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RESEARCH ARTICLE

Comparison of Map Visualization Techniques Used for Spatial and Spatio-Temporal Data: An Analytical Survey Applied to COVID-19 Data

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ABSTRACT

Currently, there are numerous techniques that are either in use or proposed for use for spatial and spatio-temporal visualization of data. Visualization techniques are commonly used in various areas including errands of daily life, weather, medical care, economics, social media, politics, and science, among many others. We have previously demonstrated the application of several tools and spatial data visualization techniques to visualize and analyze COVID-19 data. In this study, we aim to investigate the frequency of encounter and the extent and type of use of six data visualization techniques, namely: Choropleth maps, Heat maps, Hexagonal binning, Dot maps, Bubble maps, and Cartogram maps, using a survey of popular techniques.

CCS Concepts

• Human-centered computing ~ Visualization ~ Visualization application domains ~ Geographic visualization

• Information systems ~ Information systems applications ~ Spatiotemporal systems ~ Geographic information systems

Keywords: **S**patial Data, Spatio-Temporal Data, Visualization Techniques, Data Visualization and Analysis.

1. Introduction

All aspects of daily human life, such as errands, weather conditions, medical care systems, communication patterns, economics, social media, politics, scientific research, and so on, are becoming increasingly technology dependent. An important source of information that is steadily growing is the daily collection of data from such human activities. The best way for end users to interact with and analyze such data is to have it organized, processed, cleaned, analyzed, and visualized. Regardless of its significance, data remains facts with no meaning. To obtain meaning, raw data such as numbers (1, 14, 100, 1500, etc.) must be examined and cleaned. When raw data is given meaning, it transforms into useful information. To have a correct explanation of the data, the end-user must be able to communicate with the data in an easy and clear manner. This is best accomplished using data visualization. Data visualization includes displaying data in tables or maps. Presenting collected spatial data graphically (visualizing it on a map) makes it easier to interpret and analyze, as well as allowing the user to identify areas of interest in the data for additional computation and further analysis [1]. Maps are a common way of data visualization where features of relevant objects and areas are easily visualized through different kinds of maps (geographical maps, building plan maps, website layouts, *etc.*). Maps are utilized by data visualization techniques.

In a previous work, 6 data visualization techniques (Choropleth maps, Heat maps, Hexagonal binning, Dot maps, Bubble maps, and Cartogram maps) were used to visualize and analyze COVID-19 data in the state of Texas [1]. Along the same lines, the purpose of this study is to report on the results of a survey (https://spatialvisualizationtechniquesi.questionpro.com) carried out to explore the use and popularity of data visualization techniques, focusing on these six techniques. The survey also attempts to categorize the use of the various techniques by end users and field of application.

2. Survey methodology

In this section we outline how we conducted the survey. The survey was conducted between April 22, 2021, and August 18, 2021.The survey questionnaire was shared with 527 participants located in different countries. It was designed using questionpro (https://spatialvisualizationtechniquesi.questionpro.com) and disseminated through social media and targeted emails to undergraduate and graduate students as well as professionals from various disciplines including computer sciences, medical, business administration, engineering, and others.

2.1. Survey questions

At the beginning of the survey, there were 2 demographic questions that allowed us to determine: 1) the familiarity of the respondents with the spatial visualization techniques; and 2) the area of study/work/research the respondents were involved in. The survey consisted of 61 questions that are divided into 7 parts. Each part is related to one of the spatial visualization techniques.

The first question (Figure 1) checked the familiarity of the respondents with the spatial visualization techniques. Four levels of familiarity were evaluated, and some respondents had more than one level of familiarity, depending on the visualization technique.

Knowledge (encountered an example while browsing the web; 71 respondents)
Introductory Knowledge (got introduced to them in a course; 29 respondents)
Intermediate Knowledge (analyzed or drew several spatial visualization maps; 17 respondents)
Advanced Knowledge (used spatial visualization maps frequently at work/study/ research; 7 respondents)

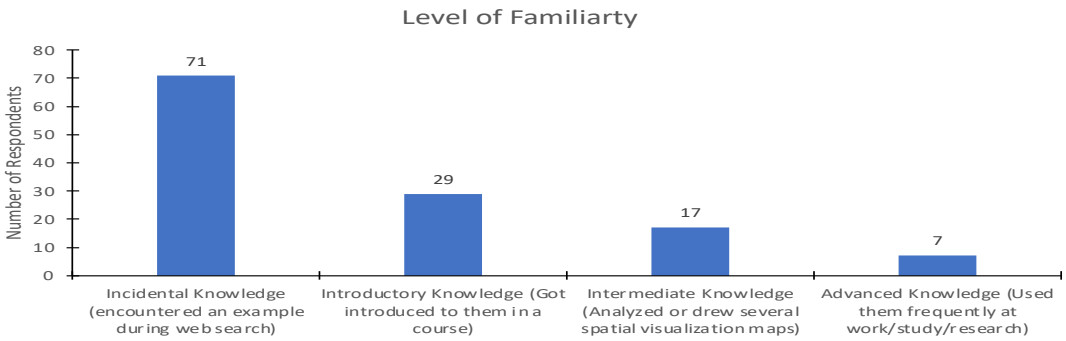

Figure 1: Familiarity with visualization techniques

The second question (Figure 2) checked the area of study/work/research the respondents were involved in. 62 of 117 (53%) were in computer science area, 20 (17%) were in the engineering (architecture, mechanical engineering, and telecommunication engineering) area,16 (13.5%) were in the business area (business analyst, MBA, and business computer), 11 (9.5%) were in health care area (medicine, nursing) and 8 (7%) were in the teaching, journalism, education and food technology areas.

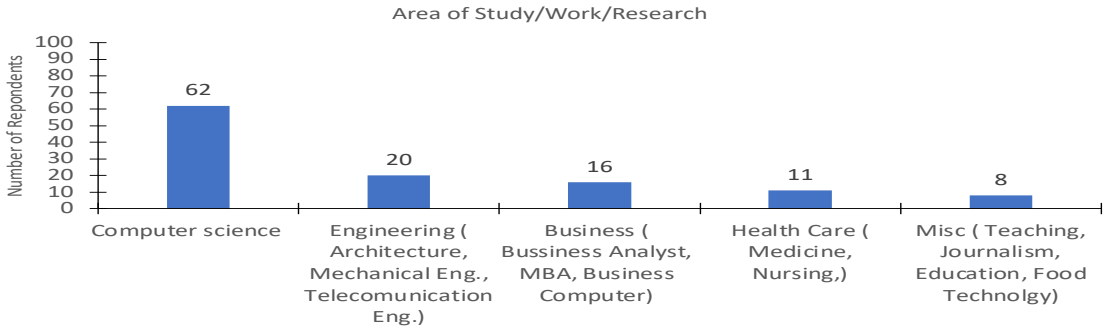

Figure 2: Respondents' area of study, work, or research

In addition, the survey questions the participants if they have encountered the techniques; in case they did not use it to visualize data.

2.2. Survey response rate

There were 117 responses out of which 99 fully completed the survey (Table 1). Out of the 527 respondents who accessed the survey, 212 (40.17%) work/study/research was in the USA, 202 (38.46%) was in Lebanon, 32 (5.98 %) was in Canada, 27 (5.13%) was in Saudi Arabia and 54 (10.24%) was in Australia, United Arab Emirates, India, Bangladesh, Germany, and Qatar (Figure 3).

Viewed	Started	Response rate	Completed	Completion rate
527	117	22%	99	85%

Table 1: Survey respondents

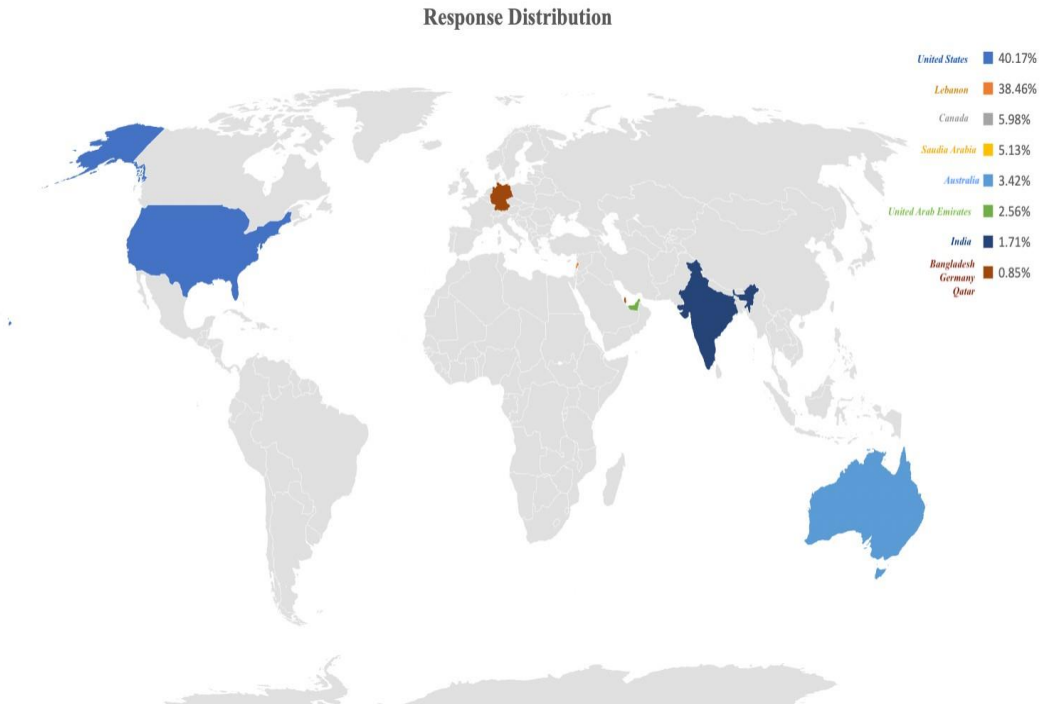

Figure 3: Distribution of survey respondents by country

3. Spatial and Spatio-Temporal Visualization Techniques

Spatial/Spatio-Temporal data, is any data set that contains geographic information, such as (x, y) coordinates, which are necessary for data visualization. Spatial/Spatio-Temporal visualization techniques were developed to provide visual information about spatial data to researchers and other end users, allowing for better data processing and analysis. Below we define the 6 visualization techniques and give examples of their representation of data by visualizing the daily confirmed cases of COVID-19 in the counties of the state of Texas, USA on July 19, 2022. In addition, each section contains the results of the question related to the specific technique.

3.1. Choropleth Map

A choropleth map is a thematic map that represents the value or range of values of some variable by using various colorings, color shades, or pattern fills in various areas of the map. For the represented geographic areas, different color shades are used. The shaded areas are employed according to statistics and values that are displayed on the map [1]. Significant efforts have been invested into development of various methods of data classification using choropleth mapping including visualization of data of population density, women participation in labor force, per capita income, presidential election vote percentages, *etc.* [2].

Figure 4 shows daily COVID-19 confirmed cases per county in Texas using the choropleth map technique. Each county has a different number of cases, so it is colored differently based on the legend found on the right of the figure. In Figure 4, dark colors represent counties with more confirmed cases on a particular date, in this case July 19, 2022. Lighter colored counties represent counties with fewer cases on that date.

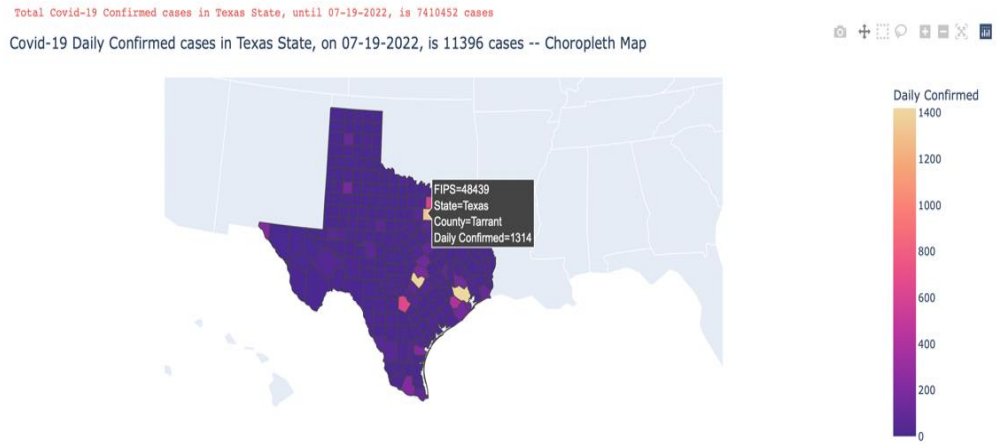

Figure 4: Choropleth Map showing the total COVID-19 cases in the state of Texas, USA by county on July 19, 2022

3.1.1 Choropleth Map Survey Answers and Analysis of Responses. The respondents to the first question in this section, who had various backgrounds and fields of study/work, were asked if they had ever encountered the Choropleth Maps technique. sixty-seven respondents (around 54%) have previously encountered Choropleth Maps (Figure 5A). This is a relatively high percentage, but given the widespread use of Choropleth Maps, a higher percentage of encounters was anticipated. A total of 35 respondents have used Choropleth Maps to visualize census and election data, 26 visualized pandemic spread data, 16 visualized GIS data, and 12 visualized business data using Choropleth Maps (Figure 5B). Eleven respondents have previously applied and used Choropleth Maps (Figure 5C). Three of these 11 respondents knew more about Choropleth Maps than the other five techniques (Figure 5D).

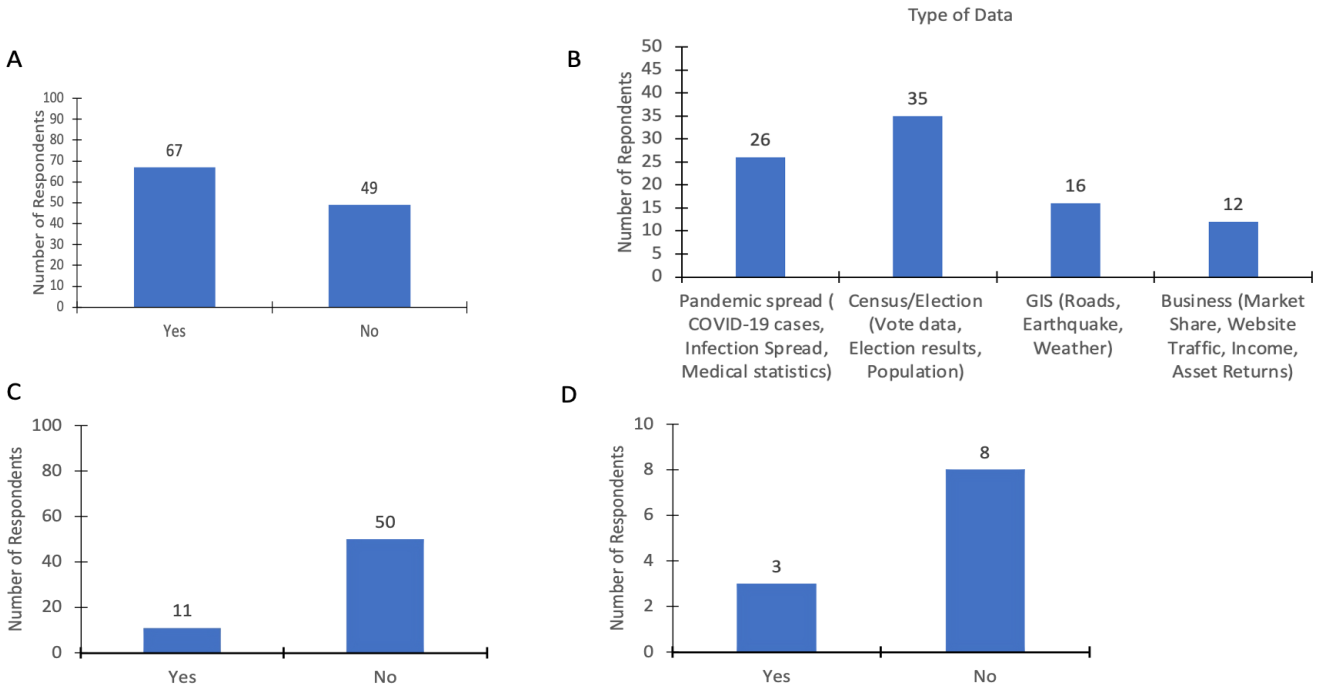

Figure 5: (A) Respondents' encounter of Choropleth Maps. (B) Type of data encountered with Choropleth Maps. (C) Respondents that have applied Choropleth Map to visualize data. (D) Choropleth Map usage based on Knowledge.

3.1.2 Choropleth Map Advantages and Disadvantages. The advantages and disadvantages of Choropleth Map visualization technique, based on the respondents' answers, are summarized in Table 2. The answers correlate with the level and type of acquaintance of the respondents with the technique.

Advantages	***Disadvantages***
It represents the 3D dimension in measuring and diagnosing of cornea.	Combines data with geographic analysis.
Helped display distribution with color gradients very clearly.	
Simplicity, beauty.	
Balance between description and insight.	
Better visualization.	
Choropleth maps are easy to design when compared to other techniques.	
Comprehensive data are explained visually with ease.	
Ability to drill-down into data based on geo-locations.	

Table 2: Advantages and disadvantages of Choropleth Map according to study participants

3.2. Heat Maps

Colors are used in heat maps to convey numerical data in red, green, and blue (RGB) colors as a linear function of the data value and shades [3]. Instead of having discrete changes by boundaries, as in the case of a Choropleth Map, the color variations depict continuous changes in the data values on the map.

It is simpler to understand relationships between data points and make generalizations about trends when using heat map spatial representation. It is a continuous space that is represented by color intensities, with some areas having denser color representations than others. On the other hand, a visualization's legibility may be negatively affected if colors are used excessively. The color scheme must also consider cultural association with different characteristics, such as red has connotations with heat, anger, passion, and diverse political interpretations.

As an example, daily confirmed cases of COVID-19 in the state of Texas per county are presented on a Heat Map (Figure 9). The visualization used Python coding of COVID-19 data to obtain the heat maps. Only counties which are hot spots of COVID-19 infection could be identified in the figure, and the actual number of confirmed cases cannot be determined. No statistical numbers could be inferred.

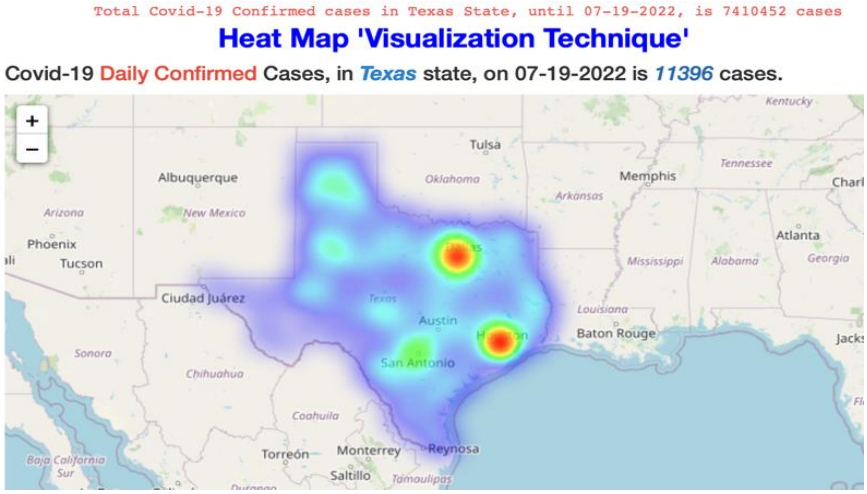

Figure 6: Heat map visualization for COVID-19 data in the state of Texas by county on July 19, 2022 generated using a Python code

3.2.1 Heat Map Survey Answers and Analysis of Responses. 91 respondents (almost 74%) reported having encountered the Heat Map technique before (Figure 7A). This is a high encounter rate knowing that that Choropleth Maps are more commonly used, in general. Out of the 91 respondents, 55 visualized GIS data, 11 betting data,7 pandemic spread data, and 5 respondents visualized other sorts of data (Figure 7B). 19 respondents indicated that they have previously not only encountered but also applied Heat Maps (Figure 7C). Five of the 19 respondents had higher knowledge of this visualization technique than any of the other techniques (Figure 7D).

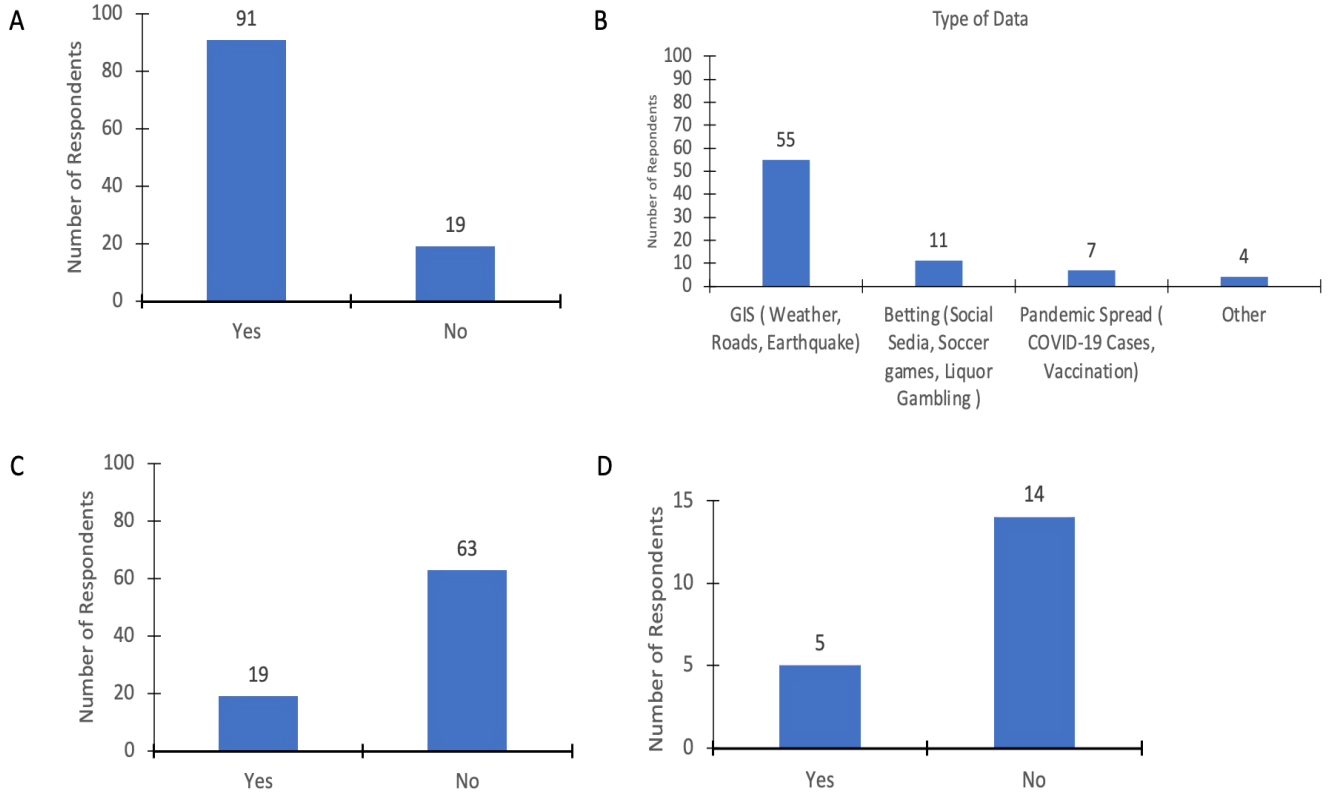

Figure 7: (A) Respondents' encounter of Heat Map. (B) Type of data encountered with Heat map. (C) Respondents that have used Heat Map. (D) Heat Map usage based on Knowledge.

3.2.2 Heat Map Advantages and Disadvantages. The respondents' answers concerning the advantages and disadvantages of Heat Map visualization technique are more numerous than those for Choropleth Maps, reflecting the popularity of Heat Maps among the respondents, and are summarized in Table 3.

Advantages	***Disadvantages***
It gives the required visual data	Sometimes an intensive real time heat map might cause overheating and restarting of the machine
It is the common standard in measuring corneal topography and tomography	Limited discernibility due to color map choice
Performs survey and process modeling	Methods of calculation can get complicated
Conveys message clearly	
The visualization is easier to understand depending on the colors and densities visualized	
It's quite simple and a suitable way for visualizing data in a way that satisfies the users' eyes	
Clarity	
Explains the datasets very well and shows the area with large number of traffic clearly	
Displays shear and stress levels on 3D surfaces	
It gives a concise and large view of the data	

Table 3: Heat Map technique: advantages and disadvantages

3.3. Dot Maps

Dot maps, also known as point maps, dot density maps, or dot distribution maps, represent data with dots. Dots are placed into an approximate location where the data value was obtained. In general, dots are of equal size and are distributed geographically. By hovering around the dot on the map, the user can obtain information [1].

Figure 8 shows a dot map of the state of Texas counties with 11396 daily confirmed COVID-19 cases on July 19, 2022. Each county was assigned a single red dot, but the actual number of daily confirmed cases in that county cannot be interpreted from the size of the dot as they are equally sized. By hovering over the dot on the map, a small pop-up window will show the name of the county and how many confirmed COVID-19 are present. In Figure 8, the popup window illustrates that the daily confirmed cases of COVID-19 in Dallas County is 729.

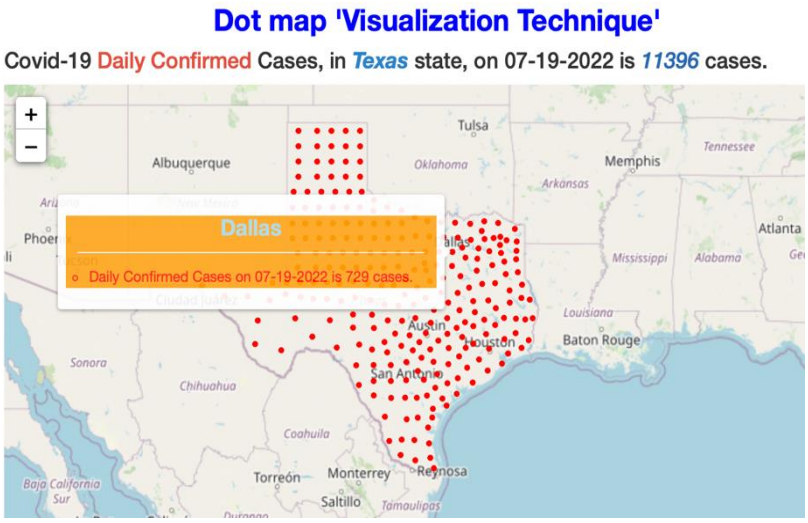

Figure 8: Dot map visualization of confirmed cases in Texas counties on July 19, 2022

3.3.1 Dot Map Survey Answers and Analysis of Responses. Dot Maps have been experienced by 23 respondents (around 19%) (Figure 9A). Eight respondents visualized GIS data, 7 visualized population data, and 5 visualized pandemic spread data (Figure 9B). One of the six respondents who had previously used a Choropleth map (Figure 9C) knew more about this technique than any other visualization technique (Figure 9D).

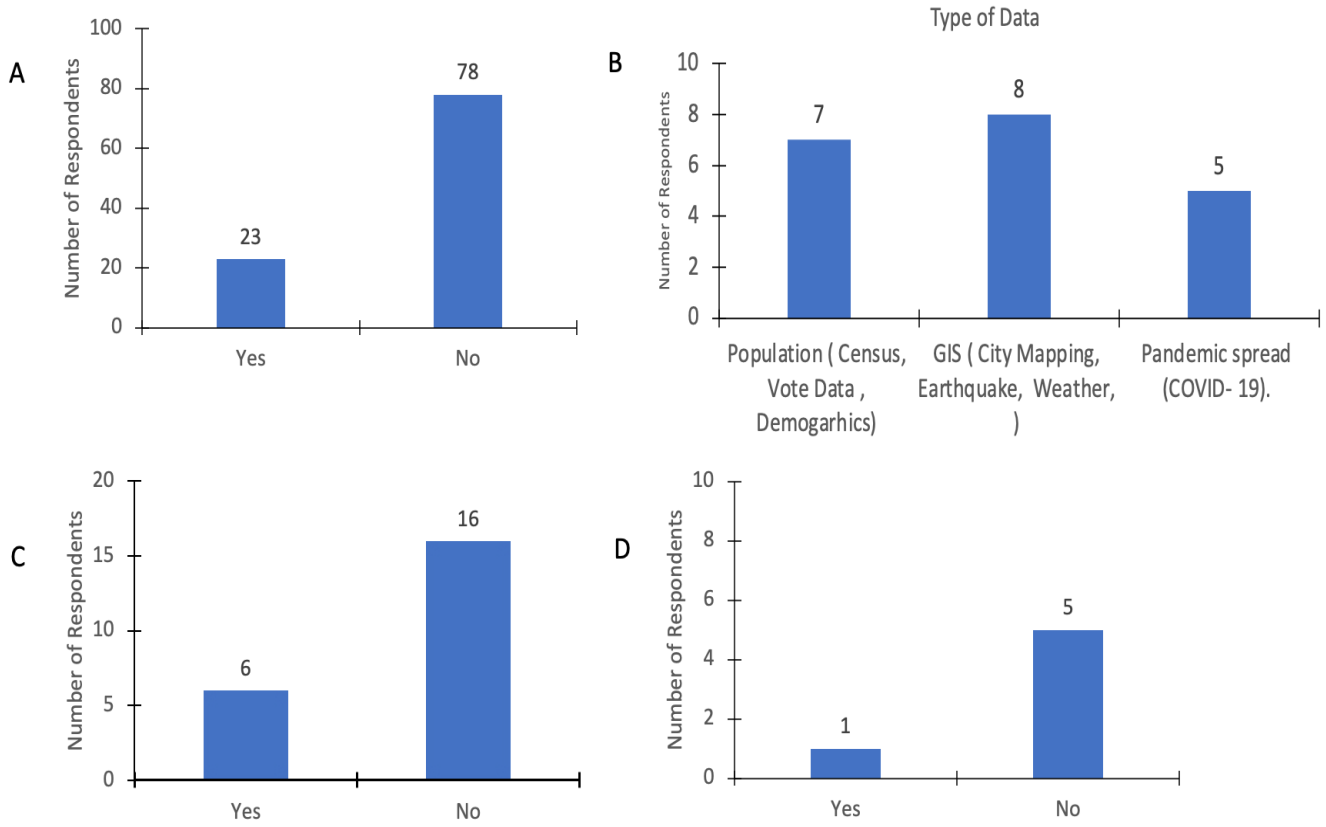

Figure 9: (A) Respondents' encounter of Dot Map. (B) Type of data encountered with Dot map. (C) Respondents that have used Dot Map. (D) Dot Map usage based on Knowledge

3.3.2 Dot Map Advantages and Disadvantages. Advantages and disadvantages of Dot Map visualization technique, based on the respondents' answers, are summarized in Table 4.

Advantages	***Disadvantages***
Clear to understand	It gets clumsy as data increases
It is easy to point out in the map	Hard to identify other classes if densely populated in one area
Easier to analyze and can be constructed easily	
Pinpoints the exact location based on address or coordinates	

Table 4: Advantages and disadvantages of Dot Map

3.4. Hexagonal Binning

Hexagonal binning is a better way to map the distribution of large amounts of data. To create continuous bins, regular polygons are used [1]. Hexagonal binning is a map visualization technique that uses hexagons as a framework to display the needed information [4]. Different colors and shades can be used for the created hexagons, just like in a choropleth map.

The map in Figure 10 represents the daily confirmed COVID-19 cases in Texas counties on July 19, 2022. Each county is represented by a hexagon of different color based on the number of confirmed COVID-19 cases in that county.

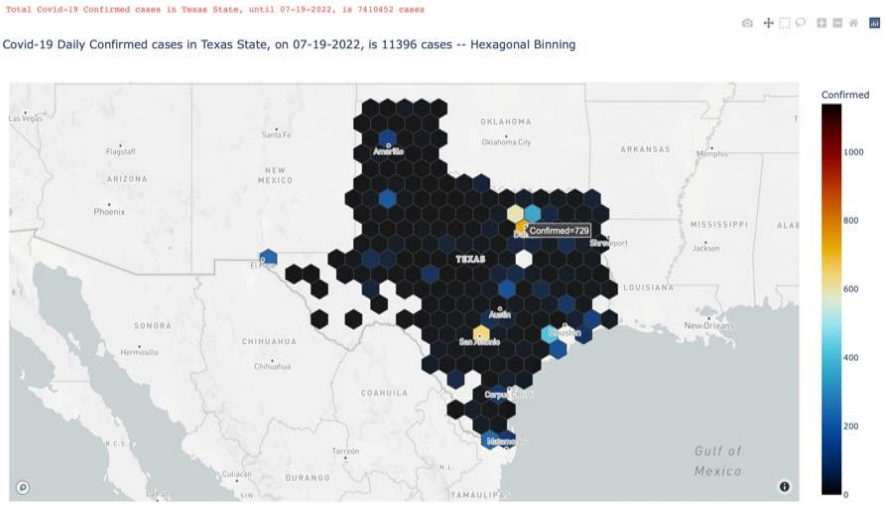

Figure 10: Hexagonal Binning showing number of daily confirmed COVID-19 cases in Texas counties on July 19, 2022

3.4.1 Hexagonal Binning Survey Answers and Analysis of Responses. Eleven of the respondents (around 11%) have encountered Hexagonal Binning before (Figure 11A). Four respondents visualized population data, 3 visualized GIS data, 2 visualized pandemic spread data, and two visualized other types of data (Figure 11B). One of the three respondents who had previously used hexagonal binning (Figure 11C) was more knowledgeable about this technique than any other visualization technique (Figure 11B).

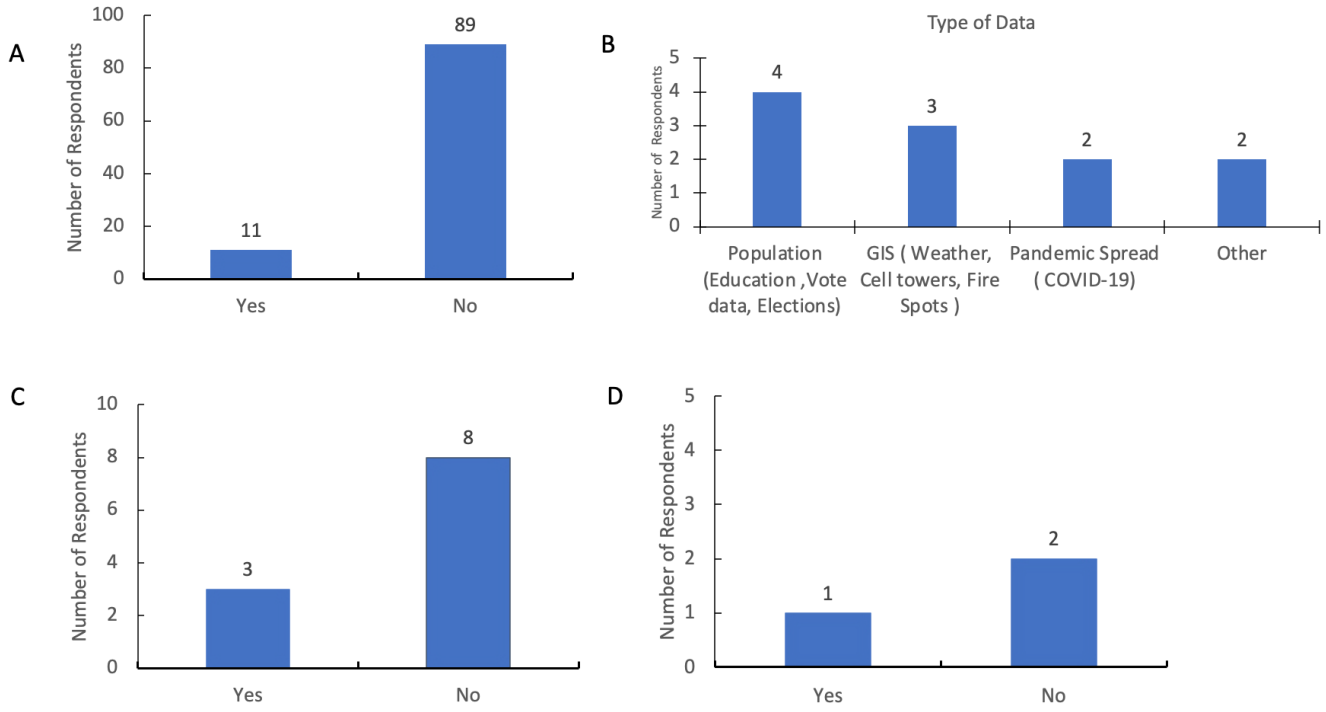

Figure 11: (A) Respondents' encounter of Hexagonal Binning. (B) Type of data encountered with Hexagonal Binning. (C) Respondents that have used Hexagonal Binning. (D) Hexagonal Binning usage based on Knowledge

3.4.2 Hexagonal Binning Advantages and Disadvantages. The advantages and disadvantages of Hexagonal Binning visualization technique, according to respondents, are summarized in Table 5.

Advantages	***Disadvantages***
Ease of computing counts of incidences within a hexagonal bin	Computing presence within a bin was nontrivial
It provided good, desired results	

Table 5: Hexagonal Binning: Advantages and disadvantages

3.5. Bubble Maps

A data source is properly represented in a bubble map (or proportional symbol map) by a bubble (circle) of a variable size. The size of the bubble represents the number of cases in each location. The bubbles are distributed across the map based on their geographical coordinates [1]. Bubble maps can also display multiple types of data in a single view by using a different color for each type of data. The size of the bubble represents the value of data. A color gradient can be added to show the type of value corresponding to the map legend. One of the disadvantages of Bubble Maps is that when the size of the data varies within large ranges, large bubbles may overlap with other bubbles and regions, masking smaller bubbles [5] .

Figure 12 depicts a Bubble Map of COVID-19 cases distribution in Texas counties. The size of each bubble represents the number of daily confirmed COVID-19 cases in various Texas counties on July 19, 2022. The figure suggests that bubble maps visually display data better than dot maps. The county with the greatest number of COVID-19 cases is easily obtained. A popup window also displays the statistical number of COVID-19 cases in each county. On July 19, 2022, Dallas county had 720 confirmed COVID-19 cases.

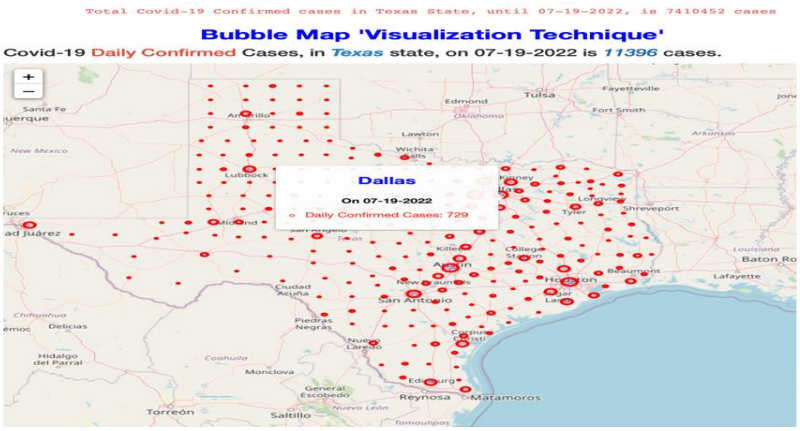

Figure 12: Bubble Map showing COVID-19 Confirmed cases in Texas counties on July 19, 2022

3.5.1 Bubble Map Survey Answers and Analysis of Responses. Thirty-one of the respondents (roughly 25%) had previously encountered Bubble Maps (Figure 13A). Fourteen respondents visualized population data, 8 visualized pandemic spread data, 6 visualized GIS data, and 3 visualized other data (Figure 13B). Four of the seven respondents who had previously used and applied Bubble Maps (Figure 13C) knew more about this technique than the other visualization techniques (Figure 13D).

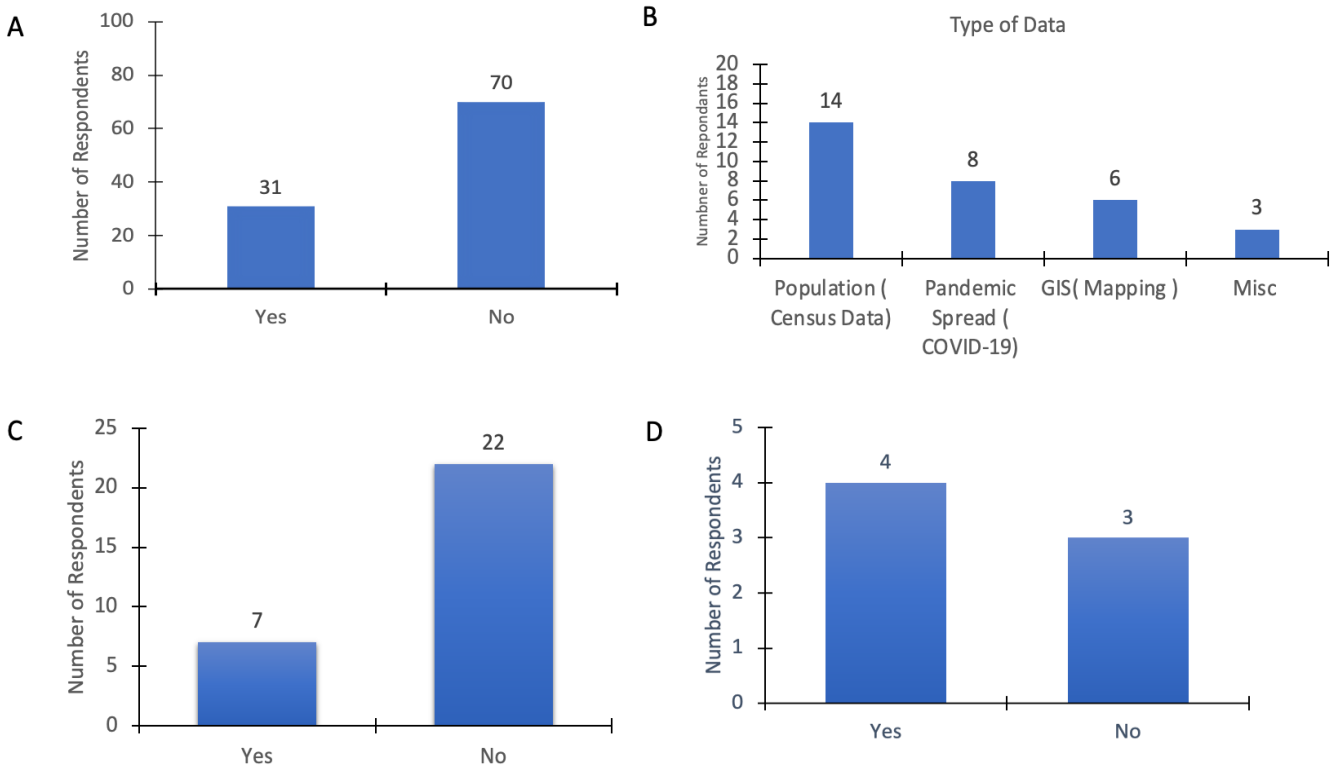

Figure 13: (A) Respondents' encounter of Bubble Map. (B) Type of data encountered with Bubble Map. (C) Respondents that have used Bubble Map. (D) Bubble Map usage based on Knowledge

3.5.2 Bubble Map Advantages and Disadvantages. Table 6 summarizes the advantages and disadvantages of the Bubble Map visualization technique as reported by respondents who have used it. The responses are based on the respondents' level and type of familiarity with the technique.

Advantages	*Disadvantages*
Easily understandable	Hard to estimate the proportional difference
It was required along with heat map to show concentration crime in areas	Doesn't always standout visually when combined with other geo-mapping data
More visibility than other applications	
Dense crowd sourcing	
Ease of use and availability of tools to integrate with datasets	
Ability to see higher volumes compared to other locations	

Table 6: Advantages and disadvantages Bubble Map

3.6. Cartogram Maps

Cartograms are used to manage geological locations (countries, states) based on a specific variable of interest (population, income, number of confirmed COVID-19 cases, etc.). They can contain both factual and topographical data and have been used for as a visualization means for geo-referenced data for over a century [1].

Cartograms are widely used in newspapers, magazines, textbooks, websites, and introductions to show political race results, popularity, and regional patterns in general [6]. To clearly convey related data, the true size and state of geological districts are contorted in cartogram maps [7].

The daily confirmed cases of COVID-19 in Texas state counties on July 19, 2022 are shown in the cartogram of Figure 14. The map shows accurate shape of Texas counties, yet the size of each county is distorted to show corresponding COVID-19 statistics. This causes a change in the real borders of the counties. These are known as non-contiguous cartograms.

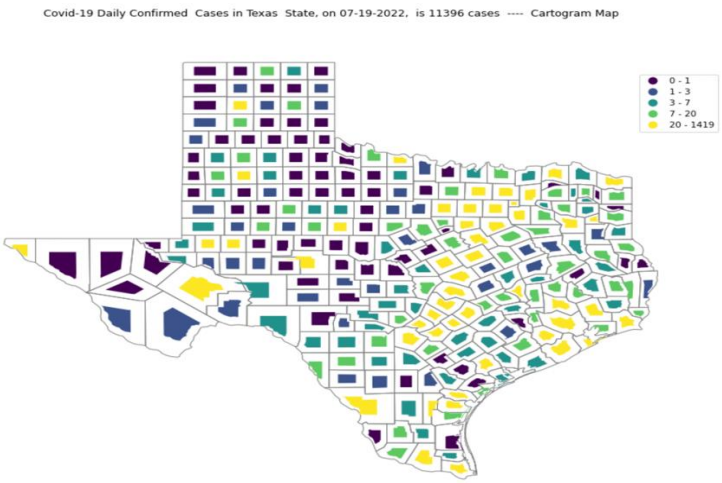

Figure 14: Cartogram Map showing the daily confirmed cases of COVID-19 in Texas Counties by July 19, 2022

3.6.1 Cartogram Map Survey Answers and Analysis of Responses. Cartogram Maps were the least commonly encountered among survey respondents, with only 6 (approximately 5%) having previously encountered Cartogram Maps before (Figure 15A). Three respondents visualized data on pandemic spread, 2 visualized population data, and 1 visualized media data (Figure 15B). Only one respondent was familiar with the use and application of Cartogram Maps (Figure 15C), and he had previous knowledge about Cartogram maps (Figure 15D)

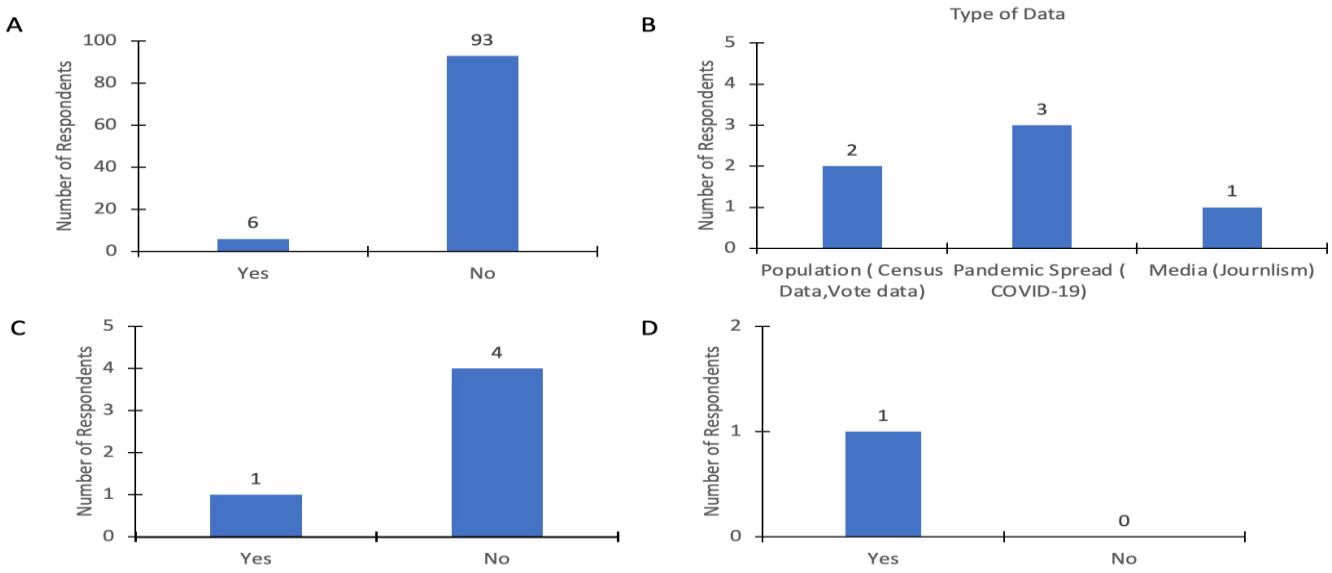

Figure 15: (A) Respondents who have used Cartogram Map. (B) Type of data encountered with Cartogram Maps by survey respondents. (C) Respondents that have used Cartogram Map. (D) Cartogram Map usage based on Knowledge.

4. Choosing Visualization Techniques Based on Type of Application

Recently, daily human life has become more information technology-dependent, starting from daily activities, weather, medical care, communication technologies, scientific research, economics, social media, and even politics. This has resulted in the accumulation of a lot of data. As a result, many applications have been developed to collect the resulting data, which needs to be processed, stored, analyzed, and visualized. As an example, when visualizing geographical data, it is important to figure out which visualization technique needs to be used, whether a special representation is needed, or the data should be presented on a map or not.

In the conducted survey, the encounter of respondents with one of the 6 popular visualization techniques in his field of study/work/research was questioned. Each respondent used a different type of visualization technique depending on the application he/she was working on.

Most visualizations assume 2-dimensional space but some applications, such as medical images need to be visualized as 3-dimensional objects. There may be two or more ways of categorizing applications to visualize them. One includes applications which need to be visualized on maps versus those that can be visualized as images. The following are the common map visualization applications according to survey respondents:

1. Applications related to population demographics (education, birth, age)
2. Applications related to climate (weather, air pollution)
3. Applications related to disasters (earthquake, fire, war)
4. Applications related to pandemics (cholera, HIV, Covid19)
5. Applications related to human daily life (directions, shopping, dining, traffic, tracking, etc.)

The following are the common image visualization applications based on respondents' answers:

1. Applications related to sport games (soccer, basketball, football, etc.)
2. Applications related to human biology (human anatomy, cancer, etc.)

5. Discussion

Data visualization is used to show data by drawing graphic displays, scatterplots, histograms, tables, or maps. It helps users to easily analyze and interpret the data. It even helps identifying areas of interest in the data for further analysis and computation. Map visualization techniques are used for spatial and spatio-temporal data as there is a geographical attribute included in the data. It is a great method that helps in analyzing and displaying geographically related data. Data visualization enables users to quickly understand complex data and begin making decisions based on the visualized data. Visual exploration and presentation of the underlying spatial data contributes to acquirement of knowledge [8].

The following is a brief historical background showing when each of the map visualization techniques was first used. The choropleth map, which was created by Ch. Dupin, can be seen as having its "birth" on November 30, 1826, when Dupin used it to visualize the availability of elementary education in France per department [9]. Cormac Kinney, a software designer, is regarded as the father of heat maps. He first used the method and the term heat map to describe a 2D display of financial market data in 1991 [10]. The outbreak of the cholera pandemic in London in 1854 was illustrated using a dot map that the physician Jack Snow used to locate the source of the outbreak [11]. Daniel B. Carr, Anthony R. Olsen, and Denis White [12] may have been the first to discuss the explicit use of hexagonal binning for spatial data aggregation and sampling. Since then, there has been little scholarly discussion of hexagonal binning theories for spatial and visual analysis [13].For centuries, bubble maps (proportional symbol maps) have been used. In 1837, Henry Drury Harness developed the first proportional symbol map. He made a map of Irish train routes that showed the population sizes of cities connected by the routes. Many cartographers and data scientists followed his footsteps, popularizing the symbol map in books and reports [14]. The term cartogram is widely attributed to the French engineer Charles Minard. In the mid-1800s, Minard was a pioneer of statistical graphs and charts [15] .

Recently, choropleth maps were widely used by most news media during the US presidential elections. Heat maps are widely used for weather forecast and medical imaging of cancer patients. We and others have applied visualization techniques to visualize and analyze COVID-19 data sets.

Visualization of COVID-19 data sets has helped the researchers, doctors, climate analysts, and other end-users to offer better analysis of the data sets. The results of this study have shown that some visualization techniques have more prevalent use than others (Table 7). Heat maps were the most commonly used among survey respondents; even more than the widely used Choropleth maps.

Technique	Encountered	Used
Choropleth Map	67	11
Heat Map	91	19
Dot Map	23	6
Hexagonal Binning	11	3
Bubble Map	30	7
Cartogram Map	6	1
Other visualization technique	3	2

Table 7: Encounter and use of each of the six-visualization technique according to survey participants

6. Conclusion

In this study, six popular spatial data visualization techniques were encountered, used, and applied by respondents with different levels of familiarity with the techniques to determine which of the techniques is widely used. The most common spatial visualization technique was heat map.

The finding of the study will aid in the development of guidelines and criteria that will help in the selection of an appropriate visualization technique based on the task at hand.

7. References

1. Shaito M, Elmasri R. Map Visualization using Spatial and Spatio-Temporal Data: Application to COVID-19 Data. Paper presented at: The 14th Pervasive Technologies Related to Assistive Environments Conference, 2021; Corfu Greece.
2. Andrienko G, Andrienko N, Savinov A. Choropleth Maps: classification revisited. Paper presented at: ICC 2001, 2001; Beijing.
3. Kuhfeld WF. Heat Maps: Graphically Displaying Big Data and Small Tables. Paper presented at: SAS Institute Inc., 2017; Cary,North California.
4. Ayalasomayajula V. *7* Techniques to Visualize Geospatial Data. *humans of data*. October *5*, 2016. Available at: https://humansofdata.atlan.com/2016/10/7-techniques-to-visualize-geospatial-data/. Accessed August 18, 2020.
5. Severino R. Bubble Map. *The Data Visualisation Catalogue*. 2017. Available at: https://datavizcatalogue.com/methods/bubble_map.html. Accessed June 30, 2020.
6. Nursat S, Kobourov. Visualizing cartograms: Goals and task taxonomy. *ArXiv*. 2015;abs/1502.07792.
7. GISGeography. Cartogram Maps: Data Visualization with Exaggeration. *GISGeography*. May 30, 2022. Available at: https://gisgeography.com/cartogram-maps/. Accessed June 15, 2022.
8. Tennekes M. tmap: Thematic Maps in R. *Journal of Statistical Software*. 2018;84(6):1-39.
9. Korycka-Skorupa J, Pasławski J. The beginnings of the choropleth presentation. *Polish Cartographical Review*. 2017;49(4):151–162.
10. Netek R, Pour T, Slezakova R. Implementation of Heat Maps in Geographical Information System – Exploratory Study on Traffic Accident Data. *Open Geosciences*. August 2018;10(1):367-384.
11. Snow J. *On the Mode of Communication of Cholera*. 2nd Edition ed. London; 1855.
12. Carr DB, Olsen AR, White D. Hexagon Mosaic Maps for Display of Univariate and Bivariate Geographical Data. *Cartography and Geographic Information Systems*. 1992;19(4):228-236.
13. Battersby S, Strebe D, Finn MP. Shapes on a plane: evaluating the impact of projection distortion on spatial binning. *Cartography and Geographic Information Science*. May 2016;44(5):1012.
14. Robinson AH. The 1837 Maps of Henry Drury Harness. *The Geographical Journal*. December 1955;121(4):440-450.
15. Field K. *The Geographic Information Science & Technology Body of Knowledge*: University Consortium for Geographic Information Science; 2017.