Chapter 0

Literature Review

Tyler Wiederich

1 Motivation and Background

Data visualizations play an essential role in understanding patterns in the structure of data. They allow for a programmatic mapping of data into a "picture" that can be used to gather insight from the viewer (Tukey 1965; Tufte 2001; Wilkinson and Wills 2005). Since the early 20th century, researchers have been exploring the question: what defines a good graph? (Croxton and Stryker 1927; Croxton and Stein 1932; Cleveland and McGill 1984; Vanderplas, Cook, and Hofmann 2020). Many attempts to answer this questions have provided good recommendations, but are largely limited to the projection of graphs onto 2-dimensional (2D) surfaces. While this addresses many of the typical use cases for data visualizations, graphs created in our 3-dimensional (3D) world are largely unexplored.

Due to the practical constraint of needing to be produced on paper or digital monitors, many charts exist within the confines of a 2D space. ....

2 Overview of Physical 3D Visualizations

The popularity of the 3D printer exploded in the early 2010's as the technology became increasingly available and cheaper. This has led to increase usage of 3D printing in many focus areas, including healthcare (Dodziuk 2016) and engineering (V et al. 2023), but has only seen novel use cases for statistical graphics. Many software programs have the ability to create 3D statistical graphics, but lack the ability to easily export the graphics into files suitable for 3D printing.

FIGURE PLACEHOLDER: Examples from citations above

2.1 Creating 3D-Printed Visualizations

Many software programs have the ability to create renderings of 3D charts. Excel (Microsoft Corporation 2025) has native support for creating charts with 3D depth cues, but requires add-ins to produce charts using 3 axes. R (XXX) has a several options for creating 3D charts that have data on 3 axes (e.g., Murdoch and Adler 2024; Morgan-Wall 2024; Sievert 2020), but lacks support for creating depth charts. SAS (XXX) has options such as PROC GCHART for adding depth cues and PROC G3D for surface charts. Other popular software programs contain similar capabilities, such as JavaScript libraries, MATLAB, Python, and more.

While a number of tools exist for creating 3D data visualizations, the pipeline of getting these charts into files compatible with 3D printing is not widely automated. For example, R has some options using the `rgl` (Murdoch and Adler 2024) and `rayshader` (Morgan-Wall

2024) packages, but both packages have limited tuning parameters for the resulting output files. Another option is to use 3D software, such as OpenSCAD (Kintel 2023), to manually create the charts, but these software programs lack the ability to directly integrate statistical information.

Another consideration for 3D-printed charts is the inclusion of text labels. With single-filament 3D printers, text can be incorporated in three primary ways: (1) embossing, in which the text is raised above the surface of the print; (2) engraving, in which the text is recessed into the surface; or (3) applying external labels, such as stickers or ink. Multi-filament 3D printers have the additional option to use a different color to make text labels flush with their surfaces. However, Munzner (n.d.) cautioned that the text of 3D charts will suffer from legibility issues due to the distortion of the text when viewed at an angle.

FIGURE PLACEHOLDER: examples of implementations of text on the charts

2.2 Current use cases

The use of 3D-printed data visualizations for statistical graphics is largely a novelty in the early 21st century. Services such as WhiteClouds (www.whiteclouds.com) offer the ability to create a wide variety of 3D-printed graphics, and more "do-it-yourself" options can be achieved with $300-$500 in start-up costs.

NOVEL GRAPHICS CASES

- https://vizworld.com/2014/11/a-new-way-of-representing-data-with-3d-printing-visualizing-data-with-3d-printed-sculptures/
- https://www.whiteclouds.com/services/data-visualization/

3 Bar Charts in Research and Practice

One of the most common types of charts is the bar chart, characterized by the use of rectangular geometries. Two variables are mapped to the geometries of the bar chart, where one axis is dedicated to a categorical variable of nominal or ordinal nature, and the other axis is for a (typically) continuous variable to denote magnitude or a response.

- Use cases and history?

The use of 3-dimensional elements in bar charts typically involve converting the rectangular bars into rectangular prisms. The naming convention for these types of charts is not consistent, sometimes referred to as 2.5D charts when the additional dimension does not covey extra information (e.g., Tractinsky and Meyer 1999) or, more commonly, as 3D bar charts (e.g., Zacks et al. 1998; Fischer 2000) . In this dissertation, they will be consistently referred to as "3D bar charts."

3.1 Against 3D Bar Charts

(**tufte?**) called the use of 3d elements a "fake perspective" in his description of "chart junk", which is where visual elements add clutter the data visualization. Other researchers (Zacks et al. 1998; Stewart, Cipolla, and Best 2009) have termed the perspective effect "extraneous" when referring to depth cues. The reasoning behind this is fairly intuitive: why include additional noise when simpler alternatives exist?

The seminal work of Cleveland and McGill (1984) theorized that encoding information in volumes would provide worse numerical estimation than for encodings using positions, lengths, and areas. Their reasoning stems from Steven's Power Law (XXX), a psychophysics formulation that estimates a perceived stimuli magnitude p with the actual magnitude a by $p = ka^\alpha$. The estimation of α provides guidance to what types of stimuli are subject to the most distorted to their true scale when $\alpha = 1$. (alpha for volume estimated to be X, area is Y, and length is Z). While the 3D bar charts do not lose their 2D encodings, they do gain depth, and thus volume encodings. The effect of volume versus area comparisons was noted earlier by Croxton and Stein (1932), where metrics of accuracy were the worst for cubes as compared to bars and circles.

- Casali and Gaylin (1988)
-

3.2 For 3D Bar Charts

If empirical studies have shown that the use of depth cues on bar charts does not provide added benefits, then why are 3D bar charts used?

Levy et al. (1996) made an argument for the use of depth cues in certain situations. In a series of three experiments, Levy et al. (1996) tasked over 100 psychology students at Stanford with selecting one of various 2D and 3D charts that they thought would be best for certain scenarios. What they found was that students tended to pick 3D charts over 2D charts when needing to increase memory recollection of the chart, and about equal preference for 2D and 3D charts when presenting the information to others. Levy et al. (1996) theorized that the depth embellishments in the graphic may increase memorability of the chart by making the chart stand out. Several other studies have shown that other types of "chart junk" can increase recollection, but at the cost of participants needing longer times to process the charts (Bateman et al. 2010; Borgo et al. 2012; Peña, Ragan, and Harrison 2020).

The increase of time for reading 3D bar charts was noted by Fischer (2000), lending some credibility

Preference for memorability. Noted with other chart junk.

3.3 Conflicting Empirical Studies

When accuracy is the goal, 2D is not better than 3D in some cases

- All the new articles from https://measuringu.com/is-3d-worse-than-2d/

- Melody Carswell, Frankenberger, and Bernhard (1991), should include this one!
- Spence (1990)

Although Tufte (2001) argued against the use of 3D charts when possible, studies involving direct comparisons of 2D and 3D bar charts have shown mixed results. In general, these studies focus on metrics of accuracy and find that 3D bar charts tend to be less accurate. Another common metric is response time, where 3D charts tend to have longer response times….

3.3.1 Accuracy

Accuracy is a common metric in studies comparing 2D and 3D bar charts, typically measured by either extracting a single numeric estimate or making comparisons between two values. Many studies used controlled environments for constructing stimuli, often using one or two stimuli at a time. In practice, charts are often more complex, displaying many stimuli without drawing attention to particular values.

When only measuring accuracy, 3D bar charts tend to be less accurate than their 2D counterparts (Zacks et al. 1998; Stewart, Cipolla, and Best 2009). However, this result is less prominent when introducing time delays (Zacks et al. 1998, Experiment 2) or easier task complexity (Stewart, Cipolla, and Best 2009). Siegrist (1996) noted that bar positions and sizes also affected performance accuracy, emphasizing that other factors contribute to accuracy. It is also important to note that metrics of accuracy are not conclusive, where sometimes there is no evidence of a difference between 2D and 3D bar charts (Melody Carswell, Frankenberger, and Bernhard 1991).

Of course, there are other less-studied factors that could affect perceptual judgments of accuracy in 3D bar charts. In addition to viewing parameters found in 2D bar chart studies (Fischer, Dewulf, and Hill 2005; Rice et al. 2024), adding depth cues are also subject to viewing angles, amount of depth, and field of view parameters. Viewing angle, with respect to the axis, can mislead the reader into overestimating or underestimating numerical quantities (FIGURE X). Zacks et al. (1998) did not find a significant effect for the amount of perception depth, but noted a trend such that increased exaggeration of depth lowered their accuracy metric. Lastly, field of view is fixed for the viewer, but can widely distort 3D renderings. These factors add additional complexity, but are not widely studied for the use of statistical graphics.

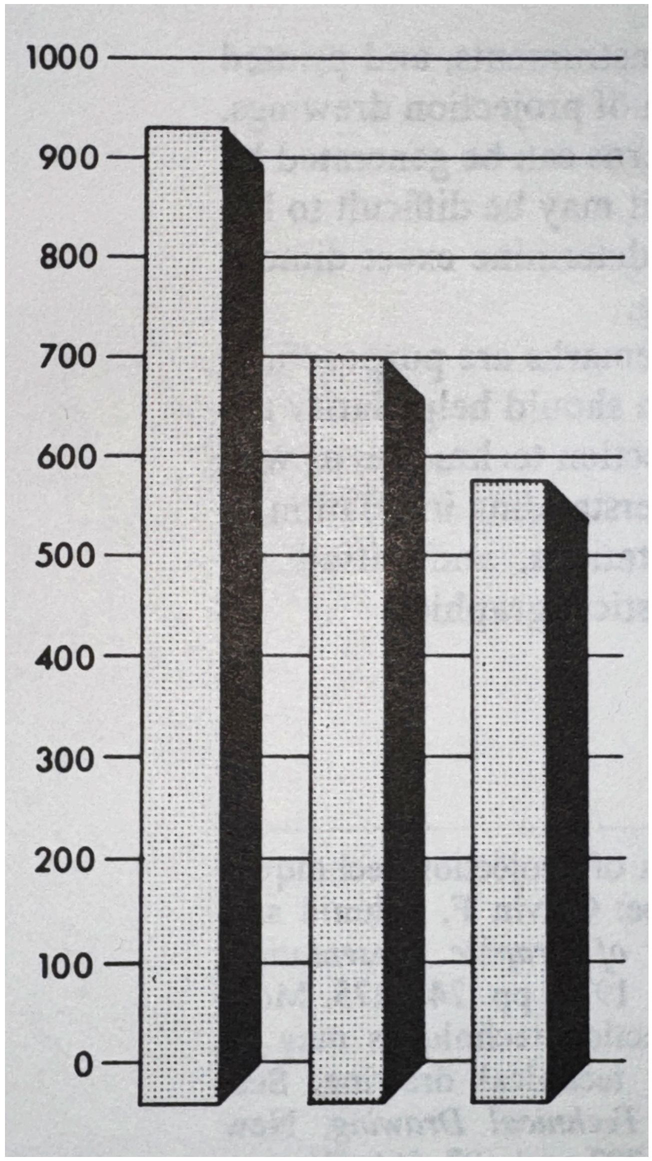


Figure 1: Figure in Statistical Graphics: Design Principles and Practices. The viewing angle for this chart would have viewers overestimate the values of the bars

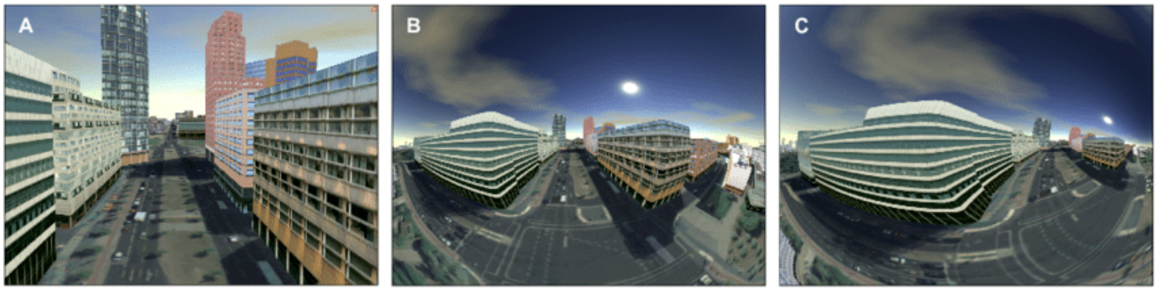


Figure 2: Placeholder image for fov comparisons

3.3.2 Response Times

The speed in making perceptual judgments is another common metric in studies comparing types of charts. In theory, charts where questions can be answered more quickly implies that the chart is better at communicating information. However, response time is a poor metric in situations of exploratory data analysis and long term interactions with complex graphics (Vanderplas, Cook, and Hofmann 2020). When a question of interest is known in advance, response time becomes a more viable metric.

Depth cues from 3D bar charts tend to increase the amount of time required to answer questions (Siegrist 1996; Fischer 2000; Stewart, Cipolla, and Best 2009). Intuitively, additional complexity should require additional time to process. For 3D bar charts, viewers need to align the response axis with the rectangular prisms in order to determine the approximate magnitude of the bar. Consider Figure X, where the y-axis denotes magnitude with respect to a hidden face of the bar. In order to extract a numerical quantity, the viewer first has to align the axis with the correct face of the prism before processing the magnitude. (sentence about chart junk and how the rest of the prism goes against the data-ink thing)

3.3.3 Preference

The debate between whether to use 2D or 3D graphics stems from a wider adoption of 3D charts in practice. Computer graphics have made it easy to produce charts of either dimensionality, resulting in creative liberties for the creation of the chart for publication. Figures X and X showcase two examples of 3D bar charts from the 1978 Handbook of Agricultural Charts (XXX) where other options exist for displaying the data. Schmid (1983) (Ch. 8) discusses many other 3D charts found in official reports.

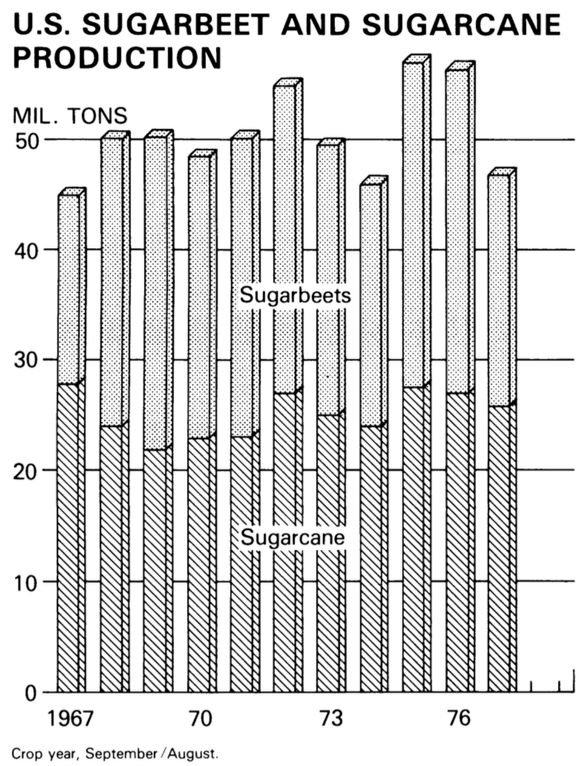
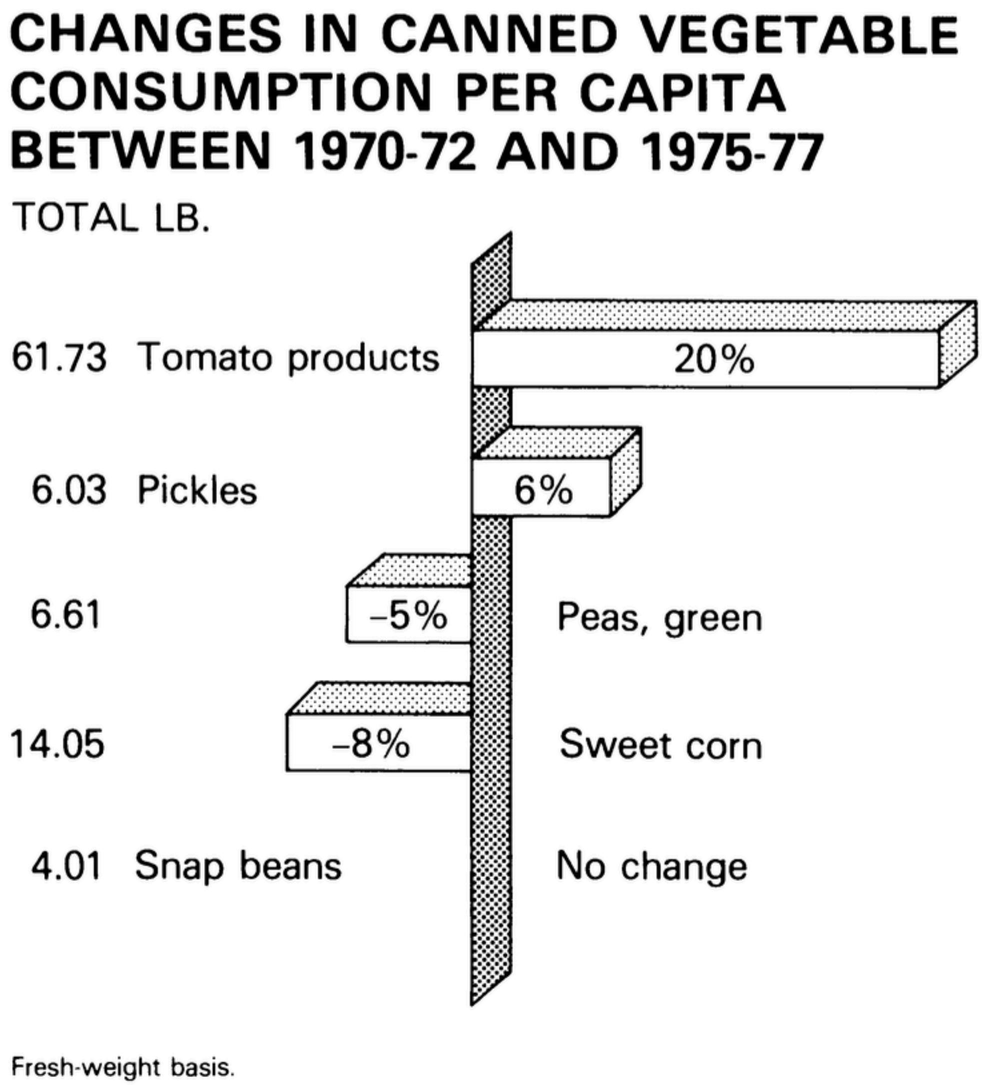


Figure 3: Located from 1978 HANDBOOK OF AGRICULTURAL CHARTS



Preference can be broken down into two broad categories: (1) visual appeal, and (2) usefulness. Visual appeal is where perceptual tasks are not a priority, and the goal is to have an image that is pleasant to the viewer. Usefulness, on the other hand, is a rating of how effective the viewer thought the chart was in order to answer the question. Both are subjective measures

When not tasked with estimating values, 3D bar charts tend to be more visually appealing

(Levy et al. 1996; Fisher, Dempsey, and Marousky 1997; Stewart, Cipolla, and Best 2009). This may be in part due to the forced illusion of depth which creates additional embellishments that would increase the impression and memorability of the chart, as seen by other types of Tufte's so called "chart junk" (Borgo et al. 2012; Peña, Ragan, and Harrison 2020). Despite the visual appeal, 2D charts tend to be chosen for preference and ease of use when making numerical estimations (Levy et al. 1996; Stewart, Cipolla, and Best 2009).

3.4 Construction of 3D Bar Charts

All of the aforementioned studies have one key limitation: they are conducted in environments where the 3D bar charts are projected onto 2D surfaces. An argument could be made that tactile charts created for persons with vision impairments could be considered 3D (Goncu and Marriott 2008; Engel and Weber 2017; Watanabe and Inaba 2018), but current implementations are vastly different from the typical design of 3D bar charts.

4 Heat Maps in Research and Practice

Probably need to use studies where the third dimension is for data, not depth. Not a whole lot out there on 3D heat maps in particular

- Barfield and Robless (1989)
- Kraus et al. (2020)
- Jeong et al. (2025) would be good, but uses VR

- Casali and Gaylin (1988)

When creating charts for three or more variables, it becomes increasingly more complex to visualize data (Grinstein and Trutschl 2001). One option is to map the additional variables using gestalt principles (Vanderplas, Cook, and Hofmann 2020) (Original citation?), which includes making use of color, size, and/or shapes to denote information.

Heat maps are a solution to three variable visualization when the primary response of interest is quantitative.

- Use in maps, geom_tile, etc.

5 Cognitive and Perceptual Frameworks Relevant to 3D Visualization

- Welchman (2016)
- Munzner (n.d.)
- Field of view

6 Methods for Evaluating Visualization Effectiveness

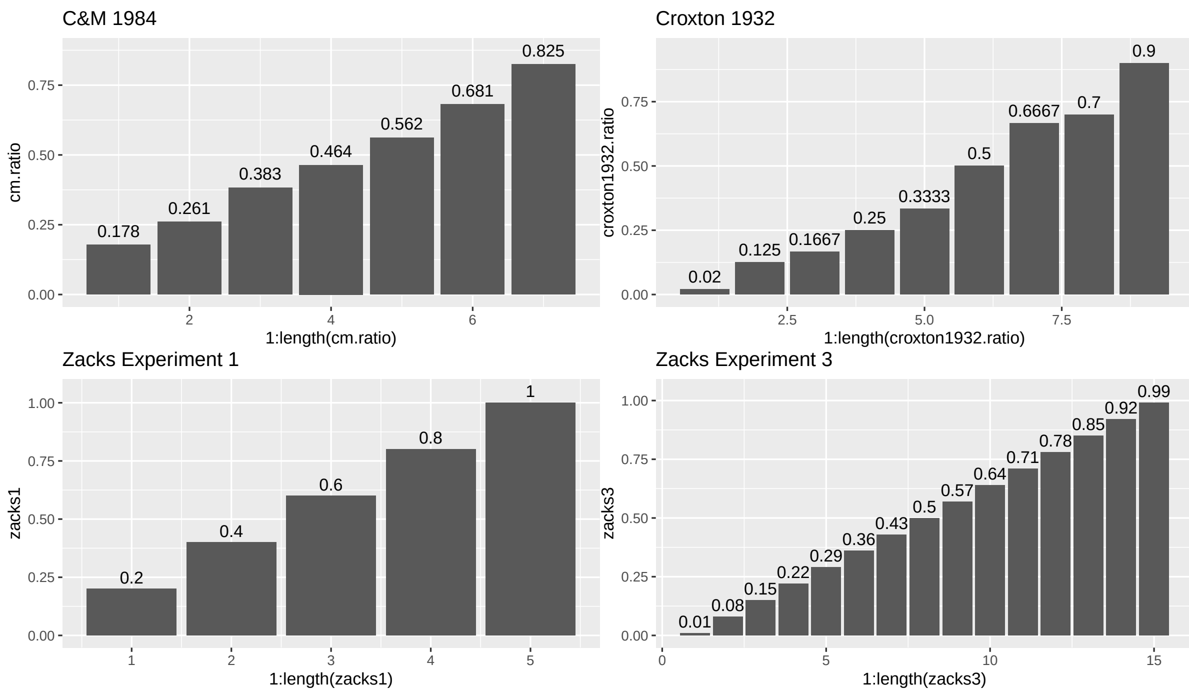
6.1 What makes a good chart?

Vanderplas, Cook, and Hofmann (2020) discussed various approaches to testing graphics, including numerical estimations, speed, and error rates. These metrics are fairly common when comparing 2D and 3D charts (Croxton and Stein 1932; Cleveland and McGill 1984; Hughes, n.d.).

6.2 Designing studies for numerical estimations

Over 2,500 citations have referenced the work of Cleveland and McGill (1984) when discussing properties of statistical graphics. Since 1984, the methods of analyzing and conducting studies on statistical graphics have evolved (e.g., Vanderplas, Cook, and Hofmann 2020; Hofmann et al. 2012), but yet the structure of experimental designs involving numerical estimations tend to remain similar

Cleveland and McGill (1984) asked participants two questions when making comparisons between two values on a chart: (1) which of the two values was the smaller, and (2) what percentage the smaller was of the larger. The first question clarified if the participants were looking at the values correctly for the second questions, and the second question is an estimation of A/B, where $A < B$. Accuracy was measured by $\log_2(|\text{True value} - \text{Estimated value}| + 1/8)$, using the trimmed averages when bootstrapping confidence intervals.



The estimation of A/B is fairly common in testing statistical graphics

Subtractive vs. ratio processes Veit (n.d.); Park, Viegut, and Matthews (2021); Narens (1996); Hagerty and Birnbaum (1978);

6.3 Limitations due to population

Quick section about populations of studies. I'm thinking about including Heer and Bostock (2010) for crowdsourcing, but many studies use students. Barfield and Robless (1989) used novice and experienced managers and found differences in results for 2D vs. 3D. Other studies on how different populations perceive differently, such as Rice et al. (2024). Or maybe exclude this section entirely?

References

Barfield, Woodrow, and Robert Robless. 1989. "The Effects of Two- or Three-Dimensional Graphics on the Problem-Solving Performance of Experienced and Novice Decision Makers." *Behaviour & Information Technology* 8 (5): 369–85. https://doi.org/10.1080/01449298908914567.

Bateman, Scott, Regan L. Mandryk, Carl Gutwin, Aaron Genest, David McDine, and Christopher Brooks. 2010. "CHI '10: CHI Conference on Human Factors in Computing Systems." In, 2573–82. Atlanta Georgia USA: ACM. https://doi.org/10.1145/1753326.1753716.

Borgo, R., A. Abdul-Rahman, F. Mohamed, P. W. Grant, I. Reppa, L. Floridi, and Min Chen. 2012. "An Empirical Study on Using Visual Embellishments in Visualization." *IEEE Transactions on Visualization and Computer Graphics* 18 (12): 2759–68. https://doi.org/10.1109/TVCG.2012.197.

Casali, John G., and Kenneth B. Gaylin. 1988. "Selected Graph Design Variables in Four Interpretation Tasks: A Microcomputer-Based Pilot Study." *Behaviour & Information Technology* 7 (1): 31–49. https://doi.org/10.1080/01449298808901861.

Cleveland, William S., and Robert McGill. 1984. "Graphical Perception: Theory, Experimentation, and Application to the Development of Graphical Methods." *Journal of the American Statistical Association* 79 (387): 531–54. https://doi.org/10.1080/01621459.1984.10478080.

Croxton, Frederick E., and Harold Stein. 1932. "Graphic Comparisons by Bars, Squares, Circles, and Cubes." *Journal of the American Statistical Association* 27 (177): 54–60.

https://doi.org/10.1080/01621459.1932.10503227.

Croxton, Frederick E., and Roy E. Stryker. 1927. "Bar Charts Versus Circle Diagrams." *Journal of the American Statistical Association* 22 (160): 473–82. https://doi.org/10.2307/2276829.

Dodziuk, Helena. 2016. "Applications of 3D Printing in Healthcare." *Polish Journal of Cardio-Thoracic Surgery* 3: 283–93. https://doi.org/10.5114/kitp.2016.62625.

Engel, Christin, and Gerhard Weber. 2017. "PETRA '17: 10th International Conference on PErvasive Technologies Related to Assistive Environments." In, 197–200. Island of Rhodes Greece: ACM. https://doi.org/10.1145/3056540.3064955.

Fischer, Martin H. 2000. "Do Irrelevant Depth Cues Affect the Comprehension of Bar Graphs?" *Applied Cognitive Psychology* 14 (2): 151–62. https://doi.org/10.1002/(SICI)1099-0720(200003/04)14:2%3C151::AID-ACP629%3E3.0.CO;2-Z.

Fischer, Martin H., Nele Dewulf, and Robin L. Hill. 2005. "Designing Bar Graphs: Orientation Matters." *Applied Cognitive Psychology* 19 (7): 953–62. https://doi.org/10.1002/acp.1105.

Fisher, Samuel H., John V. Dempsey, and Robert T. Marousky. 1997. "Data Visualization: Preference and Use of Two-Dimensional and Three-Dimensional Graphs." *Social Science Computer Review* 15 (3): 256–63. https://doi.org/10.1177/089443939701500303.

Goncu, Cagatay, and Kim Marriott. 2008. "ASSETS08: The10th International ACM SIGACCESS Conference on Computers and Accessibility." In, 255–56. Halifax Nova Scotia Canada: ACM. https://doi.org/10.1145/1414471.1414525.

Grinstein, Georges, and Marjan Trutschl. 2001. "High-Dimensional Visualizations." *In: 7th Data Mining Conference-KDD 2001: San Francisco, California*, January.

Hagerty, Michael, and Michael H. Birnbaum. 1978. "Nonmetric Tests of Ratio Vs. Subtractive Theories of Stimulus Comparison." *Perception & Psychophysics* 24 (2): 121–29. https://doi.org/10.3758/BF03199538.

Heer, Jeffrey, and Michael Bostock. 2010. "CHI '10: CHI Conference on Human Factors in Computing Systems." In, 203–12. Atlanta Georgia USA: ACM. https://doi.org/10.1145/1753326.1753357.

Hofmann, Heike, Lendie Follett, Mahbubul Majumder, and Dianne Cook. 2012. "Graphical Tests for Power Comparison of Competing Designs." *IEEE Transactions on Visualization and Computer Graphics* 18 (12): 2441–48. https://doi.org/10.1109/TVCG.2012.230.

Hughes, Brian M. n.d. "Just Noticeable Differences in 2D and 3D Bar Charts: A Psychophysical Analysis of Chart Readability."

Jeong, Jongwook, Ayoung Choi, Dongwoo Kang, and Youn Kyu Lee. 2025. "A Comparative Study of 2D Vs. 3D Chart Visualizations in Virtual Reality." *Journal of Visualization* 28 (1): 239–53. https://doi.org/10.1007/s12650-024-01033-6.

Kintel, Marius. 2023. "OpenSCAD. OpenSCAD.org." July 17, 2023. http://openscad.org/documentation.html.

Kraus, Matthias, Katrin Angerbauer, Juri Buchmüller, Daniel Schweitzer, Daniel A. Keim, Michael Sedlmair, and Johannes Fuchs. 2020. "CHI '20: CHI Conference on Human Factors in Computing Systems." In, 1–14. Honolulu HI USA: ACM. https://doi.org/10.1145/3313831.3376675.

Levy, Ellen, Jeff Zacks, Barbara Tversky, and Diane Schiano. 1996. "The SIGCHI Conference." In, 42–49. Vancouver, British Columbia, Canada: ACM Press. https://doi.org/10.1145/

238386.238400.

Melody Carswell, C., Sylvia Frankenberger, and Donald Bernhard. 1991. "Graphing in Depth: Perspectives on the Use of Three-Dimensional Graphs to Represent Lower-Dimensional Data." *Behaviour & Information Technology* 10 (6): 459–74. https://doi.org/10.1080/01449299108924304.

Microsoft Corporation. 2025. "Microsoft Excel." https://office.microsoft.com/excel.

Morgan-Wall, Tyler. 2024. "Rayshader: Create Maps and Visualize Data in 2D and 3D." https://CRAN.R-project.org/package=rayshader.

Munzner, Tamara. n.d. "Visualization Design and Analysis: Abstractions, Principles, and Methods."

Murdoch, Duncan, and Daniel Adler. 2024. "Rgl: 3D Visualization Using OpenGL." https://CRAN.R-project.org/package=rgl.

Narens, Louis. 1996. "A Theory of Ratio Magnitude Estimation." *Journal of Mathematical Psychology* 40 (2): 109–29. https://doi.org/10.1006/jmps.1996.0011.

Park, Yunji, Alexandria A. Viegut, and Percival G. Matthews. 2021. "More Than the Sum of Its Parts: Exploring the Development of Ratio Magnitude Vs. Simple Magnitude Perception." *Developmental Science* 24 (3): e13043. https://doi.org/10.1111/desc.13043.

Peña, Alyssa, Eric Ragan, and Lane Harrison. 2020. "Memorability of Enhanced Informational Graphics." *Interdisciplinary Journal of Signage and Wayfinding* 4 (1). https://doi.org/10.15763/issn.2470-9670.2020.v4.i1.a54.

Rice, Kiegan, Heike Hofmann, Nola Du Toit, and Edward Mulrow. 2024. "Testing Perceptual Accuracy in a U.S. General Population Survey Using Stacked Bar Charts." *Journal of Data*

Science, 280–97. https://doi.org/10.6339/24-JDS1121.

Schmid, Calvin F. 1983. *Statistical graphics: design principles and practices*. A Wiley-interscience publication. New York: Wiley.

Siegrist, Michael. 1996. "The Use or Misuse of Three-Dimensional Graphs to Represent Lower-Dimensional Data." *Behaviour & Information Technology* 15 (2): 96–100. https://doi.org/10.1080/014492996120300.

Sievert, Carson. 2020. "Interactive Web-Based Data Visualization with r, Plotly, and Shiny." https://plotly-r.com.

Spence, Ian. 1990. "Visual Psychophysics of Simple Graphical Elements." *Journal of Experimental Psychology: Human Perception and Performance* 16 (4): 683–92. https://doi.org/10.1037/0096-1523.16.4.683.

Stewart, Brandie M., Jessica M. Cipolla, and Lisa A. Best. 2009. "Extraneous Information and Graph Comprehension: Implications for Effective Design Choices." Edited by M. Henderson. *Campus-Wide Information Systems* 26 (3): 191–200. https://doi.org/10.1108/10650740910967375.

Tractinsky, Noam, and Joachim Meyer. 1999. "Chartjunk or Goldgraph? Effects of Presentation Objectives and Content Desirability on Information Presentation." *MIS Quarterly* 23 (3): 397–420. https://doi.org/10.2307/249469.

Tufte, Edward R. 2001. *The Visual Display of Quantitative Information*. 2nd ed. Cheshire, Conn: Graphics Press.

Tukey, John W. 1965. "The Technical Tools of Statistics." *The American Statistician* 19 (2): 23–28. https://doi.org/10.2307/2682374.

V, Sundaram, Vidhya Lakshmi Sivakumar, Anand Raju, Saravanan A, and Titus Richard. 2023. "The Role of 3D Printing in Engineering and Its Historical Perspective in Civil Engineering - A Review." *International Journal of Civil Engineering* 10 (12): 58–68. https://doi.org/10.14445/23488352/IJCE-V10I12P107.

Vanderplas, Susan, Dianne Cook, and Heike Hofmann. 2020. "Testing Statistical Charts: What Makes a Good Graph?" *Annual Review of Statistics and Its Application* 7 (1): 61–88. https://doi.org/10.1146/annurev-statistics-031219-041252.

Veit, Clairice T. n.d. "Ratio and Subtractive Processes in Psychophysical Judgment."

Watanabe, Tetsuya, and Naoki Inaba. 2018. "Textures Suitable for Tactile Bar Charts on Capsule Paper."

Welchman, Andrew E. 2016. "The Human Brain in Depth: How We See in 3D." *Annual Review of Vision Science* 2 (1): 345–76. https://doi.org/10.1146/annurev-vision-111815-114605.

Wilkinson, Leland, and Graham Wills. 2005. *The Grammar of Graphics*. 2nd ed. Statistics and Computing. New York: Springer.

Zacks, Jeff, Ellen Levy, Barbara Tversky, and Diane J. Schiano. 1998. "Reading Bar Graphs: Effects of Extraneous Depth Cues and Graphical Context." *Journal of Experimental Psychology: Applied* 4 (2): 119–38. https://doi.org/10.1037/1076-898X.4.2.119.