Toward a Unified Framework for Visualization Design Guidelines

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Visualizations are now widely adopted across disciplines, providing effective means to understand and communicate data. However, people still frequently create misleading visualizations that distort the underlying data and ultimately misinform the audience. While design guidelines exist, they are currently scattered across different sources and devised by different people, often missing design trade-offs in different contexts and providing inconsistent and conflicting design knowledge to visualization practitioners. In this work, our goal is to investigate the ontology of visualization design guidelines and derive a unified framework for structuring the guidelines. We collected existing guidelines on the web and analyzed them using the grounded theory approach. We describe the current landscape of the available guidelines and propose a structured template for describing visualization design guidelines.

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

Additional Key Words and Phrases: visualization, guidelines, visualization literacy

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1 INTRODUCTION

The benefit of intuitively understanding and communicating data through visual means has made visualizations gone mainstream. They are now commonly used by millions of people across disciplines from business analytics and science communication to data journalism and personal informatics. Although there is an abundance of visualization tools, many practitioners have a lack of awareness of perceptive and cognitive trade-offs in different visualization designs. As a result, they often create misleading visualizations that distort the underlying data and fail to convey the intended message in a trustful manner.

Design guidelines exist more than ever before to help inform people about creating the right visualizations, including from Data to Viz, DataVizProject, the Data Visualization Catalogue, and Financial Times Visual Vocabulary [1–3, 6]. These guidelines mainly focus on choosing a specific chart based on types of data and tasks (e.g., use a scatter plot for showing the relationship between two data variables). They mainly serve as a chart typology which has been well established from the decade of visualization research and is already embedded in many visualization tools such as Excel, Tableau, and PowerBI.

The existing guidelines currently lack in providing perceptual and cognitive design considerations including potential design pitfalls, caveats, and trade-offs (e.g., save the pies for dessert). Only a few discuss these considerations such as from Data to Viz and individual blogs hither and thither [5, 7]. A problem with such scattered design resources

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developed by individual practitioners is that it provides inconsistent and often conflicting design knowledge. This often encourages people to blindly follow a guideline without acknowledging trade-offs in different contexts. On the other hand, there are no concrete rules and principles for how a guideline should be structured to avoid such problem.

In this work, we set out to investigate the ontology of the current guidelines available on the web and develop a unified framework for describing visualization design guidelines. Using the grounded theory approach, we collected existing guidelines from various online sources archiving articles on data visualization, reviewed and analyzed guidelines to derive high-level attributes and a structure of guidelines. We identified eight attributes: purpose, problem, approach, alternative, chart type, chart elements, task type, and data type and classified three different types of guidelines according to their combination: problem-solving, enhancement, and alternative suggestion. Based on it, we also propose a template for structuring design guidelines.

2 BACKGROUND & RELATED WORK

Theories and frameworks developed by the visualization community for the past decades provide well-established vocabularies for reading and constructing visualizations such as visual encoding channels, data types, and analytical tasks [12]. To quantify the effectiveness of a visualization design, researchers run controlled experiments comparing design alternatives. The results of these experiments provide guidelines for choosing specific perceptual channels [14, 18] and determining their effectiveness for different tasks [19, 23]. An empirical study mostly focuses on a particular aspect of a visualization in a highly controlled context but often its result is translated into a dictative guideline.

With the increasing importance of data in our lives, there has been a growing interest in data visualization literacy. Chevalier et al. observed that, while data visualizations are prevalent in K-4 education, students are rarely taught how to read and construct them [8]. Visualization literacy is defined as the skill to read information encoded in data visualizations as well as create ones to answer questions in the data [10, 11, 20]. Most works in this area focus on developing formally assessing visualization literacy. Boy et al. developed literacy tests for line charts, bar charts, and scatter plots based on item response theory [11]. Lee at al. designed similar assessment tests for an extended list of visualization types, following the procedure of test development in Psychological and Educational Measurement [20]. The assessment questions asked in those tests are based on low-level analytical tasks such as finding extremum and making comparisons. More recently, Borner et al. present a holistic framework for teaching and assessing data visualization literacy [10].

In addition to formally assessing visualization literacy, there have been a few recent works to develop guidelines for helping practitioners design effective visualizations. Diehl et al. launched a discussion platform to facilitate the discussion of visualization guidelines [15]. The platform provides a centralized place for practitioners to ask questions about the validity and quality of their own visualizations. Wang et al. proposed a cheatsheet structure to introduce a visualization technique, including its construction, similar techniques, and potential issues [25]. In the recent VisGuides workshop, Brown proposed a conceptual data model for a repository of guidelines using tags for a structured organization as well as references to empirical evidence [24]. Meyer et al. similarly described a guideline model for representing choices within the four-level nested model spanning from domain characterization to visual and algorithm design [21].

Our work builds on the existing work to analyze how design guidelines are currently shared on the web and investigate ways to derive a structured framework for describing visualization design guidelines.

3 METHODOLOGY

As the main methodology of the study, we took the grounded theory [13, 16], an inductive reasoning approach for gathering and analyzing data to generate a high-level theory or structure. The approach typically has a series of steps: collecting, coding, and theorizing data and requires rigorous and iterative analysis throughout the procedure. We followed the steps of the approach, and the details are below.

3.1 Selecting Guideline Sources

First, we selected sources of the guidelines for data visualization. Since guidelines are scattered hither and thither, we aimed to collect them from various sources as comprehensively as possible. We started this with commercial blogs run by companies that deal in data visualization software (e.g., Datawrapper [5]) as they provide useful tips for visualization to entice practitioners to visit them frequently. We also selected popular non-commercial blogs that archive posts related to data visualization (e.g., from-Data-to-Viz [1], Data Journalism [4]). Other blog articles that share various information for not only visualization but also data science practitioners have also been selected as our data source, if relevant. Besides, we included relevant web pages in the source via Google Search. We searched a combination of query words such as data visualization, guidelines and similar synonyms. From these sources, we snowball sampled [17] and included only highly relevant and non-overlapping articles.

3.2 Extracting and Listing Guidelines from the Sources

After the selection, we extracted and listed guidelines from the sources. For blogs, we reviewed all the posts related to data visualization. Most of the posts focused on specific chart types like bar plots, while some posts present a list of general and high-level guidelines. Except for several posts, most posts contained multiple guidelines. Some were explicitly stated as guidelines, while others were implicitly contained in ordinary sentences or paragraphs of the text. We carefully reviewed each post and extracted as many guidelines as possible. We listed them in a spreadsheet with summary text and source links for further analysis. For the summary text, we tried to borrow the original expressions as much as possible but made some modifications when helpful for the analysis. Throughout the process, we obtained 513 potential guidelines from 84 posts of 23 sources.

3.3 Reviewing and Coding the Guidelines

We followed an iterative process of reviewing the listed guidelines. We started with a subset of 20 examples and tried to identify common features that construct the guidelines. In the first round, we roughly captured that guidelines are essentially imperative sentences along with conditional clauses of a particular context or situation if necessary. We also noted that guidelines suggest a certain chart type or elements of a chart instead of its counterpart. Some guidelines were very abstract, while others were too specific. Some guidelines overlapped each other. We derived initial codes from the first round and refined them by applying them to the remaining guidelines. The iterative refinement process continued until the entire case was covered and three researchers reached an agreement. Through this process, we filtered out overlapping guidelines, and removed both too specific (not generalizable as often dealing with very minor or subjective issue) and too general ones. Our final list has 226 guidelines from 50 posts of 19 sources, and eight codes (or attributes) for explaining each guideline — context (chart type, chart element, data type, target type), approach, alternative chart, problem, purpose.

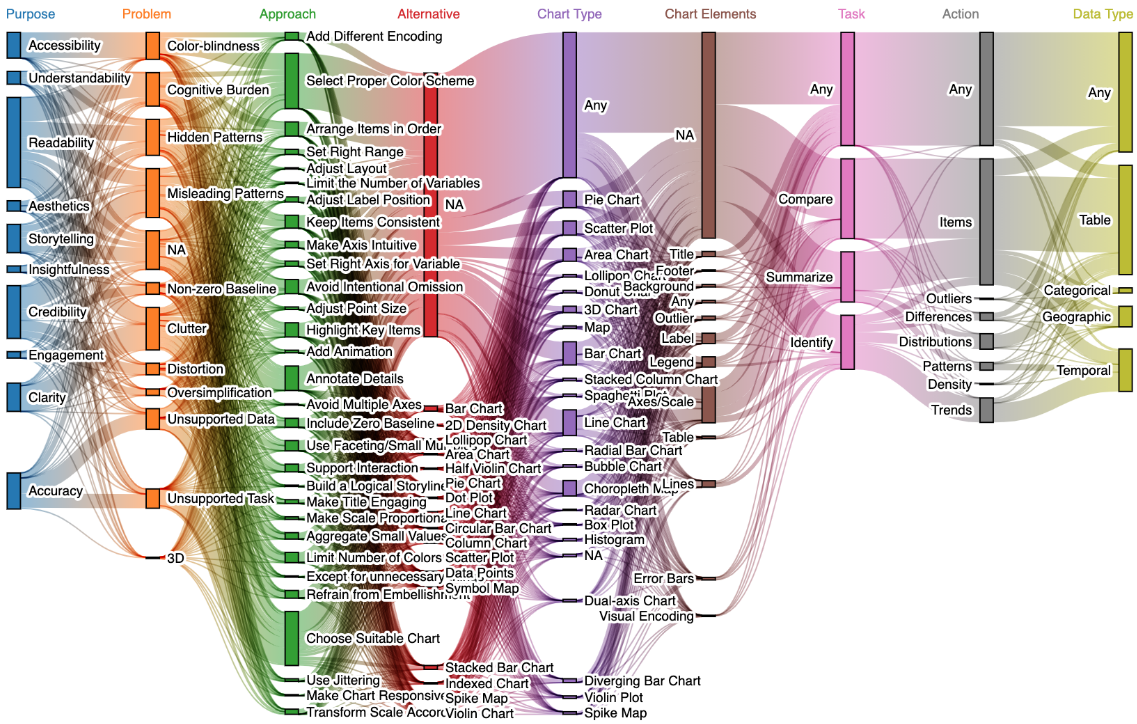


Fig. 1. A sankey diagram showing the proportional relationship among eight attributes of visualization design guidelines. Our final collection has 226 guidelines, and eight attributes for explaining each guideline — context (*chart type*, *chart element*, *data type*, *task type*= *task* + *action*), *approach*, *alternative*, *problem*, *purpose*.

3.4 Identifying the Ontology of Guidelines to Derive a Unified Structure

With the collection of guidelines and the factors, we try to link them together to identify higher-order features and relational patterns to finally create a unified and generalizable framework for structuring guidelines. We discuss the results and the framework in the next section.

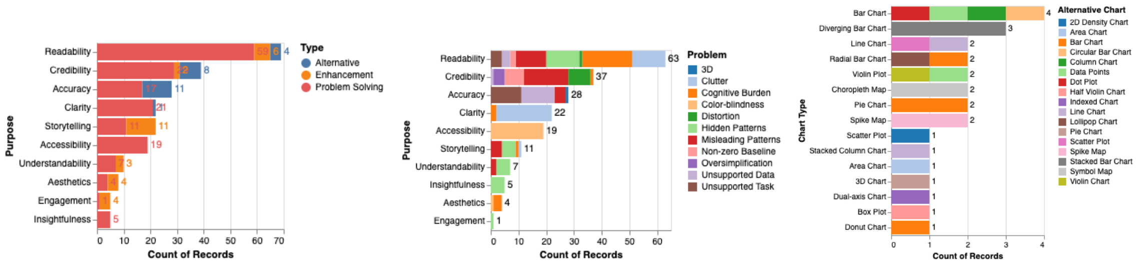
4 RESULTS

In this section, we describe the guideline attributes, characteristics of guidelines and suggest a structured framework for presenting guidelines.

4.1 Attributes of Visualization Design Guidelines

Through the analysis, we identified eight attributes of visualization design guidelines: *purpose*, *problem*, *approach*, *alternative*, *chart type*, *chart elements*, *task type*, *data type*.

4.1.1 Purpose. This refers to a goal that a guideline is trying to achieve. Among the 226 guidelines, *readability* (28%) was the most, followed by *credibility* (16%), *accuracy* (12%), *clarity* (10%), *accessibility* (8%) and others (*understandability* (10), *aesthetics* (8), *engagement* (5), *insightfulness* (5)).



(a) (b) (c)

Fig. 2. The number of guidelines (a) by characteristics per purpose, (b) by problem per purpose about problem-solving. (c) Chart type and its alternative charts

4.1.2 Problem. This refers to a matter or a situation that is needed to be dealt with and overcome with the guideline. While the guideline is often intended to solve a problem in nature, 30 guidelines (13%) did not have a specific problem situation. Among the guidelines for dealing with the problem, we found each problem has a majority of purposes. *Misleading patterns* (16%) are mostly related to *readability* and *credibility*. *Clutter* (15%) hinders *clarity* and *readability*.

Hidden patterns (12%) and *cognitive burden* (11%) are also relevant to *readability*. *Color-blindness* (8%) is *accessibility*. *Unsupported data* (7%), *unsupported task* (7%), and *3D* (1) are about the *accuracy*. Lastly, *distortion* (4%), *non-zero baseline* (4%), and *oversimplification* (2%) are related to *credibility*.

4.1.3 Chart Type, Chart Elements, Data Type, and Task Type. We identified attributes that can compose the context of guidelines. *Chart type* is a target that a guideline deals with. We found various chart types, among which *line chart* (20) was the top, followed by *bar chart* (18), *pie chart* (13), *choropleth map* (12), and *scatter plot* (11). *Chart elements* are components that cause problems in the chart mentioned in the guideline, and the top 5 are *axes/scale* (22), *legend* (8), *label* (6), *lines* (5), and *title* (4).

In terms of *data type*, we classified them using Tamara's taxonomy (table/geographical/networks) [22]. We found guidelines that have *table* (83) and *geographic* (16) datasets but not *networks*. We also tagged the attributes of the data such as *temporal* (32) and *categorical* (4), if the guideline refers to a specific dataset type.

We tagged tasks of guidelines as "*action-target*" form according to Tamara's work [22]. Actions can be classified into three query tasks: compare, identify, and summarize. *Compare* was the most frequent, and *comparing individual items* is the most common. *Identify* was the second most and was mostly paired with *temporal* data. *Identify* action has various targets— *trends*, and *distributions*, *differences*, and *density*. *Summarize* was more likely to be paired with *geographic* data than the others.

Bar chart, *pie chart*, and *line chart* are most frequently mentioned for comparison. *Line charts*, *scatter plots*, and *area charts* are mostly used for identification. *Choropleth map*, *bar chart*, and *pie chart* are the top three for summarization.

4.1.4 Approach. This refers to how a guideline handles the problem context. It suggests practitioners what to do with the problem. The most frequent five approaches are *select a proper color scheme* (42), *choose a suitable chart* (41), *annotate details* (18), *highlight key items* (11), *arrange items in order* (11).

4.2 Characteristics of Visualization Design Guidelines

We identified that design guidelines could be categorized into three: (a) problem solving, (b) enhancement, (c) alternative suggestion according to the combination of the attributes. Not all guidelines have all attributes, but some do not have specific attributes. The guidelines in category (a) problem-solving include attributes "problem" as a necessity, as they literally have to solve the problematic situations. Meanwhile, for the guidelines in (b) enhancement and (c) alternative suggestion, "problem" is not essential but optional. (b) enhances the user experience by finding areas to improve, even in situations that are not too problematic. (c) compares options in a particular context and suggests a better alternative among them while dissuades the other. For this reason, guidelines in (c) must include attribute "alternative".

4.2.1 Guidelines as a Problem Solving. Problem-solving is the major characteristic of the guidelines. The most common purpose of these guidelines is to solve the issue of *readability*. For mitigating readers' *cognitive burdens*, the guideline suggests *arranging items in order* or *making axis intuitively*. It is also important to use a color-blind friendly color scheme to address *accessibility* issues. For *accuracy*, it is necessary to introduce shapes proportional to the actual value, rather than simply coloring each area with the same color when drawing a choropleth map.

4.2.2 Guidelines as an Enhancement. Unlike the problem-solving guidelines, some guidelines do not have issues that need to be resolved. (e.g., use direct labels if possible as they may improve readability, to give readers extra bits of information, annotate additional elements such as ranges, arrows, contours.) The most common purposes in these types of guidelines are storytelling, engagement, and aesthetics. The main approaches covered in storytelling are to annotate details, make title engaging, highlight key items, and build a logical storyline. It supports interaction for engagement and chooses an appropriate color scheme for aesthetics. These guidelines can be helpful in improving visualization quality and user experience.

4.2.3 Guidelines as an Alternative Suggestion. Situations that need to be replaced when there is a problem with visualization, such as considering different chart types representing data types, handling tasks that the chart does not support, or situations where data patterns are misleading, hidden or oversimplified. There is an approach to this type of guidance called "Use Alternate Charts." This guideline type suggests alternative options to address the problem. For example, using a horizontal bar chart instead of a vertical bar chart to make more room for long data labels, or when creating a box plot, display the sample size for each group such as by using a half violin plot or showing raw data distributions.

4.3 Structured framework for describing guidelines

In this section, we suggest a template structure for data visualization guidelines. To derive the template, we referred to Amershi's work [9] that extract and discuss design guidelines for human-AI interaction. The work also noted that design suggestions are scattered throughout different circles, which makes them difficult to discover and to extends to others. It noted the importance of a unified set of guidelines from a variety of communities and sources and tried to systematically organize them with iterative reviews. While consolidating them, the work suggests criteria for guidelines that they should adhere to a consistent format and clarify issues in them. We tried to design our template to have a systematic structure accordingly and clearly convey the features we found through the analysis in the previous section. We derived the guidelines through multiple ideation sessions in which three researchers rigorously reviewed and analyzed the final set of guidelines to produce a representative and generalizable structure.

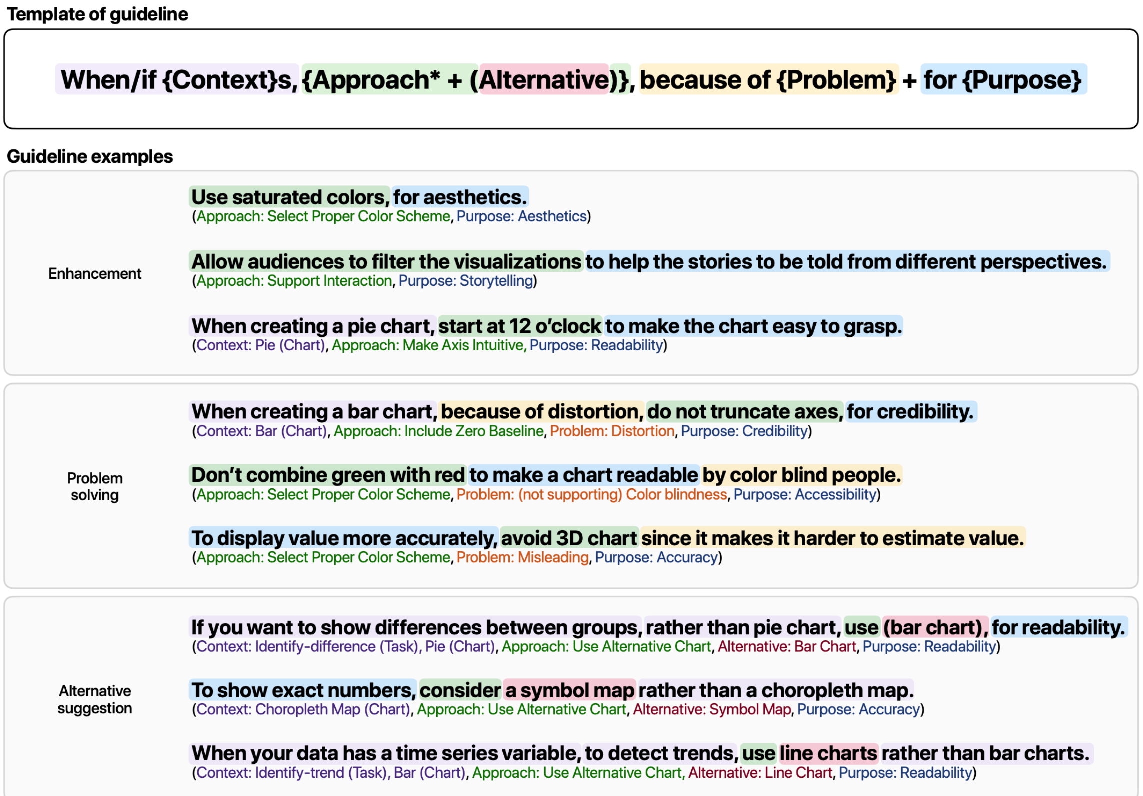


Fig. 3. The structure template of guidelines and examples across the three different characteristics: enhancement, problem-solving, and alternative suggestion. The template consists of a combination of attributes and components of a sentence. Each component of the sentence is color-tagged according to each attribute in includes

The baseline structure of our template and examples are detailed in Figure 3. The template consists of a combination of attributes listed in the previous section and components of a sentence. Each component of the sentence is color-tagged according to each attribute in includes.

Although the template is presented as a single concise sentence, it is not our intention to claim that all guidelines should be presented in this way. Also, they do not have to include all the attributes mentioned or follow a fixed order. Different levels of guidelines can be made depending on the combination of each component. The order of the components may vary depending on their use. For example, Enhancement does not need "Problem," which makes it shorter and more applicable to various context. On the other hand, Problem-solving requires problem attribute as an essential component. Alternative suggestion requires "Alternative chart" as an essential component and its context should be narrowed and specified with multiple context attributes. We explain each component of the example template in the figure in detail.

- **When/if Context** is an adverb clause for providing specific context to a guideline while narrowing down its use. Context attributes such as chart type, data type, and task type can be used with time adverb (e.g., when) or conditional adverb (e.g., if). The former is usually for broader context, while the latter is for more determinative and detailed context. This clause is optional, and various combinations can be made from one to several, depending on the depth of each guidelines' context.

- **Approach* + Alternative** is an imperative phrase that delivers clear instruction that the author should follow. As a key component of the template, it should be included in any guideline. The attribute "Approach" can be used for this part, which usually starts with a verb. Depending on the verb of the attribute, the guideline can be categorized into positive and negative imperative sentences. The former is for affirming certain actions (e.g., do, use, choose, include) while the latter is for dissuading (e.g., don't avoid, limit). Alternative is not required but should be inserted if Approach is *Choose ([Inserted] Alternative Chart)*.
- **because of Problem + for Purpose** is prepositional phrase for describing a reason for a guideline. The attribute *Problem* and *Purpose* can be used with prepositions such as because of and for. While the former is optional, the latter is required for a guideline to be of good quality.

This unified form of guidelines allows the guideline-makers to create more systematic and accessible guidelines. It will make it easier for practitioners to find guidelines that meet their specific needs/situations they face in practice.

5 DISCUSSION AND CONCLUSION

Despite the importance and popularity of data visualization and its diverse applicability in practice, its design guidelines have been somewhat spread across different sources and maintained by individual practitioners. Each of them provides helpful tips in a specific context, but it has been difficult to grasp the holistic view of guidelines and understand if and how they relate to one another. To this end, this study presents the ontology of visualization design guidelines and a consolidated framework for structuring the guidelines. We collected, reviewed, and analyzed guidelines distributed in various online sources with the grounded theory method. We identified the common attributes of the existing guidelines and their characteristics. Based on it, we designed a template structure that is generally applicable to data visualization guidelines.

In addition to our findings, we would like to conclude this paper by presenting discussion points regarding extending our study. In the analysis, we found some guidelines conflicting with each other, even though they were useful individually. For example, while most guidelines for 3D charts advise against using it, a few implies they can be beneficial in a specific context such as redundantly encoding data histograms along the perspective dimension. Also, we found some of the guidelines seemed to be somewhat less credible, raising how much confidence each has in practice. For example, one of the guidelines recommends not to highlight one of the four or more categories in area charts, which is somewhat questionable. To address these questions, we are considering linking empirical studies to these guidelines. The visualization research community has already accumulated a variety of design knowledge for better data visualization with empirical studies. Presenting empirical evidence to support each guideline can help explain conflicts between guidelines and in what specific context they will be more meaningful, enhancing their credibility.

In addition to improving the knowledge base of guidelines, we also want to design a navigation interface that allows practitioners and researchers to access and extend our findings. We also plan to rigorously examine the usefulness or effectiveness of our knowledge base and interface with workshop-like user studies with visualization practitioners. We believe that our work contributes to help ensure truthful visualizations in the wild and alleviate the issues with misinformation and disinformation caused by ill-formed visualization designs.

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