

# Usage of Visualization Techniques in Data Science Workflows

Johanna Schmidt <sup>a</sup>

VRVis Zentrum für Virtual Reality und Visualisierung Forschungs-GmbH, Vienna, Austria

Keywords: Visualization, Visual Data Science, Applied Computing.

Abstract: The increasing interest in data science and data analytics lead to a growing interest in data visualization and exploratory visual data analysis. However, there is still a clear gap between new developments in visualization research, and the visualization techniques currently applied in data analytics workflows. Most of the commonly used tools provide basic charting options, but more advanced visualization techniques have hardly been integrated as features yet. This especially applies for interactive exploratory data analysis, which has already been addressed as the 'Interactive Visualization Gap' in the literature. In this paper we present a study on the usage of visualization techniques in common data science tools. The results of the study confirm that the gap still exists. For example, we hardly found support for advanced techniques for temporal data visualization or radial visualizations in the evaluated tools and applications. On the contrary, interviews with professional data analysts confirm strong interest in learning and applying new tools and techniques. Users are especially interested in techniques that can support their exploratory analysis workflow. Based on these findings and our own experience with data science projects, we present suggestions and considerations towards a better integration of visualization techniques in current data science workflows.

## 1 INTRODUCTION


Visualization researchers were very successful within the last decades, generating a lot of different novel techniques for the visual representation of data. These techniques range from approaches for the efficient representation of data (e.g., parallel coordinates) to proposed interaction and user guidance workflows (e.g., *overview-first, details-on-demand*). Current surveys show the large variety of visualization techniques. A survey of survey papers in information visualization by McNabb and Laramee (McNabb and Laramee, 2017) classified already over 80 survey papers describing relevant state-of-the-art techniques, and a more recent survey of books in information visualization revealed a similar quantity and variety (Rees and Laramee, 2019).

In parallel to visualization research, the growing interest in data science and data analytics lead to more and more software applications being developed, both open source (e.g., *Python Plotly*<sup>1</sup>) and commercial (e.g., *Tableau*<sup>2</sup>). A survey by Barlas et al. (Barlas et al., 2015) of open source data science tools

identified over 70 data science tools and applications commonly used by data scientists. Not all of these tools and applications offer data visualization, some of them are specifically targeted towards efficient data storage and access (e.g., for *Big Data* applications), data wrangling (i.e., mapping data to another format), or automated analysis approaches like machine and deep learning. For these tools and applications that also offer data visualization, only very little overlap between the recent developments in visualization research and the features offered by the tools and applications can be found.

Most of the tools and applications feature basic charts and plots (e.g., scatter plots, bar charts, bubble charts, radar charts), but more advanced visualization techniques (e.g., chord diagrams, horizon graphs) can hardly be found, and recent developments in visualization rarely make their way into the tools as new features or updates (Chapman, 2019). We conducted a new survey on the usage of prominent visualization techniques in 13 open source and 6 commercial tools, and could confirm that this problem still exists.

On the contrary, interviews with data scientists reveal a strong interest in applying new visualization techniques (Meeks, 2019), and great interest in trying out alternatives (Liu et al., 2019). As the main obstacles why new visualization techniques are not applied

<sup>a</sup>  <https://orcid.org/0000-0002-9638-6344>

<sup>1</sup><https://plot.ly/python/>

<sup>2</sup><https://www.tableau.com>

in their workflows, data scientists named not having enough time to learn and get familiar with these techniques, missing documentation and support, and the lack of integration of the techniques in the established data science environments.

The exchange with data analysts and data scientists (often referred to as *data workers*) is essential for visualization research. Data workers can give valuable feedback on techniques and applications to further improve the proposed research results. Data workers can also provide visualization researchers with new interesting datasets and application ideas, with new tasks, and new directions for further research. We therefore advocate for strategies towards a better integration of visualization techniques in commonly used data science tools. In this paper we present a study on the current usage of visualization techniques in data science applications. We further summarize findings from recent studies and investigations to deduce suggestions to improve the exchange between those two fields of research.

## 2 VISUALIZATION IN DATA SCIENCE

Data science has been established as an important emergent scientific field. Data science is defined as a "concept to unify statistics, data analysis, machine learning and their related methods" in order to "understand and analyze actual phenomena with data" (Hayashi, 1998). As such, data science comprises more than pure statistical data analytics, but the interdisciplinary integration of techniques from mathematics, statistics, computer science, and information science (Parsons et al., 2011). Data science also involves the consideration of domain knowledge for the analysis and the interpretation of the data and the results (Blei and Smyth, 2017).

In this highly data-driven research field, data scientists also make use of data visualization for a visual interpretation of the data and the results. The rise in data science has led to a multitude of new data visualization tools and libraries being developed (Liu et al., 2018). The tasks that data scientists have to solve and the integration of visual methods in the data science workflow poses interesting challenges for the field of visualization.

### 2.1 Data Science Requirements

Several studies were conducted within the last years to better understand the tasks and requirements of

data scientists. The survey by Harris et al. (Harris et al., 2013) among different data workers from different disciplines provides a very comprehensive overview of the different tasks data scientists have to solve and the different fields they are working in. Kim et al. (Kim et al., 2018) analyzed the role of data scientists within software development teams. In the visualization community several studies were conducted to better understand the role of visualization in data science processes. Kandel et al. (Kandel et al., 2012) conducted semi-structured interviews with data workers from different organizations, including companies from healthcare, retail, marketing, and finance. Alspaugh et al. (Alspaugh et al., 2019) focused on interviews with data workers and asked them about their descriptions of exploratory activities and tool usage in these activities. Liu et al. (Liu et al., 2019) studied how, why and to what extent data scientists consider alternatives in their workflows.

The workflow of data scientists can be summarized into five high-level categories (Kandel et al., 2012). First, data workers usually search for suitable datasets, either by locating them in databases, or online, or by asking colleagues (*Discover*). Especially within large organizations, finding and understanding relevant data is often considered as a significant bottleneck in the work process. When available, the datasets need to be brought into a desired format (*Wrangle*). Data wrangling involves parsing files, manipulating data layouts, and also integrating multiple heterogeneous data sources. After being available in the desired format, the quality of the data has to be verified, and the suitability for the analysis has to be estimated (*Profile*). Datasets very often contain severe flaws, including missing data, outlier, erroneous values, and other problems. Understanding the structure of the data is therefore considered an important task in data science. Afterwards, another important and interesting part of the data science workflow is to use the datasets as training sets to train prediction models (*Model*). All analysis results usually need to be reported to external people, which might be colleagues, or customers (*Report*).

All steps in the workflow contain circular processes where data scientists have to rethink actions they made and restart analysis processes from scratch. Due to this highly interactive and undirected workflow, no tools or applications can cover the whole data science workflow. Data scientists are therefore required to use a combination of different sets of tools to achieve their goals. Depending on their skills, data scientists prefer to use either programming interfaces or fully-featured applications (Liu et al., 2019).

## 2.2 Usage of Visualization

In all stages of the workflow data scientists could be supported by the use of visual tools. Interestingly, visualization techniques are currently mostly applied in the *Report* stage, at the very end of the data science workflow. This stands in contrast to the fact that interactive data exploration workflows are strongly promoted by visualization research. This has been identified as the "Interactive Visualization Gap" by Batch and Elmquist (Batch and Elmquist, 2018). To better quantify this gap, the usage of visualization techniques was subject of several studies within the last years within the visualization community.

### 2.2.1 Background

The interest in visualization usage lead to the initiation of online surveys collecting information on practical visualization application examples. *The Chart-maker Directory* (Kirk, 2019) creates and regularly updates a catalogue for the usage of charts in different visualization tools. On their website *From Data To Viz* (Holtz and Healy, 2017) Holtz and Healy present recent examples for the usage of visualization in data science projects.

Other studies concentrated on quantifying, evaluating, and ranking tools and applications that are used by data workers. Harger and Crossno (Harger and Crossno, 2012) evaluated the feature richness of open source toolkits for visual analytics. They evaluated the toolkits used for the study based on which basic chart types (e.g., bar charts, line charts), which types of graph visualization (e.g., circular or force-directed layouts), and which types of geo-spatial visualization techniques (e.g., choropleth maps, cartograms) they feature. They concluded that some toolkits are more targeted towards analytics, and some are more targeted towards visualization. The study by Harger and Crossno together with a study by Zhang et al. (Zhang et al., 2012) both concentrate on specific visualization techniques, and evaluate their usage in common tools. While Harger and Crossno concentrate on open source tools, Zhang et al. evaluated and compared commercial business analytics tools.

Based on the collected data, tools and applications can be compared and ranked based on classifications according to feature richness, flexibility, learning curve, and tasks (e.g., for analysis or presentation). Charlotte Rost (Rost, 2016) divided tools and applications into either being *apps* (fully-features applications) or *charting libraries* (programming toolkits), and compared these two classes according to certain features. She concluded that tools classified

as *apps* are generally targeted towards the presentation of findings, and that tools classified as *charting libraries* better support exploratory analysis and are therefore more targeted towards data exploration and analysis (with exceptions on both sides).

A very impactful comparison, called *Gartner's Magic Quadrants*, is published every year by Gartner (Gartner, 2019). In this yearly study Gartner compares 21 business intelligence applications that are considered most significant in the marketplace. The applications are evaluated and placed in one of four quadrants, rating the applications as either being *challengers*, *leaders*, *visionaires*, or *niche players*. The study gives very valuable information, especially due to the fact that it is updated every year, but, on the other hand, only covers commercial business intelligence tools. In the visualization community Behrisch et al. (Behrisch et al., 2018) conducted an exhaustive survey on commercial visual analytics tools, evaluating them according to which degree they feature data handling, visualization, and automated analysis. They also classified the applications according to whether they are more suited for presentation (all of them), or exploratory analysis (only 50%).

### 2.2.2 Survey

We conducted a survey on commonly used tools and applications and evaluated the visualization techniques they feature. The survey setting was very similar to Harger and Crossno's (Harger and Crossno, 2012) and Zhang et al.'s (Zhang et al., 2012) approach. We specifically concentrated on visualization techniques rather than on derived attributes (e.g., feature richness).

In our study we included more recent advances in visualization research, and considered open source tools as well as commercial applications to produce a more complete picture of visualization techniques usage. We concentrated on 2D information visualization techniques, as these techniques are more relevant for data science and data analytics, and disregarded spatial techniques like 3D volume rendering.

We then selected 19 tools and applications commonly used in data science, 13 of them being open source, and 28 visualization techniques from information visualization, 7 of them which have not been investigated in previous studies yet. The selected visualization techniques are divided into the following categories:

- **Basic Charts:** scatter plot, line plot, area plot, bubble chart, bar chart, pie chart, donut chart
- **Multi-dimensional Data:** parallel coordinates (Inselberg, 2009), radar chart (Chambers

Table 1: Featured visualization techniques. This table illustrates which visualization techniques are currently featured by the evaluated tools and applications. A *Y* in a table cell shows that the corresponding tool or application features this technique. *E* means that the technique is featured via an extension or plugin.

	Python Plotly	Python Seaborn	R GG-Plot2	Vega-Lite	D3	Google Charts	Chart.js	Apex-charts	dy-graphs	Bokeh	RAW-Graphs	.Net Live-Charts	Qt Charts	Micro-soft Power-BI	Tableau	SAS Visual Analytics	High-charts	Quad-gram	Matlab		
<b>Basic charts</b>	scatter plot line plot area plot bubble chart bar chart pie chart donut chart	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	
<b>Multi-d.</b>	parallel coordinates radar chart scatter plot matrix	Y Y Y	E E E	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	
<b>Flow</b>	Sankey diagram Alluvial diagram	Y		Y	Y Y	Y Y	Y Y	Y Y	Y Y	E Y	Y Y	Y Y	Y Y	Y Y	Y Y	Y Y	Y Y	Y Y	Y Y	E E	
<b>Matrix</b>	chord diagram heatmap arc diagram	Y Y Y	Y Y Y	Y Y Y	Y Y E	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	E E E	
<b>Temporal data</b>	polar area diagram Gantt chart circle view theme river data vases horizon graphs time nets people garden	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y E Y Y E Y	Y Y Y Y Y E Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	Y Y Y Y Y Y Y	
<b>Hierarchical</b>	tree diagram sunburst chart treemap contour plot crop circles	Y Y Y Y Y	Y Y Y Y Y	E E E E E	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y Y	Y Y Y Y Y

et al., 1983), scatter plot matrix (Hartigan, 1975)

- **Flow Charts:** Sankey diagram (Riehmman et al., 2005), Alluvial diagram (Rosvall and Bergstrom, 2010)
- **Matrix Data:** chord diagram (Telea and Ersoy, 2010), heatmap (Wilkinson and Friendly, 2009), arc diagram (Wattenberg, 2002)
- **Temporal Data:** polar area diagram, Gantt chart, circle view (Keim et al., 2004), theme river (Havre et al., 2002), data vases (Thakur and Rhyne, 2009), horizon graphs (Heer et al., 2009), time nets (Kim et al., 2010), people garden (Xiong and Donath, 1999)
- **Hierarchical Data:** tree diagram, sunburst chart (Stasko et al., 2000), treemap (Shneiderman, 1992), contour plot (Kubota et al., 2007), crop circles (Wang and Parsia, 2006)

We selected the following tools and applications for our study:

- **Open Source:** Python Plotly<sup>3</sup>, Python Seaborn<sup>4</sup>, R GGPlot<sup>5</sup>, Vega-Lite<sup>6</sup>, D3<sup>7</sup>, Google Charts<sup>8</sup>, Chart.js<sup>9</sup>, Apexcharts<sup>10</sup>, dygraphs<sup>11</sup>, Bokeh<sup>12</sup>, RAWGraphs<sup>13</sup>, .Net LiveCharts<sup>14</sup>, Qt Charts<sup>15</sup>
- **Commercial:** Microsoft PowerBI<sup>16</sup>, Tableau<sup>17</sup>, SAS Visual Analytics<sup>18</sup>, Highcharts<sup>19</sup>, Quadrigram<sup>20</sup>, Matlab<sup>21</sup>

Together with computer science students attending a course on visualization in data science we evaluated the usage of the selected techniques in the different tools and applications. As a result of our study, we were able to create a matrix of tools and applications and selected visualization techniques, with marked

cells if a tool or application features the specific visualization technique. The results of the study can be seen in Table 1. In this table the selected visualization techniques are listed as rows. If a tool or application, listed as columns, features a visualization technique, the corresponding cell is marked with an Y (for "yes"). A visualization technique is considered to be featured if it has been included in the basic functionalities of the tool or application. For example, a scatter plot matrix could also be created by placing several scatter plots side-by-side, but we only consider the technique to be featured if there exists a core functionality creating this visualization. If a visualization technique is provided via extensions or plugins, we placed an *E* (for "extension") in the table cell.

Not surprisingly, basic chart types like scatter plots and bar charts are highly supported by all evaluated tools and applications. From the more advanced visualization techniques, multi-dimensional techniques like parallel coordinates and radar charts are already widely used and known, and therefore included in many of the tools. The same applies for scatter plot matrices and heatmaps. Techniques for hierarchical data are also well supported, especially by the open source tools that were evaluated in the study.

Visualization techniques for temporal data are not available in the majority of the tools and applications. This is most probably due to the fact that temporal data (e.g., time-series data) is a very specific data type which is used only for specific tasks. Users usually use their own tools for these purposes. Therefore, techniques for temporal data have not been included yet in common tools and applications, as these tools usually try to address a broader range of data scientists and data analysts. There are some visualization techniques which have not been integrated into any tool or application yet, like time nets, data vases, or people garden.

From a tools and applications point of view, *Python Plotly* and *D3* notable provide the most features among all the tested open source tools. There are other tools that are targeted towards very special functionalities, like *dygraphs* for scientific plots, which therefore only feature a very limited range of visualization techniques. Other libraries which are intended to be used in web-based applications (e.g., *Chart.js* or *Google Charts*) feature only visualization techniques that will most likely be needed in a web-based context.

Open source tools, especially *R GGPlot2*, benefit a lot from input from the community, since many advanced visualization techniques are only featured via extensions. In the group of commercial tools it can be

<sup>3</sup><https://plot.ly/python/>

<sup>4</sup><https://seaborn.pydata.org/>

<sup>5</sup><https://ggplot2.tidyverse.org/>

<sup>6</sup><https://vega.github.io/vega-lite/>

<sup>7</sup><https://d3js.org/>

<sup>8</sup><https://developers.google.com/chart/>

<sup>9</sup><https://www.chartjs.org/>

<sup>10</sup><https://apexcharts.com/>

<sup>11</sup><http://dygraphs.com/>

<sup>12</sup><https://bokeh.pydata.org/en/latest/>

<sup>13</sup><https://rawgraphs.io/>

<sup>14</sup><https://lvcharts.net/>

<sup>15</sup><https://doc.qt.io/qt-5/qtcharts-index.html>

<sup>16</sup><https://powerbi.microsoft.com/>

<sup>17</sup><https://www.tableau.com/>

<sup>18</sup><https://www.sas.com>

<sup>19</sup><https://www.highcharts.com/>

<sup>20</sup><http://www.quadrigram.com/>

<sup>21</sup><https://www.mathworks.com/products/matlab.html>

depicted that *Tableau*, *Microsoft Power BI*, and *Highcharts* feature most of the hereby evaluated visualization techniques.

### 3 LEARNED LESSIONS

We consider further exchange with the field of data science as a valuable and important goal for the visualization community. Previous research efforts and our own study on the usage of visualization techniques in data science revealed that the gap between new developments in visualization research and their application "in the wild" still exists. We therefore identified the following suggestions towards a better integration of visualization in data science workflows:

- **Consider the Programming Environments Currently in Use in Data Science.** Data scientists use tools they already know and that have proved useful in their workflows. Depending on the existing skills, either programming tools or fully-featured applications are preferred. However, interview studies revealed that data scientists are very interested in exploring and integrating alternatives in their workflow. The visualization community should seize this opportunity, and should also make the changes as easy as possible. This requires to provide new visualization techniques in the programming environments currently used by data scientists. Such an integration can involve providing extensions to well-known visualization packages, or by providing command-line support for existing environments. A better integration of interactive visualization tools will especially be helpful for the *Wrangle* and *Profile* stages of the data science workflow.
- **Document and Report the Benefits for using New Tools.** Data scientists stated in interviews that one of the main obstacles for not considering new visualization techniques is that they do not have enough time to get familiar with new tools. The easier it is to access new tools (e.g., by providing them in well-known programming environments), the easier it is for data scientists to try these new opportunities. Documenting the benefits for using new tools also includes a proper documentation of the features, user guides, getting-started-guides, and example datasets and galleries.
- **Integrate Provenance in Visualization.** Especially exploratory data analysis (the *Profile* stage of the data science workflow) is an undirected process that very often requires to start from scratch again. In this process data scientists need to keep track of their findings and steps they already tried out. We therefore consider the integration of provenance mechanisms in visualization applications as an important goal. In many cases data scientists use notebook-style environments (e.g., Jupyter<sup>22</sup>) to keep track of their decisions and actions. The integration of visualization techniques in existing notebook-style environments will therefore also push their usage in data exploration.
- **Support for Collaboration** Similar to the need for keeping track of recent activities, data scientists need to communicate results and analysis stages to stakeholders, colleagues from other business units, customers, and other data scientists. This needs to be considered when creating new tools and applications. Data scientists need to be able to capture current states of an analysis (e.g., by storing the current state), so that they can later catch up on their current work, or pass on the results.
- **Provide Guidance in Visualization.** Data scientists will also benefit from guidelines suggesting suitable visualizations to be applied for certain data types or to solve certain tasks. Some suggestions for the usage of charts have been proposed outside the visualization community. Support for natural language queries has already been included in some data analysis tools (e.g., "Ask Data" by Tableau<sup>23</sup>). Findings from studies on color and shape perception have already been considered by many data science applications. Proposing certain visualization techniques during the analysis supports data scientists in their *Profile* and *Report* workflow stages. We therefore consider further research for the interpretation and usage of visualization techniques, and for a better understanding of phenomena like visual comparison or visual clutter an important goal.
- **Consider the Data Science Workflow Stages.** The workflow of data scientists can be categorized into the five stages of *Discover*, *Wrangle*, *Profile*, *Model*, and *Report*. When designing new visualization techniques, reflect upon in which stage of the workflow the visualization technique should be primarily used. Every stage required different types of visualizations. For example, data wrangling in the *Wrangle* stage requires to focus on data flaws like missing data or out-

<sup>22</sup><https://jupyter.org/>

<sup>23</sup><https://www.tableau.com/products/new-features/ask-data>

liers, while *Model* requires visualizations to understand the created models. Both stages are not supported by the available visualizations in current data science tools yet. The most demanding stage in terms of visualization design is the *Profile* stage, where data scientists need to explore the data to understand its structure. For this stage current data science tools mostly lack to provide suitable visualizations. The data exploration process also requires high degree of interactivity and inter-connectivity between different visualizations, which is not supported by all data science tools yet. In the *Report* stage mostly simple and easy-to-understand visualizations are needed, since here the results of the data analysis stage have to be presented to a broader audience. The use cases in this stage can be mostly covered by employing basic charts, which are already well supported by current data science tools.

## 4 CONCLUSION

This paper advocates for a better exchange between the two research fields of data science and visualization. Visual interfaces can provide substantial support for users working with data. However, the "Interactive Visualization Gap" for exploratory data analysis still exists. This has also been revealed by our study presented in this paper on the usage of visualization techniques in common data science tools. On the other hand, interviews with data scientists reveal a great interest in applying new techniques to get new insights into their datasets. We therefore suggest different strategies for a better integration of visualization techniques in common data science workflows.

## ACKNOWLEDGEMENTS

VRVis is funded by BMVIT, BMDW, Styria, SFG and Vienna Business Agency in the scope of COMET – Competence Centers for Excellent Technologies (854174) which is managed by FFG.

## REFERENCES

Alspaugh, S., Zokaei, N., Liu, A., Jin, C., and Hearst, M. A. (2019). Futzing and Moseying: Interviews with Professional Data Analysts on Exploration Practices. *IEEE Transactions on Visualization and Computer Graphics*, 25(1):22–31.

- Barlas, P., Lanning, I., and Heavey, C. (2015). A survey of open source data science tools. *International Journal of Intelligent Computing and Cybernetics*, 8:232–261.
- Batch, A. and Elmqvist, N. (2018). The Interactive Visualization Gap in Initial Exploratory Data Analysis. *IEEE Transactions on Visualization and Computer Graphics*, 24(1):278–287.
- Behrisch, M., Streeb, D., Stoffel, F., Seebacher, D., Matejek, B., Weber, S. H., Mittelstaedt, S., Pfister, H., and Keim, D. (2018). Commercial Visual Analytics Systems-Advances in the Big Data Analytics Field. *IEEE Transactions on Visualization and Computer Graphics*.
- Blei, D. M. and Smyth, P. (2017). Science and Data Science. *Proceedings of the National Academy of Sciences*, 114(33):8689–8692.
- Chambers, J., Cleveland, W., Kleiner, B., and Tukey, P. (1983). *Graphical Methods for Data Analysis*. Wadsworth.
- Chapman, C. (2019). A Complete Overview of the Best Data Visualization Tools. <https://www.toptal.com/designers/data-visualization/data-visualization-tools>. [accessed 2019-07-10].
- Gartner (2019). Magic Quadrant for Analytics and Business Intelligence Platforms. <https://solutionsreview.com/business-intelligence/thoughtspot-magic-quadrant-for-analytics-and-business-intelligence-platforms/>. [accessed 2019-07-09].
- Harger, J. R. and Crossno, P. J. (2012). Comparison of Open Source Visual Analytics Toolkits. *Proceedings of SPIE - The International Society for Optical Engineering*, 8294.
- Harris, H. D., Murphy, S. P., and Vaisman, M. (2013). *Analyzing the Analyzers: An Introspective Survey of Data Scientists and Their Work*. O'Reilly Media.
- Hartigan, J. A. (1975). Printer graphics for clustering. *Journal of Statistical Computation and Simulation*, 4(3):187–273.
- Havre, S., Hertzler, E., Whitney, P., and Nowell, L. (2002). Themeriver: visualizing thematic changes in large document collections. *IEEE Transactions on Visualization and Computer Graphics*, 8(1):9–20.
- Hayashi, C. (1998). What is Data Science? Fundamental Concepts and a Heuristic Example. In *Data Science, Classification, and Related Methods*, pages 40–51. Springer Japan.
- Heer, J., Kong, N., and Agrawala, M. (2009). Sizing the Horizon: The Effects of Chart Size and Layering on the Graphical Perception of Time Series Visualizations. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '09, pages 1303–1312, Boston, MA, USA. ACM.
- Holtz, Y. and Healy, C. (2017). The Chartmaker Directory - Data Story. <https://www.data-to-viz.com/#story>. [accessed 2019-10-25].
- Inselberg, A. (2009). *Parallel Coordinates: Visual Multidimensional Geometry and Its Applications*. Springer-Verlag, Berlin, Heidelberg.
- Kandel, S., Paepcke, A., Hellerstein, J. M., and Heer, J. (2012). Enterprise Data Analysis and Visualization:

- An Interview Study. *IEEE Transactions on Visualization and Computer Graphics*, 18(12):2917–2926.
- Keim, D. A., Schneidewind, J., and Sips, M. (2004). Circle-View: A New Approach for Visualizing Time-related Multidimensional Data Sets. In *Proceedings of the Working Conference on Advanced Visual Interfaces, AVI '04*, pages 179–182, Gallipoli, Italy. ACM.
- Kim, M., Zimmermann, T., DeLine, R., and Begel, A. (2018). Data Scientists in Software Teams: State of the Art and Challenges. *IEEE Transactions on Software Engineering*, 44(11):1024–1038.
- Kim, N. W., Card, S. K., and Heer, J. (2010). Tracing Genealogical Data with TimeNets. In *Proceedings of the International Conference on Advanced Visual Interfaces, AVI '10*, pages 241–248, Roma, Italy. ACM.
- Kirk, A. (2019). The Chartmaker Directory. <http://chartmaker.visualisingdata.com/>. [accessed 2019-08-13].
- Kubota, H., Nishida, T., and Sumi, Y. (2007). Visualization of Contents Archive by Contour Map Representation. In *New Frontiers in Artificial Intelligence*, pages 19–32, Berlin, Heidelberg. Springer Berlin Heidelberg.
- Liu, J., Boukhelifa, N., and Eagan, J. R. (2019). Understanding the Role of Alternatives in Data Analysis Practices. *IEEE Transactions on Visualization and Computer Graphics (Early Access)*.
- Liu, J., Tang, T., Wang, W., Xu, B., Kong, X., and Xia, F. (2018). A survey of scholarly data visualization. *IEEE Access*, 6:19205–19221.
- McNabb, L. and Laramee, R. S. (2017). Survey of Surveys (SoS) - Mapping The Landscape of Survey Papers in Information Visualization. *Computer Graphics Forum*, 36:589–617.
- Meeks, E. (2019). 2019 Annual Data Visualization Survey Results. <https://medium.com/nightingale/2019-annual-data-visualization-survey-results-334d3523073f>. [accessed 2019-11-05].
- Parsons, M. A., Øystein Godøy, LeDrew, E., de Bruin, T. F., Danis, B., Tomlinson, S., and Carlson, D. (2011). A conceptual framework for managing very diverse data for complex, interdisciplinary science. *Journal of Information Science*, 37(6):555–569.
- Rees, D. and Laramee, R. S. (2019). A Survey of Information Visualization Books. *Computer Graphics Forum*, 38(1):610–646.
- Riehmman, P., Hanfler, M., and Froehlich, B. (2005). Interactive Sankey Diagrams. In *Proceedings of the Proceedings of the IEEE Symposium on Information Visualization, INFOVIS '05*, pages 31–, Minneapolis, MN, USA.
- Rost, L. C. (2016). What I Learned Recreating One Chart Using 24 Tools. <https://source.opennews.org/articles/what-i-learned-recreating-one-chart-using-24-tools/>. [accessed 2019-07-05].
- Rosvall, M. and Bergstrom, C. T. (2010). Mapping Change in Large Networks. *PLOS ONE*, 5(1):1–7.
- Shneiderman, B. (1992). Tree Visualization with Treemaps: 2-d Space-filling Approach. *ACM Transactions on Graphics*, 11(1):92–99.
- Stasko, J., Catrambone, R., Guzdial, M., and McDonald, K. (2000). An Evaluation of Space-filling Information Visualizations for Depicting Hierarchical Structures. *International Journal of Human-Computer Studies - Empirical evaluation of information visualizations*, 53(5):663–694.
- Telea, A. C. and Ersoy, O. (2010). Image-based Edge Bundles: Simplified Visualization of Large Graphs. In *Proceedings of the 12th Eurographics / IEEE - VGTC Conference on Visualization, EuroVis '10*, pages 843–852, Bordeaux, France.
- Thakur, S. and Rhyne, T.-M. (2009). Data Vases: 2D and 3D Plots for Visualizing Multiple Time Series. In *Advances in Visual Computing*, pages 929–938, Berlin, Heidelberg. Springer Berlin Heidelberg.
- Wang, T. D. and Parsia, B. (2006). CropCircles: Topology Sensitive Visualization of OWL Class Hierarchies. In *In Proceedings of The Semantic Web, ISWC '06*, pages 695–708. Springer Berlin Heidelberg.
- Wattenberg, M. M. (2002). Arc diagrams: visualizing structure in strings. In *Proceedings of the IEEE Symposium on Information Visualization, INFOVIS '02*, pages 110–116, Boston, MA, USA.
- Wilkinson, L. and Friendly, M. (2009). The History of the Cluster Heat Map. *The American Statistician*, 63(2):179–184.
- Xiong, R. and Donath, J. (1999). PeopleGarden: Creating Data Portraits for Users. In *Proceedings of the 12th Annual ACM Symposium on User Interface Software and Technology, UIST '99*, pages 37–44, Asheville, NC, USA. ACM.
- Zhang, L., Stoffel, A., Behrisch, M., Mittelstadt, S., Schreck, T., Pompl, R., Weber, S. H., Last, H., and Keim, D. (2012). Visual analytics for the big data era – A comparative review of state-of-the-art commercial systems. In *In Proceedings of the IEEE Conference on Visual Analytics Science and Technology, VAST '12*, pages 173–182, Seattle, WA, USA.