20230421- Alessandro | I think that the document would benefit from more figures. I also think that some math here and there would have made the discussion special. A discussion on PCA & visualization of high dimensional data would help. Good set of references.

# Principles of Effective Data Visualization

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ABSTRACT: In today's visually oriented society, effective scientific images are highly val- ued due to software advancements and electronic distribution. However, many scientific figures can be misleading or poorly presented. To assist authors in strengthening their visual message, this article offers ten guidelines, including considering the message before creating the visual and understanding the differ- ent implications of color combinations. Scientists must be aware of best practices since figure drawing is often not explicitly taught, and there are no standard figures in research

CCS Concepts: • **Computer systems organization → Embedded systems**; *Redundancy*; Robotics; • **Networks** → Network reliability.

Additional Key Words and Phrases: effective scientific images, visual information, software advancements, best practices

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## 1 INTRODUCTION

Visual learning has always been a key component of understanding information, com- bining graphics like charts and graphs with text [1][2]. However, recent research on learning styles has separated visual learning into text and visuals, highlighting the importance of effective visual presentation[1]. With advancements in technology, com- plex visual information can be produced quickly and shared inexpensively via digital methods, leading to an increase in graphical information in scientific writing. Figures are now ubiquitous in scientific papers, with journals requiring graphical abstracts and often promoting articles with graphics on social media[1]. However, studies have found that a significant number of graphs and scientific numbers contain inaccuracies or

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inefficiencies. With the increasing range of visualization options available, there can be a mismatch between information and its presentation or multiple effective ways of expressing a piece of information. It is the responsibility of figure makers to evaluate the benefits and drawbacks of each option using available concepts and make informed

## 2 THE PRINCIPLES

20230421 - Alessandro | Maybe it would be good to have a running example related to the use of data science in global communities in which you apply each of the principles.

### 2.1 Principle No. 1 — Diagram First

20230421 - Alessandro | You might want to adjust your principles and have something like this:

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Principle No. 1 — Diagram First
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Good figures are important because they direct the observer through a coher- ent succession of information [2]. 20230421 - Alessandro | I would adjust the citation method to follow the one recommended by the journal style. The visual composition should be dependent on the figure's intended purpose[2]. While developing figures, take into account the audience's demographics, previous knowledge, and discipline conventions[2]. Graphics should pro- vide all of the information required for the viewer to completely understand them[2]. Additionally, it's helpful to save figures from scientific literature that you find useful as examples to learn from. By studying these examples, you can develop an eye for detail and technical skills that you can apply to your own figures. Not only will this help you produce high-quality visuals, but it will also enhance the clarity and impact of your message[2]. Some frequent errors to avoid while making scientific figures are as follows: 20230421 - Alessandro | Maybe this can be summarized in the table

(1) Adding too many data panels to pad the experimental findings, which might make the visual difficult to read.
(2) Improper labeling of figure panels and legends, can lead to data misunderstanding and misinterpretation.
(3) Selecting the incorrect type of graph or axis title, might make understanding the data displayed difficult.
(4) Employing unsuitable color schemes or font sizes, which might make the graph difficult to read or comprehend.
(5) Failure to give adequate context or explanation for the facts presented, which might make it difficult for the audience to appreciate the relevance of the findings.

Researchers may improve the clarity and impact of their message and raise the chance of their work being acknowledged and recognized in their area by avoiding these common mistakes and following best practices for generating excellent scientific figures. This principle applies to a wide range of scientific fields, including biology, chemistry, physics, and engineering

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**Common Errors in Scientific Figures**

**Error 1**: Too many panels!
**Error 2**: Improper labelings.
**Error 3**: Incorrect type of graph.
**Error 4**: Unsuitable color schemes.
**Error 5**: Provide adequate context.

## 2.2 Principle No. 2—Use the Right Software

Creating effective graphics often requires mastery of one or more software programs that are specifically designed for producing complex, technical, and meaningful visuals[14]. Using a simple spreadsheet application or other software that isn't meant for this purpose may result in impractical or ineffective figures. Fortunately, many data visualization tools are widely available, affordable, or even free, and come with extensive online resources to help users get started. It's important to note that this article does not recommend any software program, and readers should consult other sources for a comprehensive list of software resources. By utilizing appropriate software tools and resources, you can enhance the quality of your scientific figures and improve the clarity of your message. While there are several graphic design software packages available, it is critical to select the one that best meets your goals and ability level.

It is also crucial to remember that developing excellent graphics needs preparation, production, revision, and citation. With practice and experience, you can become proficient in creating effective visuals that support your research and effectively communicate your findings to your audience. While producing visuals, keep in mind the audience, objective, and type of information you want to convey. Moreover, the use of color, contrast, and symbolism may aid in the creation of powerful visuals. 20230421 - Alessandro | It might be good to mention at least one software - the one you want to use to analyze the running example across principles.

## 2.3 Principle No. 3—Use an Effective Geometry and Show Data

When creating scientific figures, it's important to consider the **data-ink ratio**, which is the amount of ink used to display data compared to the overall ink used in the figure. High **data-ink ratios** are ideal, and you may be surprised at how much non-data-ink you use and how much of it can be eliminated[6][28].

Edward Tufte, a pioneer in data visualization, developed the data-ink ratio concept[28]. It is defined as the percentage of ink utilized to display data in comparison to the total amount of ink used in the figure[6]. Tufte argues that while constructing a graph, the data-to-ink ratio should be maximized[28]. This indicates that as little ink as possible should be used simply to represent data[6]. The data-ink ratio urges chart producers to consider if all items in the chart are relevant to the message of the graphic[28]. If not, extraneous items should be removed [28].

This simplifies the picture and makes it easier to understand. The data-ink ratio is derived by dividing the total amount of ink used to produce the graphic by the amount of data-ink[6]. Therefore, your geometrical decisions should be made with the data-ink ratio in mind[14]. While lines and bar plots are among the most popular geometries, bar plots are known for their low data density[14]. They should only be used when there is no distributional information or ambiguity in the data. Despite numerous reports of their inappropriate use, bar charts remain one of the most prevalent data visualization pitfalls[14].

Compositions or proportions can be represented using a variety of geometries. While the standard pie chart is an option, it has fallen out of favor with some due to the difficulties in establishing visual comparisons. There are several comprehensive resources available that can guide you in choosing appropriate geometries for your data, and this page covers only some of the most common geometries and their uses.

By considering the data-ink ratio and selecting appropriate geometries, you can create effective and meaningful scientific figures that convey your message clearly and accurately. The data-ink ratio is significant because it facilitates data visualization[25]. A high data-ink ratio indicates that the figure is overloaded with extraneous components, making it difficult to read and comprehend[6]. A low data-ink ratio indicates that the graphic is straightforward and easy to read, including only the required elements[6]. A figure with a low data-ink ratio communicates the desired message more effectively[21].

20230421 - Alessandro | I think that all of these paragraphs need pictures - It would really help to connect them with some examples.

### 2.4 Principle No. 4—Colors Always Mean Something

Colors are a powerful tool to convey information and can enhance the visual representation of data by providing additional meaning and aiding in the differentiation between various data groups or categories. However, the use of color in data visualization requires careful consideration to ensure that it is used appropriately and effectively[14]. Purple, for example, is often linked with riches and luxury in the West, while it is connected with sadness in Thailand[17]. Color may also be utilized to convey action, alter emotion, and even physiological reactions[3].

Firstly, it is important to avoid using too many colors as this can overwhelm the viewer and create confusion. The number of colors used should be limited to the number of data categories being represented, and a consistent color scheme should be used throughout the visualization.

Secondly, it is crucial to use colorblind-friendly palettes to ensure that the visualization is accessible to all viewers, regardless of their color vision abilities. This can be achieved by using colors that are easily distinguishable by those with color vision deficiencies, such as using high-contrast color combinations or avoiding the use of similar hues. Therefore, color should be used with care and consideration. Some persons with color deficiencies have difficulty distinguishing between certain hues, such as red and green or red and black[9]. Color information is not available to screen reader users since they do not view content visually[9]. As a result, when utilizing color to identify or distinguish information, it is critical to ensure that it is still accessible to persons who cannot perceive color[9].

Lastly, it is important to consider the potential for color choices to create bias or confusion in the interpretation of the data. For example, using red to represent negative values and green to represent positive values may create a bias toward perceiving negative values as "bad" and positive values as "good". Careful consideration should be given to the meaning and connotations of the colors being used in relation to the data being presented. Color coding can be used to offer a visual key to data or to draw the eye's attention[26]. Color, on the other hand, should be utilized to communicate information only after all other possibilities have been exhausted[26]. When transmitting facts, graphic components should be chosen for their clarity[26]. The goal should not be to purposefully mislead the user in order to persuade them of something that the data does not represent[26].

### 2.5 Principle No. 5—Include Uncertainty

In any system, uncertainty is a common factor, and failing to communicate uncertainty in a visual can lead to misinterpretation[29]. Including uncertainty in a visual can be done easily with most software systems and can take the form of standard geometries such as error bars and shaded intervals[14][19]. It is important to consider whether uncertainty is included implicitly in existing geometries, such as a box plot or distribution, or explicitly as an additional geometry, such as an error bar or shaded zone. While expressing uncertainty is necessary, it is equally important to understand the proper message being conveyed.

Various measures can be used to express uncertainty, such as standard deviation, standard error, confidence intervals, and credible intervals, each representing a distinct measure. You must first identify the uncertainty in the initial measurement in order to compute uncertainty[12]. This frequently requires some subjective assessment. For example, if you're using a ruler to measure the diameter of a ball, you should consider how exactly you can interpret the measurement[12]. In certain circumstances, the uncertainty may be simply estimated. For example, if you weigh something on a scale that measures to the closest 0.1 g, you may reasonably predict that the measurement has a ±0.05 g uncertainty[12].

However, it is crucial to be specific not only about the type of uncertainty being communicated but also about its interpretation[14]. Some experts recommend using standard error, as it does not offer clear information regarding standard errors of variances among means. To minimize misinterpretations of uncertainty, especially with small sample sizes, presenting the data itself can be helpful in showing the reader where the data points lie.

## 2.6 Principle No. 6—Panel, When Possible

Repeating a figure to show contrasts is a particularly powerful visual method known as "small multiples"[31]. This technique involves creating a series of similar graphics that display different slices of the same data, allowing for easy comparison and identification of patterns or changes. It is frequently used in data visualization to demonstrate changes over time, disparities across groups, or variations in a single variable[31].

Edward Tufte[23] popularized the word – small multiples. Small multiples are also known as a trellis, lattice, grid, or panel charts[23]. The goal of small multiples is to provide a clear and effective way to compare data, and when used correctly, they can be highly informative and compelling. In fact, efficient small multiples are known to be one of the most effective ways to display complex data sets in a way that is easy to understand and interpret.

Small multiples vary from other visual approaches in that they enable the visual comparison of multivariate data that would otherwise be impossible to portray in a single chart[16]. They display distinct divisions of a dataset using numerous views[23]. Small multiples vary from other visual strategies in that they allow the reader to concentrate on the simplicity of the design and size; once they have learned how to read a single piece, they can apply their understanding to all the others[16]. Small multiples vary from other visual approaches in that they allow the reader to compare multiple variables in the same chart[23].

## 2.7 Principle No. 7—Label, Label, Label‼

It is not good practice to exhibit a fitted model or other model results in a figure if the reader cannot retrace the model specifics[14]. This is due to the possibility that the reader won't be able to recreate the results and won't be able to comprehend how the model was developed. It is critical to offer sufficient information about the model so that the reader understands how it was constructed and how the results were produced. This comprises information about the model's variables, the data used to generate the model, and the procedures used to assess the model's goodness of fit.

The fact that a model geometry may be introduced to a figure does not suggest that it should be. Data and Models are different things, therefore label them correctly and clearly[14]. The inclusion of geometry should be based on the data-ink ratio, which is the ratio of ink spent on data to the total ink used in a figure[30]. When it comes to data visualization, however, the focus should be on the data itself, and geometries should be employed only when they improve comprehension of the data being presented. It's crucial to adhere to the three primary parts of the modeling process while making a geometric model: building a basic geometric item, altering geometric aspects as necessary, and fusing the object's components to produce the final geometric model[**?** ][15].

Clear labeling is essential for effective data visualization. Labels should be concise, but informative and placed close to the data they represent[1]. Axis labels, titles, and legends are also important to include and should provide context and explain any abbreviations or units used. But nonetheless, there are certain typical errors individuals make when labeling data visualizations that might reduce their effectiveness[4][11].

One typical mistake is failing to provide titles or having them too tiny. Titles are critical for understanding visualizations as separate images[4]. Another mistake is having too many data labels. The inclusion of unnecessary data diverts attention from the main idea and can confuse visualizations[4]. Similarly, utilizing too many categories might result in too huge legends, making the visualization difficult to comprehend. It is advised to limit the number of categories to ten or fewer[4].

### 2.8 Principle No. 8—Annotate Wisely

According to research published in the Journal of American Medicine, more than one-third of graphs were not self-explanatory[14]. This emphasizes the necessity of captions being self-contained, which means they should be able to convey the core message of the graphic without referring to the main text[5]. Captions should also be straightforward and brief, avoiding jargon and utilizing basic language[10]. Therefore, captions should be stand-alone, which implies that the main idea can be comprehended even if the figure and caption are seen separately from the rest of the research.

When performing research, it is crucial to annotate sources appropriately in addition to captions. Annotating sources entails engaging with them critically in order to identify their value and relevance to the research question[13]. Annotated bibliographies are a popular method of organizing and summarizing materials, and they usually contain a brief description and/or critical review of each source[7]. Annotations can be used to highlight important points or features in a visualization, but they should be used sparingly and placed near the relevant data[14]. It is also important to ensure that annotations do not obscure the data or make the visualization too cluttered.

It's crucial to keep the annotation's goal in mind when writing it. Annotations that are descriptive or instructive sum up the content and explain why the source is beneficial for learning more about a certain subject or issue[5]. Analytical or critical annotations go beyond summarizing the content to examine its strengths and faults and to discuss how the author's conclusions might be applied to the ongoing research[5].

### 2.9 Principle No. 9—Strive for Clarity, Use Info-graphics

Technical visualizations frequently benefit from text or other annotations, even if info-graphics are not used in most situations. Tufte's works are excellent instances of combining textual, visual, and quantitative data into creating effective visualizations[14][27]. Tufte emphasizes the necessity of concise and simple communication in data visualization, arguing that visuals should be used as illustrations rather than as the main point of an argument[27].

Other than Tufte's principles, four methods of visual communication may be employed to successfully transmit information: concept illustration, concept production, visual discovery, and daily data viz[2]. The type of visualization utilized is determined by the nature and purpose of the data. Complex data, for example, may necessitate specialized and unconventional representations like force-directed diagrams or topographical plots[2].

While designing visualizations, keep the intended audience and their level of skill in mind. Visualizations that are understandable to a specialist audience may be incomprehensible to a wider audience[2]. It is also necessary to examine the amount of data supplied as well as the best manner to organize and show that material - it is critical to remove chart garbage and other non-essential visual components from the design [14]. Simple design components like borders, lines, circles, and squares can be used to visually organize and simplify content[18].

The primary goal of data visualization is to convey information clearly and effectively. Avoid using 3D effects, unnecessary decorations, or visual clutter that can detract from the message[14]. It is also important to use consistent formatting and avoid using different scales or units within the same visualization[14].

### 2.10 Principle No. 10—Seek Feedback

While there are several theories and criteria for good data visualization, the most effective data visualization ultimately focuses on engaging readers by presenting data in an easy-to-understand visual format that highlights key messages[14][22][20] 20230421 - Alessandro | I agree with this! . The human visual system naturally recognizes structure and patterns, making visual information easier to digest[22].

Nonetheless, data visualization must be used properly and ethically[1]. Data visualization can be compelling, but it should not be used to alter data in order to elicit a specific response[1]. Data should instead be examined and presented in such a way that it correctly portrays the information[30]. Before using a software tool, it is crucial to examine the data in order to produce good data visualizations[1]. Understanding the facts and determining the most significant information to convey is required for this[20]. It's crucial to pick the appropriate visualization style. Various types of data are better suited for certain sorts of visualizations[22].

It is highly recommended that designers of illustrations seek external feedback on their work[14]. Not only does this help to satisfy coworkers, but it also allows them to provide input specifically on the illustrations, as they will not have access to the accompanying text to fill in any gaps left by the graphics[14]. By seeking feedback, creators can identify areas for improvement and ensure that their visualizations are effectively conveying the intended message to their audience[14].

## 3 WHAT ABOUT TABLES?

20230421 - Alessandro | A table would be helpful. Tables can be a valuable and effective way to present data, even though they are not always considered part of data visualization. They are particularly useful for presenting precise numerical values and summarizing large amounts of information. However, when it comes to research and data analysis, the focus is often on making comparisons rather than just presenting absolute numbers[14]. Studies have shown that well-designed graphs and visualizations outperform tables in terms of helping readers identify patterns, make comparisons, and draw conclusions.

For example, Gelman et al [8] found that graphs were more effective than tables in presenting data, while Spence and Lewandowsky's[24] research showed that pictorial representations such as bar graphs and pie charts were more effective than tables in conveying information[14]. Tables are best used for quick reference and lookup of specific data points, but graphs and visualizations are better suited for helping readers understand relationships, trends, and patterns in the data[14].

In summary, tables can be useful for presenting specific numerical values, but graphs and visualizations are generally more effective for presenting and interpreting complex data. It is recommended to use graphics as the primary tool for data visualization and reserve tables for presenting detailed numerical information.

## 4 CONCLUSION

While certain aspects of peer-reviewed literature have remained consistent over time, others are evolving. For example, most publications today have more authors than in earlier decades, and a wider range of journals allows for greater flexibility in terms of article length and other criteria. Nevertheless, there remains a significant need for visual representations of data and results, as demonstrated by graphical abstractions, summary figures, and info-graphics. In addition to effective visual representations, it is important to consider the content of tables. Tables can be a powerful and effective method for displaying data, especially when it comes to referencing precise figures or summarizing quantities or information. However, when it comes to interpreting numerical results, well-designed graphs often outperform tables.

**Overview figure of the principles presented in this article**

Authors have significant responsibility for creating effective figures and tables, and it is important to seek out best practices from literature, seminars, and other resources. In the absence of clear rules, it is critical that a set of aesthetic criteria be established to guide the effective transmission of visual information. Ultimately, the longer someone studies a figure without grasping the message, the less likely they are to learn from it, and authors should strive to create figures and tables that are engaging and easily understood by readers.

20230420 - Alessandro | References might need to be fixed, but should be fast.

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