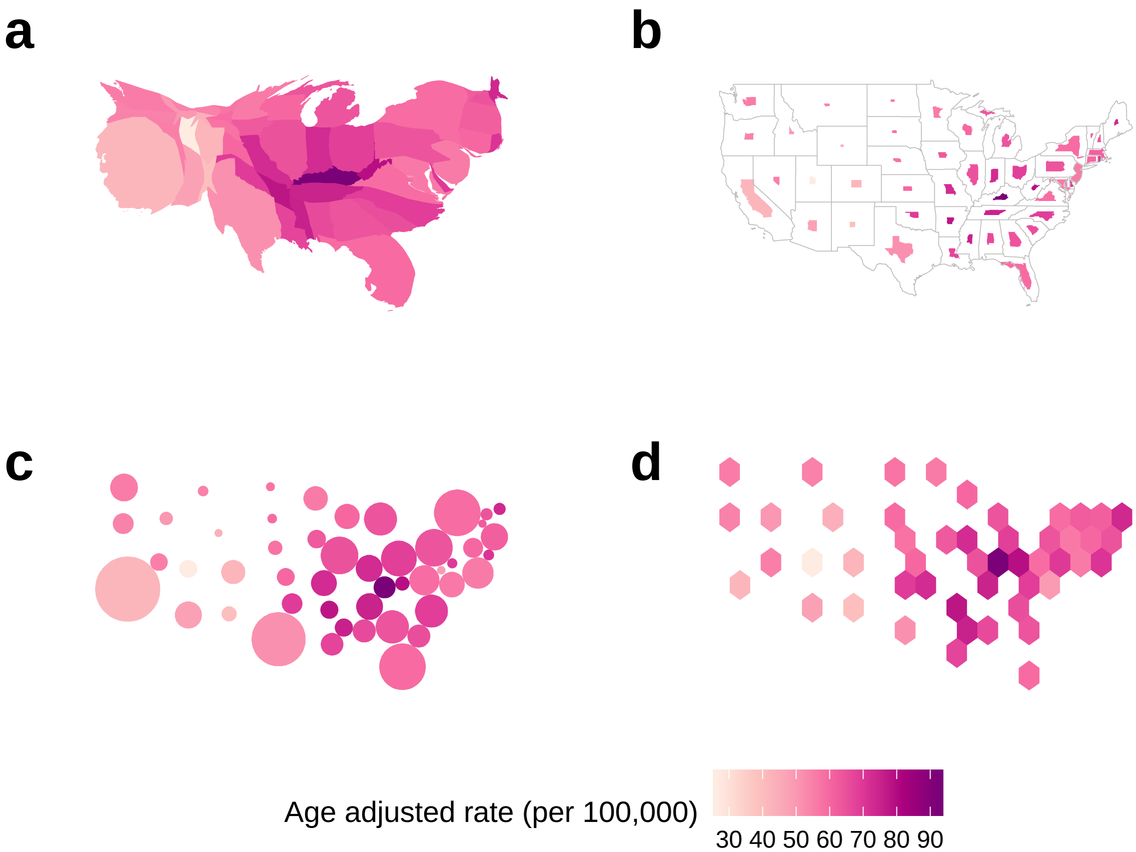

Figure 3: Common alternatives to maps, showing the same information as in Figure efchoroCRS for the United States of America: (a) contiguous cartogram, (b) non-contiguous, shape-preserved cartogram, (c) Dorling cartogram (non-contiguous), (d) hexmap (non-contiguous). In (a) - (c) the state has been resized, and reshaped, to match the 2015 population of the state. This provides a better sense of the extent of disease relative to the population in the country, and can help alleviate losing information about physically small but population dense states. In the hexmap (d) each state is given equal size, and thus equal emphasis.

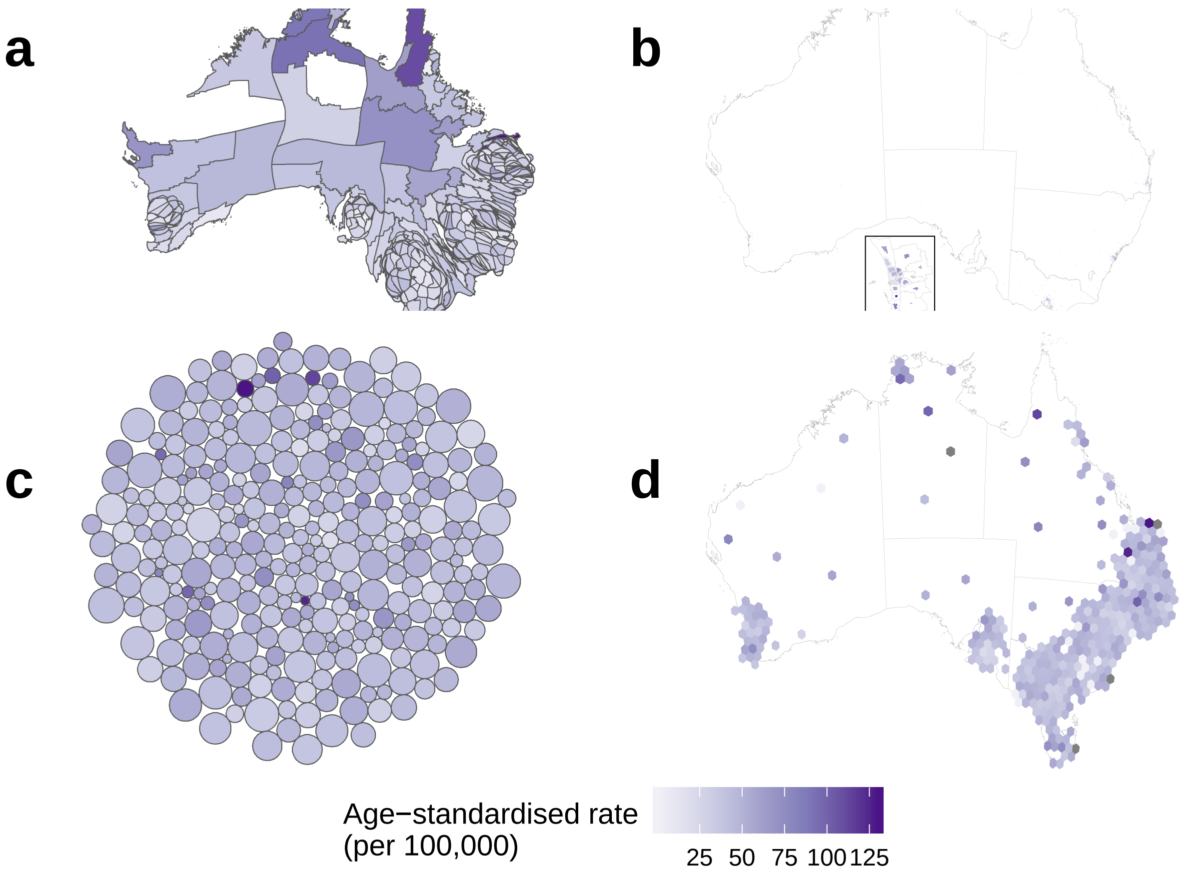

Figure 4: Alternative maps of the United States of America. Each state has been colored according to the average age-adjusted rate of incidence for lung and bronchus for females and males in the United States 2012-2016. Each stated shape has been distorted according to the population of the state in 2015. The state of California has become much larger due to it's large population density. This draws attention to the densely populated North East region, and detracts from the less populated Mid West.

4.2.2 Non-Contiguous

Non-Contiguous cartograms succeed in maintaining the shape of the areas presented. Each area stays in a similar position to their location on a choropleth map. The choropleth map base is often also plotted as a comparison point to highlight the change in area. The addition is the gap between areas, created as each individual area shrinks or grows according the associated value of the statistic. [37] discusses creation of these maps, the significance of the empty areas left between the geographic boundaries and the new shape, and the 'degree of difference from the original map that is the real message' of these displays.

As the trade-off regarding boundaries approaches simplicity, the distortion of region shapes on the contiguous cartogram presents an additional hurdle to visual recognition and this hurdle is not only eliminated on the non-contiguous cartogram but is replaced by the meaningful empty-space property [44]. The shapes are valuable for recognition and allows users to orient themselves on the display. Map creators can efficiently communicate with this kind of map by keeping the outlines or particular elements of the original in the new shape [40]. The scale of the areas does not impact on the shape recognition. However it may impact on the visibility of all areas if small areas expand beyond their boundaries. Figure 3 b shows small overlaps in the north east region of the United States. These overlaps are also shown in the non-contiguous cartogram of Australia in Figure 4 b.

4.2.3 Dorling

Daniel Dorling presented an alternative display engineers to highlight the spatial distribution and neighbourhood relationships without complex distortions of borders and boundaries. This approach opposes preserving the intricate shape details and is founded in the simple question put forward by Daniel Dorling [35]:

> "If, for instance, it is desirable that areas on a map have boundaries which are as simple as possible, why not draw the areas as simple shapes in the first place?"

He acknowledged the sophistication of contiguous cartograms but critiqued their 'very complex shapes,' he answers this with his implementation of maps created using 'the simplest of all shapes'. Circular cartograms use the same simple shapes for every region represented, and resizes the shapes according to the statistic represented or the population for a base map. This familiar shape may be more effective for understanding the spatial distribution than contiguous cartograms, as the 'nonsense' shapes used have 'no meaning' after distortions are applied [40]. To produce a compelling map, a gravity model is applied to avoid overlaps, and keep spatial relationships with neighbouring areas over many iterations. This implementation can work for up to 'one hundred thousand' areas. Figure 3 c shows the displacement of the north east region of the United States in the Dorling cartogram, the rest of the country is still recognizable. This displacement is shown to an extreme in 4 c the Dorling cartogram of Australia.

The groundwork for this approach had been laid in the mid 1930's by Raisz, and rectangular cartograms provide dramatic comparisons and are especially useful for correcting misconceptions communicated by geographic maps. [45] quotes the official definition of Value-Area Cartograms, the simplistic displays which represent each area as a single rectangle, sized according to the value of the statistic. This rectangular display also allows for tiling, where geographic neighbors placed in suitable relative positions also share borders, however contiguity may be sacrificed [46]. Rectangular cartograms allow for bi-variate displays, population can be effectively communicated by the size of each rectangular, and a second variable can be communicated using color [47].

A similar method, where each geographic area is represented using a square, tessellated to create a square grid. This method has been used by FiveThirtyEight, Bloomberg Business, The Guardian, The Washington Post, The New York Times and NPR. Each area is represented by a square of the same dimensions. Figure 3 d shows a hexagon tile map representing each state using a single hexagon.

Recommended criteria to contrast mapping methods include average cartographic error, and maximum cartographic error, correct adjacency, maximum aspect ratio, and suitable relative positions [47]. However, this does not consider the issues with actually producing rectangular cartograms. Algorithms for the creation of rectangular cartograms

4.3 Tile map

A tile map provides a tessellated display of consistent shapes. Each tile is usually one unit of measurement, this could be geographic regions such as states, or population based where one tile is used for a consistent measure of population.

A simple tile map presents the areas in a tessellated grid display, where geographic neighbors are found next to each other, with some necessary displacement employed for regions with more than four neighbors. These tiles may be labelled or colored to represent a value. Tile maps may be difficult to create, they are best created manually, with additional time and care required as the amount of geographic areas to include increases. [48] define the term 'mosaic cartograms' for hexagonal tile displays, where the number of tiles for each area can be used to communicate the statistic of regions. The complexity of the boundaries can be adjusted in the resulting display, as the size of the tiles used allows a trade-off be made between boundary complexity and simplicity.

4.4 Geofaceting

Tile maps can be extended to allow more than just simple coloring of tiles to present data. [49] formalizes the term geofaceting to describe a grid display, the arrangement of tiles to create a grid that mimics the geographic topology of the set of areas. Like tile maps, the arrangement of the areas can be reused for other spatial distribution visualizations. Geofaceting have the functionality of facets, often used to replicate visualizations for each subset of the data, in this case the data subsets are geographic. The amount of information able to be communicated has increased from one value per region in a tile map to one visualization, this is a more flexible display. Virtually any plot display can be fit into the tile representing the areas, allowing displays of multiple variables or values per geographic entity. As the amount of areas increase care must be taken to ensure legibility of the displays. [50] acknowledges that this display suffers when the areas have very irregular shapes and large size disparities, as manual creation of the grid is still required.

4.5 Multivariate displays

[51] present linked micromap plots to visually link geographic and statistical data, this serves as a solution to multi-dimensionality issues. This design is widely used in online atlas displays. Areas

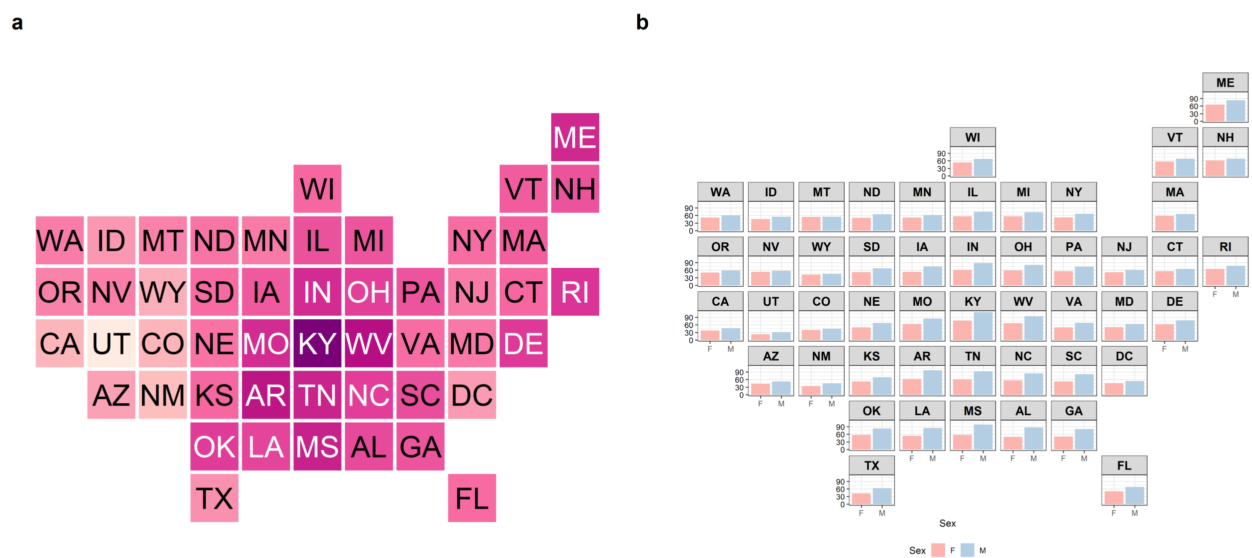

Figure 5: Two more alternative displays, tile map (left) and geofaceted map (right), showing state age-adjusted rate of incidence for lung and bronchus in the USA. In the tile map, the layout approximates spatial location, with each state being an equal box filled with colour representing cancer incidence. The geofaceted map shows bar charts laid out in a grid approximating the spatial location of the state. The age-adjusted rates for males and females is shown. This type of display allows multiple variables to be displayed for each geographic area.

are grouped based on their value for one variable, and additional columns provide displays that contrast the areas in each group by other variables. The display juxtaposes of choropleth maps and statistical plots; it shows one map per group of the key separating variable, in a row with each additional statistical plot. Linked micromaps predominantly utilize the choropleth map for displays of spatial relationships, that are seen when spatial neighbours are alotted to the same group. It is one of several alternative displays that allow maps to become bivariate displays, commonly used to present both an estimate and the associated uncertainty.

Bivariate choropleth maps [52] blend colour schemes to convey the intersection of categorised levels of an estimate and the associated uncertainty for each spatial area. [52] also suggests map pixelation, each region is broken into small pixels, the individual pixels are allocated values that reflect the uncertainty around the area's estimate by creating texture. This display can also be animated, with each frame produced by resampling the pixels. Areas with uncertain values will flicker more dramatically than areas with more certain values.

Solutions have been provided for bi-variate displays for movement data, containing Origin - Destination matrices and flow map representations [53]. This method makes the maps and matrix connections clear, and easy to link geographic areas with link lines not crossing. Bar charts can also be added to these to show group totals.

5 Comparison of maps and cartograms

To choose an appropriate map display, the map creator must consider the intended user, and message the map will communicate. Choropleth displays utilize more traditional cartographic methods, they are usually true to the topography, displaying familiar boundaries of countries, states or administrative areas. Highlighting the geographic distribution, and differences between equal spatial units. When there is a relationship between the variable being mapped and geographical features, a choropleth map would pair this information visually. Choropleth methods require a decision to be made about the projection of the display, in this case aim to find a map projection that gives the least distorted representation of the geography [54]. However a choropleth is limited to a uni-variate display, presenting a spatial distribution by filling each area with a color. These displays favor geographically large regions over small regions, though inset displays are often used to zoom in on a geographic area containing many small regions, this is seen in Figure 1 c of the state of Queensland, where the capital city Brisbane is highlighted by the inset map. Users can identify the areas relevant to them by the familiar boundaries, and can easily contrast the experience of geographic neighbors. The map is reusable and fit for many purposes.

Cartographers were historically the creators of geographic displays, and epidemiologists utilized the maps that had been prepared in advance. Cartograms with the population variable used to distortion the geographic map regions and boundaries are density equalising maps, that reduce the visual prominence of large, but low-population areas [22]. Cartogram displays incorporate the statistics and population into the design of the display, shifting and sometimes sacrificing familiar boundaries to draw attention to large outliers in the data space or population density. The unusual shapes are not longer familiar and may be difficult to compare. This can prevent effective comparison of the statistic. Cartograms also favor extreme statistics in the positive direction. Small extreme values are often lost due to the resulting small sized areas the do not draw user's attention. The change in the map based on one variable provides the opportunity for bi-variate displays, using the change in area for one variable, and color for another. The difference between the familiar map display helps highlight the impact of the disease on communities.

Alternative maps may replace the unexpected boundaries and shapes with familiar, simple shapes. This makes the spatial distribution the primary concept communicated by the display. Areas that are geographically close will maintain connectedness in some way, but the population and the statistic will dominate. Tile map displays may only allow one variable to be visualized if each region is given consistent map space, this occurs in geofaceting. Dorlings provide bi-variate displays as they use the size of the shape for one variable, and color for another. These alternatives are especially helpful for data aggregations where administrative boundaries break populations into groups. The experience of each community may be worth considering, as the experiences shared by the population within them may be similar due to the services and facilities they share. This display allows a more equitable view of each community, and does not minimise those that operate on a smaller geographic scale.

Faceting provides an opportunity to contrast the overall distribution of variables across a geographic space or collection of geographic areas. This display makes is difficult to compare specific regions.

Table 3: Summary of features and constraints on common mapping methods used to display cancer statistics (Y=Yes, N=No, S=Sometimes).

	Choropleth	Contiguous	Non-contig	Dorling	Tile maps	Geofacets
Spatial distortion	N	Y	Y	Y	Y	Y
Preserves neighbors	Y	Y	Y	S	S	S
Conceals small areas	Y	S	N	N	N	N
Uniform shape	N	N	N	Y	Y	Y
Univariate only	Y	Y	Y	S	S	N
Manual construction	N	N	N	N	Y	Y

Creating maps of diseases now involves more decisions to be made by map makers, rather than cartographers. Technology has played an enormous role in increasing the opportunities for map makers. The computation and graphics power have made creation, alteration and interactivity possible. as these options have expanded and it is the objectives of the investigator that will drive the choices. [6] and [2] have provided suggestions and comments to help map creators best communicate their health data and spatial analyses.

6 User interactions with maps

Interactivity and animation can add value to online atlases, by enabling additional information to be presented on-the-fly with one display. It also invites the viewer to engage with the display, and the information.

The word “interactive” is used, and perhaps, confused for many different graphics actions. At one extreme, it is synonymous with direct manipulation of the display, such as selecting an area, mousing over, or panning and zooming, using mouse action on the plot. At the other extreme, it refers to graphical user interfaces (GUI) such as selecting an item on a menu to change the variable being displayed, or checking a toggle box, or dragging a scrollbar. [50] provides a good overview of types of interactivity with plots. a key difference from an animation is that interactivity typically involves on-the-fly computations, and changes to the plot.

The primary interactive tools found in online cancer maps include

- drop down menus to select features,
- variable selection,
- tool tips,
- zooming and panning.

The latter two would be considered to be direct manipulation on the map display, and the former two are GUI interfaces. The effects of these actions are rapid, incremental, and reversible [55].

There is a long and extensive literature about interactivity with maps. [23] discuss the way adding interactive elements can alleviate cognitive overload caused when too much information is loaded onto a map. [24] discuss the trade-offs required for expert vs novice audiences. The expert might desire more complexity for decision-making but this could overwhelm a novice reader.

[25] says that interactivity can be used to allow users to explore the map for more information and provides flexibility for the display. The user can toggle between different variables, map views or even multiple realizations of future scenarios [27]. This provides additional mechanisms for the users to digest the uncertainty of the available information [28]. Where the needs of the audience is changeable and is the priority, the map creator can allow interactivity for map users to explore a data set through dynamic interactions that allow inspection of the data from many views [56]. [30] says user interaction with maps helps them to understand and interpret the spatial distribution of disease, to validate, explain or explore the presented statistics and their relationships to each other.

Animation, in contrast to interactivity, usually involves pre-computing views, and showing these in a sequence. [26] provided an overview of animation in association with the R package `gganimate` [57], with some focus on maps, explaining transitions between frames in a linear, to provide a fixed narrative to passive users. Animations are used to communicate a message by capturing and directing users attention. It is most often employed to show changes over time. The controls for basic animation are usually placed outside of the plot space [26], the map image is updated/replaced as the animation progresses.

[6] provide weather maps as a thoroughly developed example of animation of spatial displays to communicate information to the general public. The movement of a weather system will follow a forecasted path, all map users can follow the animated path of the weather system across the geography over a specified period of time.

The Australian Cancer Atlas [58] provides tours which change the display to draw user's attention to areas on the map that are relevant to the story. This implementation of animation gives users tools to plan their own exploration.

6.1 Interaction and animation in publicly available atlases

Many publicly available cancer atlases employ interactivity and/or animation. Figure **??** shows the interactive GUI tools provided with the public atlases discussed in Section 3.1. Mostly these are menus, and toggles, for choosing indicators, and subsets of the population.

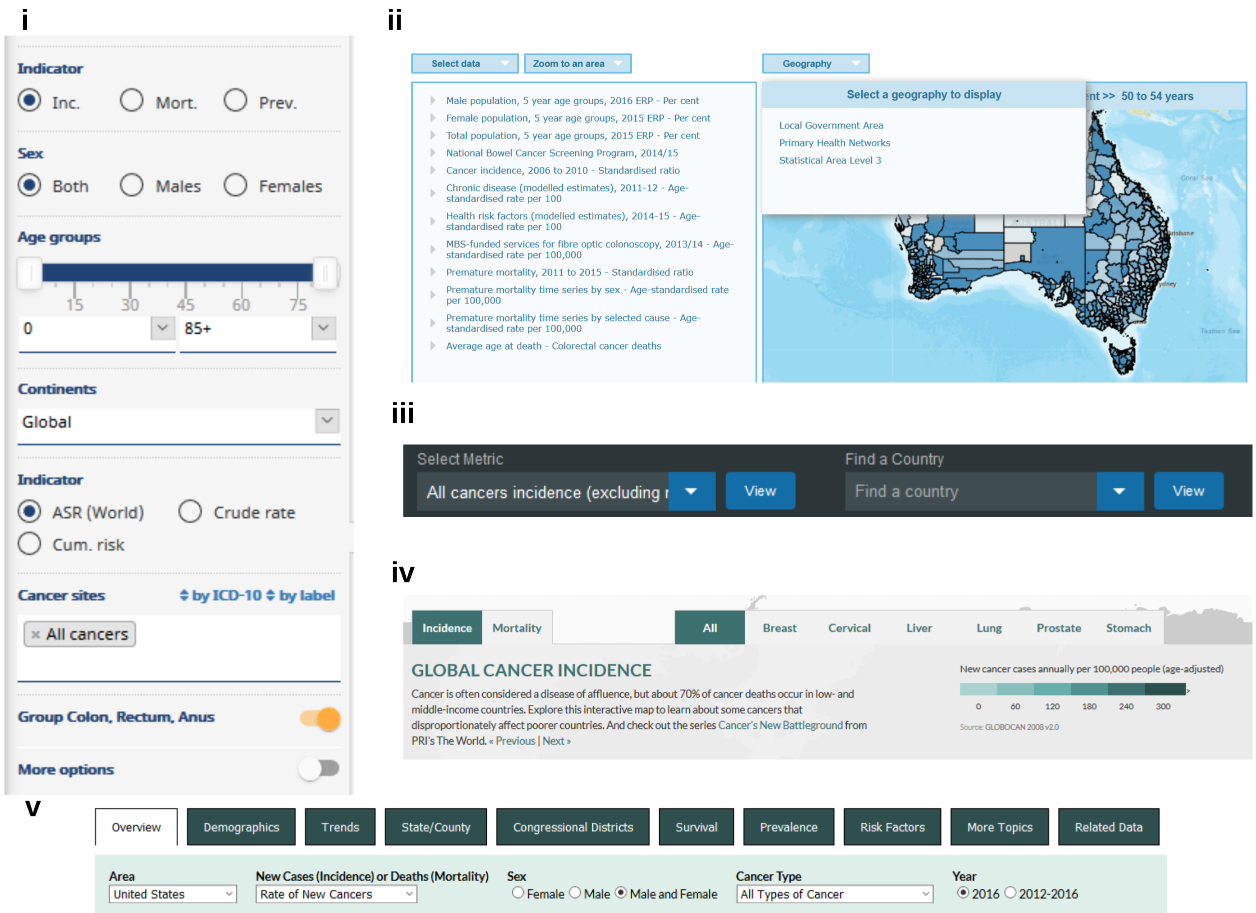

Figure 6: Interactive controls of displays in publicly available choropleth cancer maps: (i) GUI controls for statistic, sex, age groups, continents, and cancer types for Globocan 2018: Cancer Today, (ii) Menus for variable selection and zooming on Bowel Cancer Australia Atlas, (iii) Menus for choosing variables and countries in The Cancer Atlas, (iv) Tabs for different indicators and cancer types in Global Cancer Map, (v) Menus and toggles for variable and subset selection in United States Cancer Statistics: Data Visualizations.

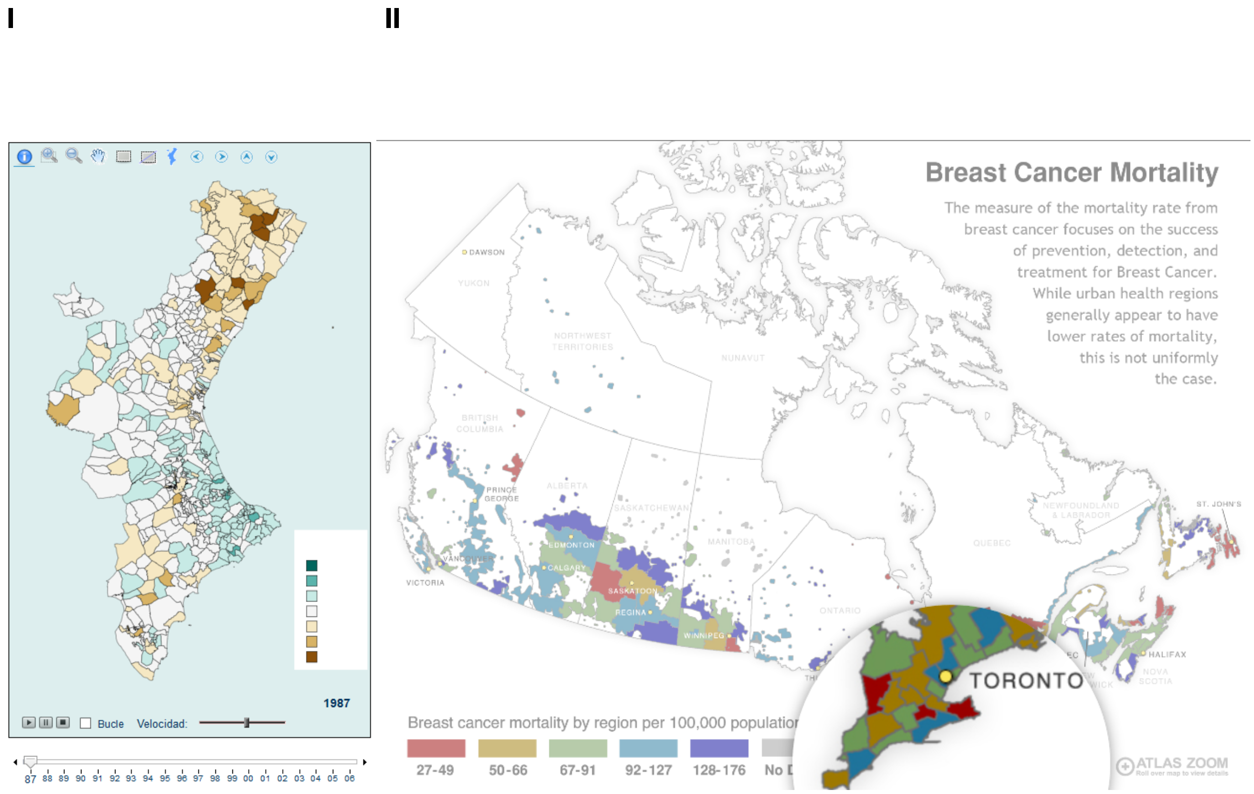

Figure 7: Two examples of advanced interactivity (and animation) in publicly available choropleth cancer maps: a. Linked maps and time series line plots, with temporal animation in Map of Cancer Mortality Rates in Spain, b. A highly responsive magnifying glass on a map of Breast Cancer Mortality in Canada.

6.2 Under-utilised techniques

Figure **??** shows two examples of more sophisticated interactive maps. The Spanish Cancer map (left) contains a linked display between a choropleth map, and time series plots of cancer change. In linked plots, changing values in one display will trigger changes of corresponding elements in another display. Here, the temporal change in the choropleth map can be played out as an animation. Mousing over the time series plots will highlight the line for a particular region. The Canadian Breast Cancer Mortality map (right) has a magnifying glass which allows the user to zoom into small areas. It is easy to control and shows precise details in the small areas.

7 Conclusions

This paper provides an overview of mapping practices as used for cancer atlases, and new approaches that could be adopted. The conventional approach is the choropleth map, and it is widely used. When there are small areas, as occurs in Australia where the population is concentrated on the coast, the information about cancer can be lost, and alternatives are needed. Making an inset can clarify congested regions but this breaks the viewers attention, because they need to shift focus from the map to the inset, and if there are many congested areas, many insets would be needed. The map alternatives, like cartograms and their variations, can be useful to allow the spatial distribution of cancer data to be digested.

There are many different statistics that are commonly used for display. The most basic is incidence rate, which is easy to understand. It is common to see relative rates in many maps which measure how far a region is above or below the average. The purpose of using a relative rate is, perhaps the desire to pinpoint the areas that need attention because they have higher than expected rates. However, we lose the incidence rate information and thus interpretability. A region might be much higher than average, but it may not be close to a health concern, because all regions have low incidence.

Interaction with maps is an important component to public atlases. A purpose is to provide access to more information than is possible to display in a single map, without overwhelming the viewer. Too many choices though can similarly overwhelm a viewer, and thus decisions do need to be made about content to provide, or hide, for accurate and comprehensive communication of information. Similarly, providing ways for users to interact with the display encourages engagement, and creative, efficient, elegant, interactive tools elicits curiosity about the data.

8 Acknowledgements

The authors would like thank Dr Earl Duncan, Professor Kerrie Mengersen, Dr Susanna Cramb and Dr Peter Baade for conversations on the content of this article.

The following R [59] packages were used to produce this paper: tidyverse [60], RColorBrewer [61], ggthemes [62], png [63], cowplot [64], sf [65], spData [66], cartogram [67], sugarbag [68], knitr [69], rmarkdown [70].

Files to reproduce the paper, and code to reproduce the plots, are available at https://github.com/srkobakian/review.

9 References

[1] Jahan F, Duncan E, Cramb S, Baade P, Mengersen K. Making More of Spatial Maps: A Bayesian Meta-analysis Approach. In:, 2018.

[2] Moore DA, Carpenter TE. Spatial Analytical Methods and Geographic Information Systems: Use in Health Research and Epidemiology. Epidemiologic Reviews 1999;21:143–61. doi:10.1093/oxfordjournals.epirev.a017993.

[3] Exeter DJ. Spatial Epidemiology. International Encyclopedia of Geography: People, the Earth, Environment and Technology: People, the Earth, Environment and Technology 2016:1–4.

[4] Tufte ER. Envisioning Information. Graphics Press; 1990.

[5] U.S. Department of Health and Human Services, Centers for Disease Control and Prevention and National Cancer Institute - Cancer Statistics Working Group. U.S. Cancer Statistics Data Visualizations Tool (data 1999-2016) 2019. http://www.cdc.gov/cancer/dataviz (accessed September 26, 2019).

[6] Bell BS, Hoskins RE, Pickle LW, Wartenberg D. Current Practices in Spatial Analysis of Cancer Data: Mapping Health Statistics to Inform Policymakers and the Public. International Journal of Health Geographics 2006;5:49. doi:10.1186/1476-072X-5-49.

[7] Walter SD. Disease Mapping: A Historical Perspective. Oxford University Press; 2001. doi:https://dx.doi.org/10.1093/acprof:oso/9780198515326.003.0012.

[8] Brewster MB, Subramanian SV. Cartographic Insights into the Burden of Mortality in the United Kingdom: A Review of "The Grim Reaper's Road Map". International Journal of Epidemiology 2010;39:1120–2. doi:10.1093/ije/dyp395.

[9] Skowronnek A. Beyond Choropleth Maps – A Review of Techniques to Visualize Quantitative Areal Geodata. Infovis Reading Group WS 2015/16 2016. https://alsino.io/static/papers/BeyondChoropleths_AlsinoSkowronnek.pdf.

[10] d'Onofrio A, Mazzetta C, Robertson C, Smans M, Boyle P, Boniol M. Maps and Atlases of Cancer Mortality: A Review of a Useful Tool to Trigger New Questions. Ecancermedicalscience 2016;10:670–0. doi:10.3332/ecancer.2016.670.

[11] Howe G. Historical Evolution of Disease Mapping in General and Specifically of Cancer Mapping. In:. Cancer mapping, Springer; 1989, pp. 1–21.

[12] Cramb S, Mengersen K, Baade P. Developing the Atlas of Cancer in Queensland: Methodological Issues. International Journal of Health Geographics 2011;10:9. doi:10.1186/1476-072X-10-9.

[13] Roberts J. Communication of Statistical Uncertainty to Non-expert Audiences. Master's thesis. Queensland University of Technology, 2019. doi:10.5204/thesis.eprints.130786.

[14] Emperial College London - Small Area Health Statistics Unit. The environmental and health atlas of england and wales: National male lung cancer rate 2010. http://www.envhealthatlas.co.uk/eha/Breast/ (accessed September 26, 2019).

[15] World Health Organization's International Agency for Research on Cancer. Globocan 2012: Estimated cancer incidence, mortality and prevalence 2017. http://globocan.iarc.fr/Pages/Map.aspx (accessed September 26, 2019).

[16] Queensland Cancer Registry. The Atlas of Cancer in Queensland (1998 - 2007) 2011. https://cancerqld.org.au/research/queensland-cancer-statistics/queensland-cancer-atlas/ (accessed September 26, 2019).

[17] Bowel Cancer Australia. Bowel Cancer Australia Atlas 2016. http://www.bowelcanceratlas.org/ (accessed September 26, 2019).

[18] El Pais. Map of Cancer Mortality Rates in Spain 2014. http://elpais.com/elpais/2014/10/06/media/1412612722_141933.html (accessed September 26, 2019).

[19] Pediatric Oncology Group of Ontario. Incidence Rate of Childhood Cancers, Atlas of Childhood Cancer in Ontario (1985-2004) 2015. https://www.pogo.ca/wp-content/uploads/2015/02/POGO_CC-Atlas-3-Incidence_Feb-2015.pdf (accessed September 26, 2019).

[20] Ferlay J, Ervik M, Lam F, Colombet M, Mery L, Piñeros M, Znaor A, Soerjomataram I, Bray F. Global Cancer Observatory: Cancer Today 2018. https://gco.iarc.fr/today.

[21] Northern Ireland Cancer Registry. All-Ireland Cancer Atlas (1995-2007) 2011. http://www.ncri.ie/publications/cancer-atlases.

[22] Kronenfeld BJ, Wong DWS. Visualizing Statistical Significance of Disease Clusters Using Cartograms. International Journal of Health Geographics 2017;16:19. doi:10.1186/s12942-017-0093-9.

[23] McGranaghan M. A Cartographic View of Spatial Data Quality. Cartographica: The International Journal for Geographic Information and Geovisualization 1993;30:8–19. doi:10.3138/310V-0067-7570-6566.

[24] Cliburn DC, Feddema JJ, Miller JR, Slocum TA. Design and Evaluation of a Decision Support System in a Water Balance Application. Computers & Graphics 2002;26:931–49. doi:10.1016/S0097-8493(02)00181-4.

[25] Monmonier M. How to Lie with Maps (Third Edition). University of Chicago Press; 2018. doi:10.1191/0309132505ph540pr.

[26] Pedersen TL. The Grammar of Animation 2018. https://youtu.be/21ZWDrTukEs (accessed November 16, 2018).

[27] Goodchild M, Buttenfield B, Wood J. On Introduction to Visualizing Data Validity. Visualization in Geographical Information Systems 1994:141–9.

[28] MacEachren AM. Visualizing Uncertain Information. Cartographic Perspectives 1992:10–9. doi:https://doi.org/10.14714/CP13.1000.

[29] Van der Wel FJ, Hootsmans RM, Ormeling F. Visualization of Data Quality. In:. Modern cartography series, vol. 2, Elsevier; 1994, pp. 313–31. doi:1473871616629516.

[30] Carr DB, Wallin JF, Carr DA. Two New Templates for Epidemiology Applications: Linked Micromap Plots and Conditioned Choropleth Maps. Statistics in Medicine 2000;19:2521–38.

[31] Dougenik JA, Chrisman NR, Niemeyer DR. An Algorithm to Construct Continuous Area Cartograms. The Professional Geographer 1985;37:75–81. doi:10.1111/j.0033-0124.1985.00075.x.

[32] Tobler WR. Geographic Area and Map Projections. Geographical Review 1963;53:59–78. doi:10.2307/212809.

[33] Raisz E. Rectangular Statistical Cartograms of the World. Journal of Geography 1963;35:8–10. doi:10.1080/00221343608987880.

[34] Berry BJL, Morrill RL, Tobler WR. Geographic Ordering of Information: New Opportunities. The Professional Geographer 1964;16:39–44. doi:10.1111/j.0033-0124.1964.039_q.x.

[35] Dorling D. Area Cartograms: Their Use and Creation. In:. Concepts and techniques in modern geography (catmog), vol. 59, 2011, pp. 252–60. doi:10.1002/9780470979587.ch33.

[36] Griffin TL. Cartographic Transformation of the Thematic Map Base. Cartography 1980;11:163–74. doi:10.1080/00690805.1980.10438102.

[37] Olson JM. Noncontiguous Area Cartograms. The Professional Geographer 1976;28:371–80. doi:10.1111/j.0033-0124.1976.00371.x.

[38] Levison ME, Haddon Jr W. The Area Adjusted Map. An Epidemiologic Device. Public Health Reports 1965;80:55–9.

[39] Kocmoud C, House D. A Constraint-based Approach to Constructing Continuous Cartograms. In:. Proc. Symp. Spatial data handling, 1998, pp. 236–46.

[40] Dent BD. A Note on the Importance of Shape in Cartogram Communication. Journal of Geography 1972;71:393–401. doi:10.1080/00221347208981697.

[41] Kraak MJ. Cartographic Design. In:. The International Encyclopedia of Geography: People, the Earth, Environment, and Technology, United States: Wiley; 2017, pp. 1–16.

[42] Nusrat S, Kobourov SG. The State of the Art in Cartograms. Computer Graphics Forum 2016;35:619–42. doi:10.1111/cgf.12932.

[43] Min Ouyang, Revesz P. Algorithms for Cartogram Animation. In:. Proceedings 2000 International Database Engineering and Applications Symposium (Cat. No.PR00789), 2000, pp. 231–5. doi:10.1109/IDEAS.2000.880581.

[44] Keim DA, North SC, Panse C, Schneidewind J. Efficient Cartogram Generation: A Comparison. In:. IEEE Symposium on Information Visualization, 2002. INFOVIS 2002, vol. 2002, IEEE; 2002, pp. 33–6.

[45] Tobler W. Thirty Five Years of Computer Cartograms. Annals of the Association of American Geographers 2004;94:58–73. doi:10.1111/j.1467-8306.2004.09401004.x.

[46] Monmonier M. Cartography: Distortions, World-views and Creative Solutions. Progress in Human Geography 2005;29:217–24. doi:10.1191/0309132505ph540pr.

[47] Kreveld M van, Speckmann B. On rectangular cartograms. Computational Geometry 2007;37:175–87. doi:10.1016/j.comgeo.2006.06.002.

[48] Cano RG, Buchin K, Castermans T, Pieterse A, Sonke W, Speckmann B. Mosaic Drawings and Cartograms. In:. Computer graphics forum, vol. 34, Wiley Online Library; 2015, pp. 361–70.

[49] Hafen R. Introducing geofacet. Ryanhafen 2018.

[50] Xie Y, Hofmann H, Cheng X. Reactive Programming for Interactive Graphics. Statistical Science 2014;29:201–13. doi:10.1214/14-STS4.

[51] W. PL, Carr DB, Pearson JB. micromapST: Exploring and Communicating Geospatial Patterns in US State Data. Journal of Statistical Software 2015;63:1–25. doi:10.18637/jss.v063.i03.

[52] Lucchesi LR, K. WC. Visualizing Uncertainty in Areal Data with Bivariate Choropleth Maps, Map Pixelation and Glyph Rotation. Stat 2017. doi:10.1002/sta4.150.

[53] Yang Y, Dwyer T, Goodwin S, Marriott K. Many-to-Many Geographically-Embedded Flow Visualisation: An Evaluation. IEEE Transactions on Visualization and Computer Graphics 2017;23:411–20. doi:10.1109/TVCG.2016.2598885.

[54] Tobler W. Unusual Map Projections. In:. Cartographic Perspectives, Association of American Geographers; 1999.

[55] Perin C. Direct Manipulation for Information Visualization. Theses. Université Paris Sud - Paris XI, 2014.

[56] Dang G, North C, Shneiderman B. Dynamic Queries and Brushing on Choropleth Maps. In:. Proceedings Fifth International Conference on Information Visualisation, 2001, pp. 757–64. doi:10.1109/IV.2001.942141.

[57] Pedersen TL, Robinson D. gganimate: A Grammar of Animated Graphics. 2019.

[58] Cancer Council Queensland, Queensland University of Technology, and Cooperative Research Centre for Spatial Information. Australian Cancer Atlas 2018. https://atlas.cancer.org.au.

[59] R Core Team. R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing; 2019.

[60] Wickham H. tidyverse: R packages for data science 2017. https://CRAN.R-project.org/package=tidyverse.

[61] Neuwirth E. RColorBrewer: ColorBrewer palettes 2014. https://CRAN.R-project.org/package=RColorBrewer.

[62] Arnold JB. ggthemes: Extra Themes, Scales and Geoms for 'ggplot2' 2019. https://CRAN.R-project.org/package=ggthemes.

[63] Urbanek S. png: Read and write PNG images 2013. https://CRAN.R-project.org/package=png.

[64] Wilke CO. cowplot: Streamlined Plot Theme and Plot Annotations for 'ggplot2' 2019. https://CRAN.R-project.org/package=cowplot.

[65] Pebesma E. Simple Features for R: Standardized Support for Spatial Vector Data. The R Journal 2018;10:439–46. doi:10.32614/RJ-2018-009.

[66] Bivand R, Nowosad J, Lovelace R. spData: Datasets for Spatial Analysis 2019. https://CRAN.R-project.org/package=spData.

[67] Jeworutzki S. cartogram: Create Cartograms with R 2018. https://CRAN.R-project.org/package=cartogram.

[68] Kobakian S, Cook D. sugarbag: Create Tessellated Hexagon Maps 2019. https://CRAN.R-project.org/package=sugarbag.

[69] Xie Y. knitr: A General-Purpose Package for Dynamic Report Generation in R. 2019.

[70] Allaire J, Xie Y, McPherson J, Luraschi J, Ushey K, Atkins A, et al. rmarkdown: Dynamic Documents for R. 2019.