Guidelines for Presenting Quantitative Data in HFES Publications

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This article provides guidelines for presenting quantitative data in papers for publication. The article begins with a reader-centered design philosophy that distills the maxim "know thy user" into three components: (a) know your users' tasks, (b) know the operations supported by your displays, and (c) match user's operations to the ones supported by your display. Next, factors affecting the decision to present data in text, tables, or graphs are described: the amount of data, the readers' informational needs, and the value of visualizing the data. The remainder of the article outlines the design decisions required once an author has selected graphs as the data presentation medium. Decisions about the type of graph depend on the readers' experience and informational needs as well as characteristics of the independent (predictor) variables and the dependent (criterion) variable. Finally, specific guidelines for the design of graphs are presented. The guidelines were derived from empirical studies, analyses of graph readers' tasks, and practice-based design guidelines. The guidelines focus on matching the specific sensory, perceptual, and cognitive operations required to read a graph to the operations that the graph supports.

Editor's Note: This article was prepared at my invitation following a discussion with the editorial board over a rather ironic situation that we face in reviewing manuscripts. Whereas one would expect a discipline that claims special expertise in information display to be exemplary in presenting its own graphic material for publication, we find quite the contrary. The illustrations accompanying the typical manuscript submitted to Human Factors *border on the abysmal. So I decided to approach several well-known researchers in this topic area with the idea of distilling their expertise into a set of useful guidelines. They agreed. However, for the sake of consistency, I felt it necessary to have the manuscript reviewed, and it was – by the HFES Communications and Publications Subcouncil. The end result is published here for the benefit of all would-be authors. Excerpts will be included in future editions of the* Authors' Guide.

INTRODUCTION

The communication of scientific research requires decisions about how to present quantitative data (e.g., Loftus, 1993). Many options are available for presenting data, especially with the increasing capabilities of word-processing, spreadsheet, and graphics software for creating tables and graphs. However, having all of these options may complicate decisions concerning the communication of the data. This article attempts to help researchers to sort through the options by distilling the research and state-of-the-practice literature into a set of guidelines.

A concise statement of the philosophy of human factors is "know thy user." One way that this translates into specific design decisions concerning graphs is that designers should understand the tasks in which readers engage when they look at the displays. Users'

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tasks require certain sensory, perceptual, and cognitive operations (e.g., Gillan & Lewis, 1994; Lohse, 1993; Pinker, 1990; Simkin & Hastie, 1987). For example, a well-designed line graph can ease the discrimination of differences in the slopes of the lines (or of the differences in the angles among lines), which is valuable if the user's task involves identifying statistical interactions. However, if the user's task involves adding the values of conditions at various points, then discriminating among slopes would be of little value. In other words, a well-designed graph achieves a correspondence between the task demands and the operations the graph affords.

The philosophy that underlies the guidelines presented here extends the maxim "know thy user" to "know your users' tasks" and "know the operations supported by your displays." Finally, knowledge of tasks and display-supported operations can be integrated into "match the operations supported by your display to those the user needs to perform the task" (see also Larkin & Simon, 1987).

Deciding How to Present Quantitative Data

Making decisions about how to present data involves a multistage process, as illustrated in Figure 1. The first decision concerns the amount of data being presented. When presenting a small amount of data, authors should weigh the communication benefits of tabular or graphical presentation against the reader's cognitive costs (e.g., processing the data display and integrating the information from the display and text). Typically, a few data points that have a simple relation, such as one value being substantially greater than a second, would not require a graphical display for the reader to apprehend the difference; a table that simply showed the numbers would provide little communication benefit over listing those same numbers in the text. Consequently, those few data points might best be presented in the body of the text. In contrast, certain relations, even in a small amount of data, can be communicated more quickly and clearly by means of a graph. For example, if a 2 × 2 factorial experiment produced an interaction in the data, that interaction might best be communicated with two nonparallel lines in a graph, even though the lines would contain only two mean values each.

With a substantial amount of data, the next decision concerns readers' use of the data, especially the degree of precision that readers are likely to need. If they need to apprehend the relations within the data, not precise amounts, then the data would probably best be displayed in a graph (e.g., Loftus, 1993). However, if the reader might need both precise values and specific visualizable relations, such as an interaction or a logarithmic function, then the data should be displayed in a graph with quantitative labels next to the indicators showing their values (e.g., see Figure 6B later in this paper; also see Hink, Wogalter, & Eustace, 1996). If the reader needs precise values and the relations in the data do not lend themselves to visualization (e.g., an irregular pattern of means), then the data should be presented in a table.

Finally, different readers will have different needs for information as they read an article and look at the graphs and tables. For example, someone with a general interest in a topic but no specific interest may examine a graph holistically to get the main idea or ideas. For that person, the graph serves a communicative function. In contrast, readers who have done extensive work on a topic may examine the data in detail. For them, the graph should both communicate the major point and allow them to explore the data to generate their own hypotheses. In addition, some readers may change strategies – from a quick perusal to a detailed examination – during the course of reading an article. Ideally, the design of a data display should support readers' comprehension of its message and exploration of its details.

In the remainder of this article, the numbered paragraphs describe general considerations concerning users, graphs, and the interactions between users and graphs. Specific design implications derived from those general considerations appear after the numbered paragraphs in bulleted paragraphs.

CHOOSING THE GRAPH TYPE

Having decided to present the data in a graph, one's next decision concerns the type of

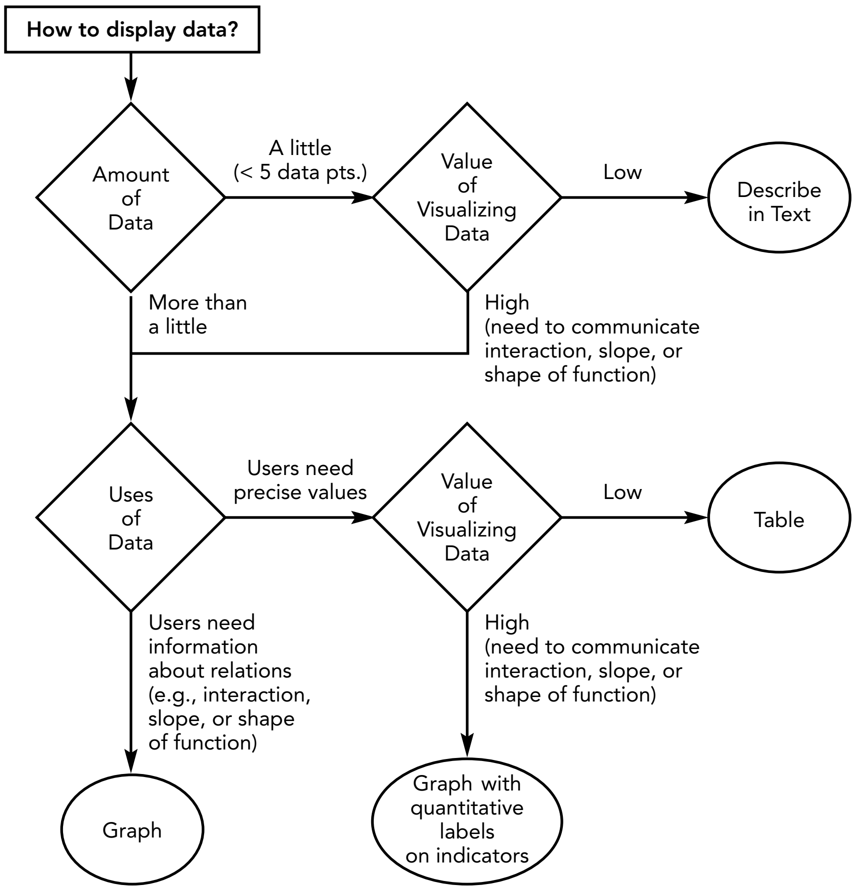


Figure 1. A flowchart showing the steps involved in deciding how to present data. The diamonds indicate decision points.

graph. This decision depends on both the characteristics of the readers and of independent and dependent variables.

Guidelines

1.1. The choice of graph type (e.g., line, bar, stacked bar, scatter plot, pie chart) depends on the readers' experience, knowledge, and expectations.

- Use common graphs with which all readers are likely to have experience (e.g., line graphs, bar graphs, pie charts, and scatter plots) *except* when (a) the data are normally shown in a certain format, such as a Receiver Operating Characteristic curve for signal detection data; (b) readers are familiar with a special-purpose graph (e.g., visual sensitivity functions in which increasing *y*-axis values indicate less sensitivity); or (c) readers need to accomplish a specific task for which the graph is well suited (e.g., a stacked bar graph for determining the sum value of several conditions).

1.2. The choice of graph type depends on the readers' informational needs.

- Use either a *line graph* or a *bar graph* if readers need to determine relative or absolute amounts.
- Use a *line graph* if readers need to determine the rate of increase in the means of the dependent (criterion) variable as a function of changes in the independent (predictor) variable.
- Use a *bar graph* if readers need to determine the difference between the means of the dependent variable across different levels of the independent variable.
- Use a *pie chart* or *divided bar graph* (i.e., stacked bar graph) if readers need to determine proportions but not absolute amounts.

- Use a *scatter plot* if readers need to determine the degree of correlation between two variables.
- Use a *line graph* if readers need to detect interactions between independent (or predictor) variables.

1.3. The choice of graph type depends on the characteristics of the independent variable or variables in the research.

- Use a *line graph* to represent a continuous independent variable.
- Use either a *line graph* or a *bar graph* to represent an ordinal independent variable.
- Use a *bar graph* to represent a categorical independent variable. However, in a graph in which an interaction should be the main focus, using a line graph to represent a categorical independent variable would be appropriate, particularly if that variable contains more than two levels.

DESIGNING THE GRAPH

Designing a usable graph requires consideration of the readers' tasks in comprehending it. Software applications for the production of graphs may not support the design of a usable graph, especially if the graph designer uses default settings. If an application produces graphs that fail to support the readers' tasks, then the graph designer should (a) learn to use the optional settings on the software, (b) copy or otherwise transfer the graph into a general graphics program that provides control over the features of the graph and edit it into a usable graph, or (c) use a different application that provides the necessary control. "My software wouldn't let me produce a usable graph" is no more acceptable an excuse than "My response time recorder wouldn't record the data accurately." Articles bear the name of the author, not that of a software application. Consequently, unusable graphs will be attributed to the author and will impede readers' understanding. In addition, if readers have to exert a substantial amount of cognitive effort to read a paper, they may be less likely to finish it.

Definitions

Figure 2 provides a visual reference for the following definitions.

Indicators. Indicators are the elements in a graph that express the value of the dependent variable for a given value or category of an independent variable. Examples include the plotting symbols and lines in a line graph, bars in a bar graph, pie segments in a pie chart, and plotting points in a scatter plot.

Axes. The *y* axis is a vertical line at the left edge of the graph (and sometimes is repeated at the right edge). The *x* axis is a horizontal line at the bottom of the graph.

Labels. Verbal labels are used for variable names on the *x* and *y* axes. In addition, verbal labels can be used to name levels of a categorical independent variable. In a graph that contains only one independent variable, the levels would be represented as specific points on the *x* axis corresponding to bars in a bar graph or points in a line graph. In a figure that contains multiple independent variables, the levels of one categorical independent variable might be represented as separate lines in a line graph or as separate graphs; each level should have a unique label.

Quantitative labels include the scale values associated with the axes. Quantitative labels may also be used to provide values for levels of an independent variable.

Background. The background includes any graphical marks falling within the axes in addition to the indicators. In scientific graphs, one common background is an extension of the tick marks from one or both axes, forming a grid that appears to be behind the indicators.

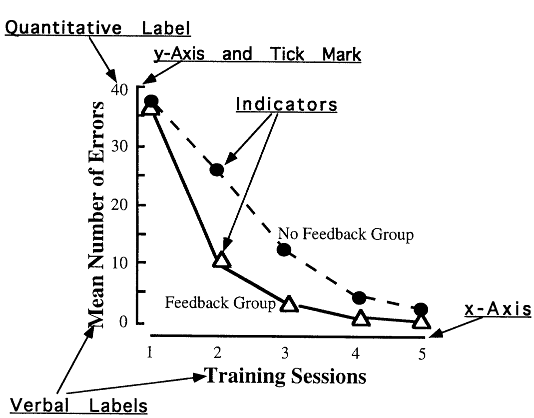


Figure 2. A graph showing examples of the terms used in these guidelines.

Tick marks. Tick marks are short lines that cross or meet an axis at regular intervals to signal a value or, sometimes, a level of a categorical independent variable (on the *x* axis). Tick marks may extend from the axis toward the labels, across the axis, or from the axis toward the indicators.

Guidelines

2.1. Graph designs should take into account readers' sensory capabilities and limitations. Graph designers have little influence over the conditions under which a reader may read a graph; for example, a degraded visual image may be caused by poor eyesight, reduced image size, a multigeneration photocopy, or a transparency rendering for an oral presentation (Wickens, 1992).

Figure 3 contrasts two graphs, one that violates the principles to be described in the following sections (Figure 3A) and one that follows those principles (Figure 3B).

2.1.1. Readers will need to detect all indicators, verbal labels, and quantitative labels.

- Indicators, verbal labels, and quantitative labels should be large.
- Indicators, verbal labels, and quantitative labels should be made salient in relation to the background by contrasting a light background with dark symbols and characters.
- If the lines or plotting symbols in a graph intersect with the axes, consider offsetting the axes to reduce perceptual clutter and impaired symbol detection (see Figures 3B, 4A, and 4B).
- Keep in mind that during layout of the article, graphs are often reduced to fit them into a single column. Try to make your graph reducible to this size. For example, avoid long verbal labels that extend horizontally beyond the graph.

2.1.2. Readers may need to discriminate among different indicators (e.g., multiple lines and associated plotting symbols in a line graph or bars in a bar graph).

- Make all indicators discriminable from one another by selecting symbols or textures with distinctly different features.
- Code plotting symbols and lines redundantly, as shown in Figure 3B.
- Use large geometric shapes as the plotting symbols, as shown in Figure 3B. Small shapes are difficult to discriminate, especially if the paper has been photocopied.
- When it is important to communicate information about the variability of data, scientific graphs often display error bars. Error bars typically indicate plus and minus one standard error of the mean by placing an "I" bar on each plotting symbol in a line graph or on the topmost horizontal line of a bar in a bar graph. When a line graph contains multiple lines, error bars may overlap so that the

A. Violates Guidelines **B. Follows Guidelines**

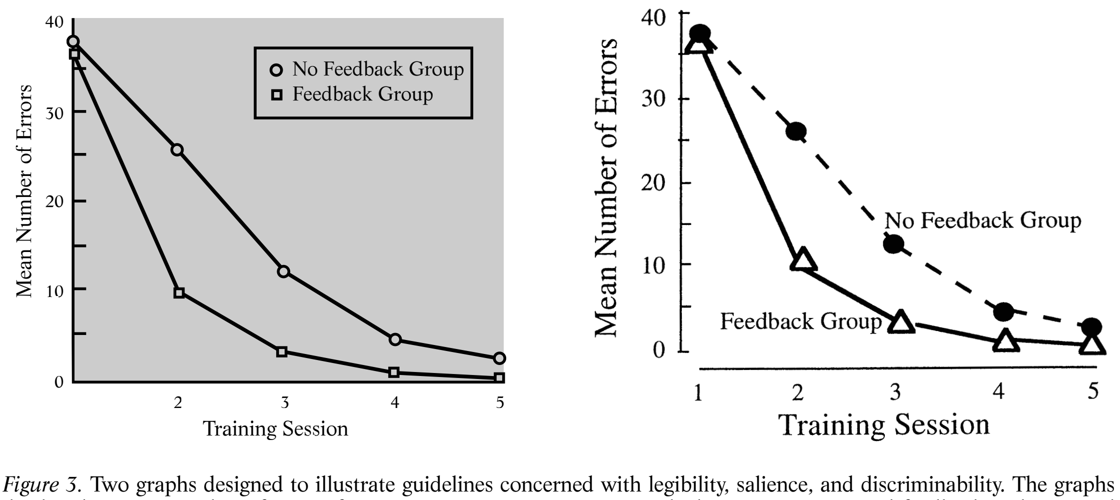


Figure 3. Two graphs designed to illustrate guidelines concerned with legibility, salience, and discriminability. The graphs display the mean number of errors from an imaginary experiment in which one group received feedback and a second group received no feedback during five training sessions. (A) A graph designed to violate the guidelines. (B) A graph designed to follow the guidelines.

reader can't discriminate the error bars for data at the same level of the independent variable on the *x* axis. In such cases either (a) display the data in a bar graph (because the bar indicators for data at the same level of the independent variable are not vertically aligned, so the error bars won't overlap) or (b) show only the top half of the error bars on the upper line and the bottom half of the error bars on the bottom line.

2.2. The graph design should take into account readers' perceptual tasks of comprehending the graph and determining its meaning.

2.2.1. Readers of graphs of the size published in journals tend to examine the global features of the graph and/or indicator before examining the local features.

- Make the main point of the graph available to the reader at the global level. In other words, avoid making the reader search for the main point in the details of the graph. Figure 4 provides two examples.

2.2.2. Readers will process the most salient features of the graph first.

- Make the main point of the graph the most salient feature. In other words, attract the reader's attention to the data most relevant to the message of the paper.
- In bar graphs, use dark, heavy lines as the pattern code of a bar if the reader should pay particular attention to those data.
- In line graphs, use dark, filled plotting symbols or dark, thick lines if the reader should pay particular attention to those data.
- In scatter plots that show a best-fitting line that summarizes the data, make the best-fitting line thick and dark relative to the data points so that the reader will pay particular attention to the summary.
- In line or bar graphs that use error bars to show variability, do not make the error bars thick and dark relative to the indicator. Longer error bars show the conditions with the greatest variability. Typically, readers want to attend to the conditions with the least variable, most reliable data points.

2.2.3. Readers will engage in serial search across indicators.

- Unnecessary visual elements tend to slow search, so eliminate clutter by graphing only essential information. Make less essential information less salient by "ghosting" or "lowlighting" it (i.e., by representing it in a shade of gray that is visible but discriminably lighter than that used for more salient information).
- Search will be particularly challenging for readers looking across multiple graphs with many levels of an independent variable. To design multiple graphs with many levels of an independent variable, an author might (a) place all graphs in one figure to facilitate search across graphs; (b) use spatial proximity for graphs that the reader might search in sequence (e.g., a series of response time

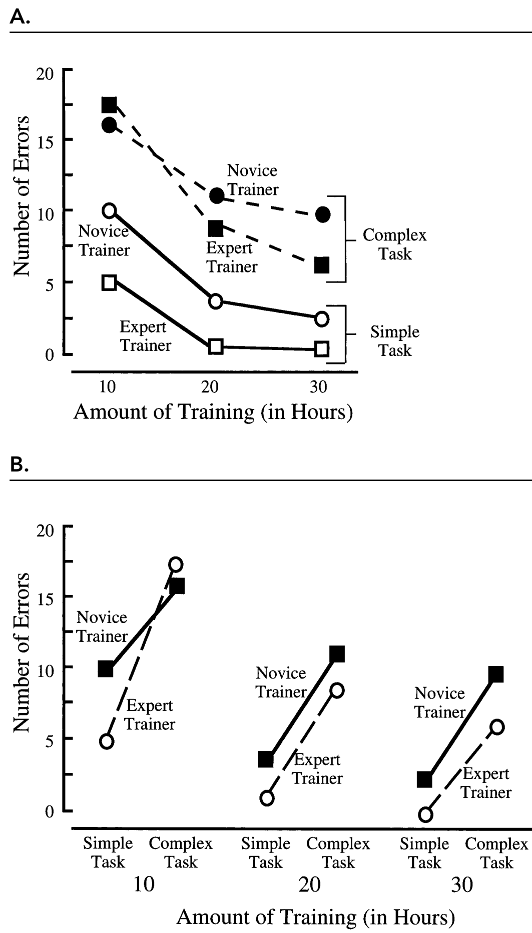


Figure 4. Two graphs of the same data designed to show the use of global and local features to communicate a message. (A) This graph represents task complexity and hours of training with globally available cues and expertise with locally available cues. (B) This graph represents task complexity and expertise with globally available cues and amount of training with locally available cues. (The figure also shows the use of similarity in coding indicators, as described in Guideline 2.2.10: Panel A codes novice trainers using circles and expert trainers using squares in both task conditions; the graph codes complex tasks using filled indicators and dashed lines, and simple tasks using open circles and complete lines.)

graphs for a sequence of conditions might be aligned horizontally); (c) maintain visual consistency across graphs (e.g., use the same size axes, the same types of indicators, and the same coding for indicators for the same variables); (d) maintain semantic consistency across graphs (e.g., use the same scale on the *y* axis); (e) eliminate redundant labels (e.g., in a series of horizontally aligned graphs, the labels for the *y* axes should be placed only by the leftmost graph, and the verbal label naming the *x* axis should be centered under the series); and (f) avoid using a legend to label indicators (a legend requires multiple scans between the indicators and the legend, thereby disrupting visual search). Figure 5 illustrates these approaches.

2.2.4. Readers need to be able to determine the relations among elements of the graph quickly.

- Place indicators that will be compared close together.
- If the reader will perform arithmetic operations on indicators, place the indicators near the numerical labels either by placing labeled axes on both sides of the graph (Figure 6A) or by placing the numerical values next to the indicators (Figure 6B).
- Place verbal labels close to the axis they label.
- Place labels close to the indicators to which they refer. For example, if a graph contains two independent variables – one independent variable plotted on the *x* axis and the second independent variable plotted as separate lines for each level of that variable – place the labels that specify the levels of the second independent variable close to the lines (see Figures 3, 4, and 5). Sometimes, however, indicators are too close to be labeled unambiguously. Use a legend only in such cases. The legend should show symbols for all indicators clearly and, for each indicator, should show the entire symbol (e.g., both the redundantly coded plotting symbol and line for each line graph indicator) with the label in close proximity. Separate the legend visually from the indicators in the graph by placing it in a box. Put the legend close to the indicators to reduce scanning distance but not so close as to interfere with reading the indicators. The order of the symbols in the legend should match the order of the indicators in the graph.

2.2.5. Minimize the number of perceptual operations required by the reader.

- If the reader will compare two indicators, orient them in the same direction. Different orientations of the indicators will increase graph reading time.
- If the reader will compare two indicators, use a common *x* axis. For example, if the reader needs to compare two indicators, do not display them in a graph that involves stacking indicators on top of each other (such as a stacked bar graph). Forcing the reader to compare two indicators that have *x* axes with different vertical positions will increase graph reading time and reduce accuracy.
- If the reader will judge a proportion (i.e., compare a part to a whole object), display the whole object, especially if the object consists of many parts. For example, a pie chart displays parts and whole simultaneously. To draw the readers' attention to one

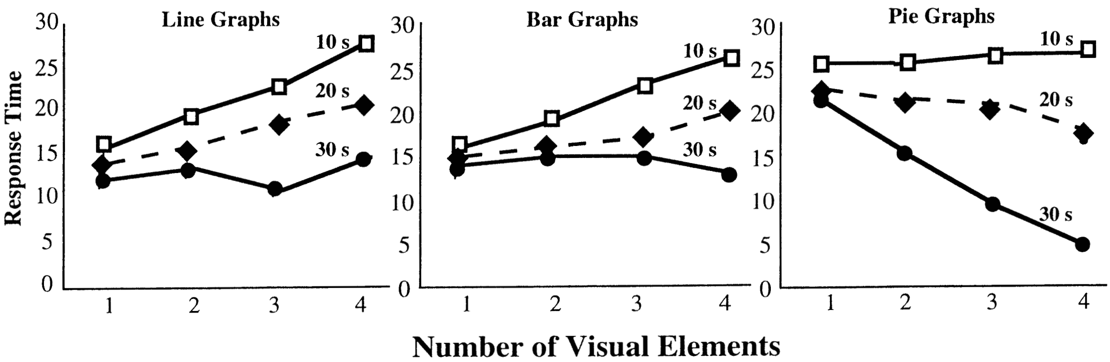


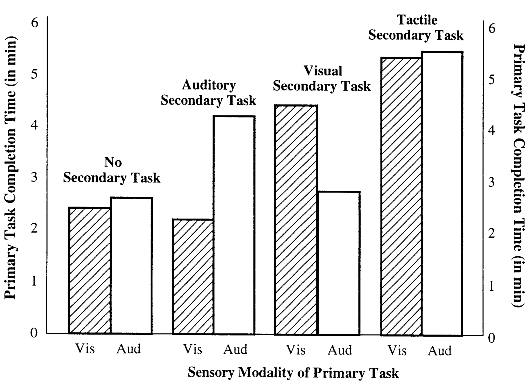
Figure 5. Three graphs that represent three levels of an independent variable (type of graph). The figure design is based on Guideline 2.2.3. The graphs display the mean response times from an imaginary experiment in which three independent variables were manipulated: the type of graph, the number of visual elements in a graph, and the duration of preview time (in seconds) prior to receiving a task.

part from the whole, one approach is to separate that part from the whole (e.g., in an exploded pie chart). However, overuse of this technique by separating more than one part will lead to little increase in salience and will require the reader to perceptually reorganize the parts.

2.2.6. Although axes and tick marks do not communicate meaning directly, they help readers to determine the meaning of other elements of the graph. Specifically, axes help the reader to parse the graph; tick marks can help the reader to estimate the value of an indicator.

- Make the axes salient (e.g., by use of wide lines and high contrast between dark axes and the light background). However, the axes should not be more salient than the labels or indicators.

A.



B.

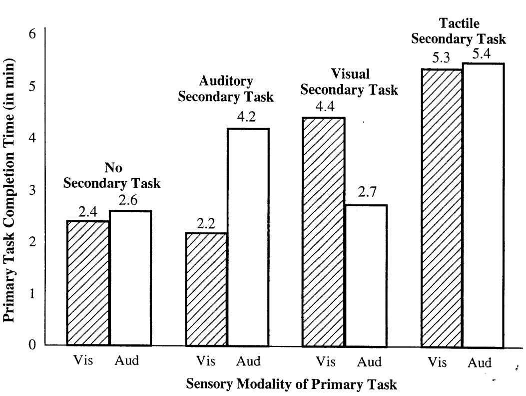


Figure 6. Two ways of helping readers determine the values of indicators on both sides of a graph as described in Guideline 2.2.4. (A) A graph with a double *y* axis. (B) A graph with the indicators labeled.

- Tick marks will be of no value if they provide information also provided by the quantitative labels for the scale values. Placing tick marks only next to each label is redundant and can increase the time to read a graph. Accordingly, either use tick marks between infrequent scale values on the *y* or *x* axis or use frequent scale values and no tick marks. Figure 7 provides examples concerning tick marks.

2.2.7. Stevens's law describes the general relation between physical amount and perceived amount as a power function: *perceived amount = a(physical amount)*^{b} (e.g., Stevens, 1975). When the exponent $b = 1.0$, the increase in perceived amount corresponds to the increase in the physical amount; when $b < 1.0$, the perceived amount increases more slowly than the physical amount; and when $b > 1.0$, the perceived amount increases more rapidly than the physical amount. Because the physical dimensions that display simple linear extent in either vertical height or horizontal length produce Stevens's law exponents of 1.0, a reader's perception of extent with bar graphs and line graphs will accurately correspond to the physical distances shown in the graph.

In contrast, the physical dimensions of the area of a rectangle or a circle and the volume of a cube typically produce exponents in Stevens's law of less than 1.0, resulting in misestimation of the size of indicators. The physical dimension of the lightness of shades of gray typically produces an exponent in Stevens's law of greater than 1.0.

- When possible, use a physical dimension with a Stevens's law exponent close to 1.0, such as linear extent, to indicate values in a graph. Psychophysical studies on segments of pie charts have been less consistent than those on linear extent. Some studies have shown a Stevens's law exponent of 1.0 relating the perceived proportion indicated by a pie segment and the actual proportion of that segment, but other studies have shown a Stevens's law exponent less than 1.0. Accordingly, use of a pie chart to display proportions may lead to misperception by the reader under some (as yet unknown) conditions. One solution would be to label the proportional value of each pie segment.
- Avoid using physical dimensions that have Stevens's law exponent values substantially below or above 1.0 (e.g., area, volume, and

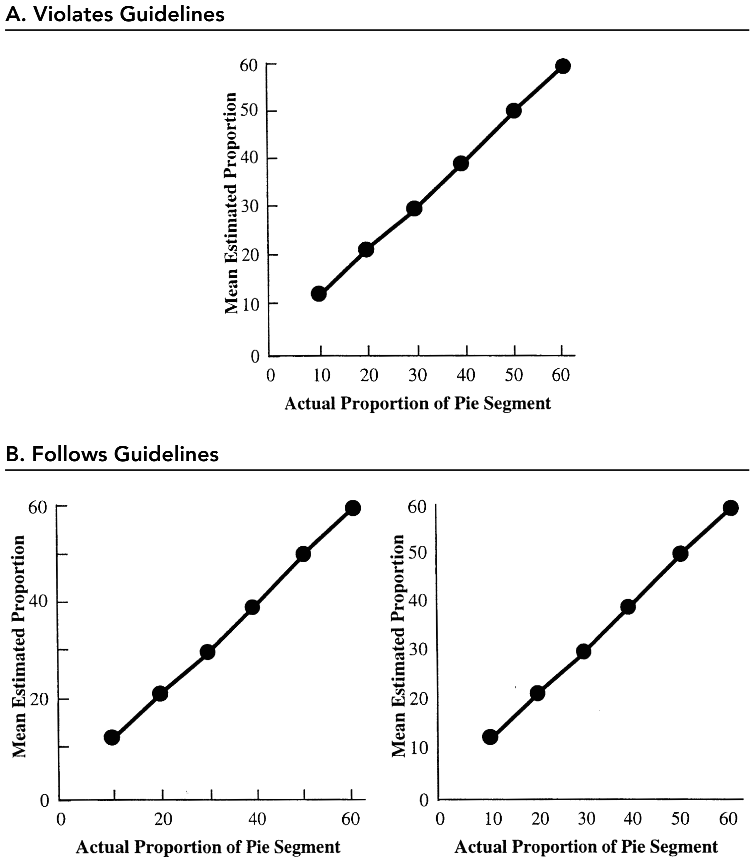


Figure 7. Examples related to Guideline 2.2.6 concerning tick marks. Panel A violates the guideline by having redundant tick marks and numerical labels. The examples in Panel B are consistent with the guideline by having tick marks between infrequent scale values or by using frequent scale values with no tick marks.

shades of gray), because these may lead to misjudgments by the reader.

2.2.8. Exercise caution in the use of "3D" (perspective) graphs. In general, the perception of the size of an object depends on its perceived distance from the viewer. If Object A and Object B have the same physical size (e.g., height) but Object B appears to be at a more distant location within a perspective image, then Object B will typically be perceived as greater in size. (This perceptual bias plays a key role in several well-known illusions of size, including the Mueller-Lyer illusion and the Ponzo illusion.) However, the amount of this increase in perceived size of Object B will depend on factors such as the number and fidelity of depth cues incorporated into the display. Specifically, more depth cues with high fidelity will reduce the perceptual bias. As a consequence, comparisons of height or length at different depths may be variable.

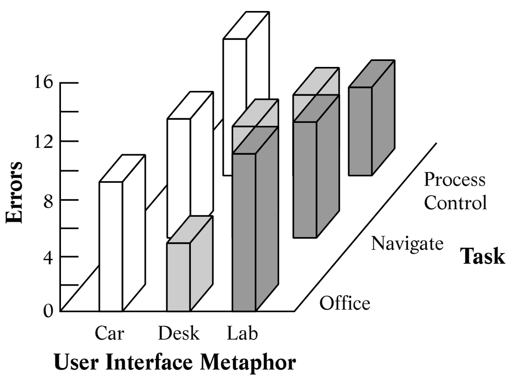
- Avoid using depth (i.e., distance in the *z* dimension) in a 3D graph to show the values of an independent variable; this can lead to misperception of the values of that variable and of the dependent variable.
- A depth axis (i.e., *z* dimension) might be used only if it portrays two levels and if readers will not need to use the graph to determine the amount of difference in the *z* dimension.
- Rather than using a 3D graph to show the relation between two independent variables, consider using multiple lines in a line graph, one line for each level of the second predictor variable, or multiple bars with pattern coding (see Figure 8 for an example). Rather than using a 3D graph to show the relations

among three independent or predictor variables, consider using multiple graphs, one for each level of the third predictor variable (Figures 4B and 5 show examples of this design).

2.2.9. Although the human visual system is typically very accurate and flexible, many well-known illusions can affect graph perception. In general, the perceived length of a line can be affected by lines that surround it, and the perceived shape or angular size of an object can be affected by lines in the background or in its surround.

- Do not ask readers to compare or estimate the lengths of a vertical indicator and a horizontal indicator that it intersects. The length of the horizontal line will be underestimated relative to that of the vertical line (the hat illusion).
- Readers will tend to underestimate the values of indicators at the right of a line graph if they have to estimate it using only a *y* axis on the left. In addition, in line graphs containing a diagonal segment followed by a horizontal or a blank segment, then followed by another diagonal segment, the upper segment will appear to be higher than it actually is (the Poggendorf illusion). These effects can be overcome by the use of axes at the left and right of the graph.
- These illusions, as well as the perceptual biases inherent in Stevens's law and size constancy as described in Guidelines 2.2.7 and 2.2.8, will have a pronounced effect on performance if readers need to determine the precise quantitative amount of the indicators rather than the qualitative direction of the data.

A. Violates Guidelines



B. Follows Guidelines

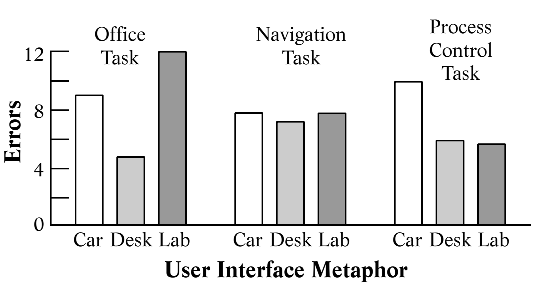


Figure 8. (A) A 3D graph that violates the guidelines described in Guideline 2.2.8. Readers may have trouble estimating the values of the bars and comparing the bars across levels of the Task variable. (B) A 2D bar graph that displays that same data as the graph in Panel A. However, all of the indicators have a common horizontal baseline, making comparisons across the bars easy. In addition, the absence of depth cues will not lead readers to misapply size constancy.

2.2.10. People tend to perceive similar-looking objects as part of a coordinated unit.

- Use similar patterns or shapes to indicate data from similar conditions in a study, as shown in Figure 4.
- Do not use similar patterns or shapes for indicators for conditions intended to be distinguished.

2.2.11. Readers will have certain expectations (or schemas) about the structure of a graph, based on their prior experience.

- The numerical scale on the *y* axis should go from the lowest number at the bottom of the axis to the highest number at the top.
- The numerical scale on the *x* axis should go from the lowest number at the left of the axis to the highest number at the right.
- The scaling of values (i.e., minimum and maximum values and spacing between them) on two adjacent graphs depicting the same variables should be the same.
- Whenever exceptions to the above conventions must be made, they should be clearly and explicitly stated when the figure is first introduced in the text and in the figure caption.

2.2.12. Reading the axis and indicator labels in a graph involves letter identification, word recognition, and comprehension of a phrase or sentence.

- Letters should be large and discriminable. Avoid the use of thick bold lines or unusual fonts that might interfere with readers' ability to extract the features from the letters.
- When possible, use commonplace words in labels for easier word recognition.
- Use lowercase letters (or an uppercase first letter with the rest lowercase letters) so that readers can make use of shape cues to recognize words.
- Use simple phrases consistent with the text for labels (see also Guideline 2.3.1).

2.3. The graph design should take into account readers' cognitive tasks. Cognitive tasks include integrating the meaning of the graph with the text and storing the meaning of the graph in long-term memory so that it can be retrieved accurately when needed.

2.3.1. Information in the graph should be congruent with the information in the text.

- Label the *y* axis with the name of the dependent variable used in the text.
- Label the *x* axis with the name of the relevant independent variable used in the text.
- Labels for indicators should use the same names as those in the text for the levels of the relevant independent variable.
- The relations shown between the independent and dependent variables should both relate to the hypotheses described in the paper's introduction and reflect the analyses described in its results section.

2.3.2. The graphical representation of the data should help the reader to interpret the results that are described in the text.

- Refer to the graph in the text early in the section in which its data are being described. Do not cite it only after describing the data.
- To the extent possible, coordinate the text and graph so that the same printed page will contain the graph(s) and text that describe the same data. For HFES proceedings papers, the author has this responsibility. For journals this is the typesetter's responsibility, but the author can do several things to increase the likelihood that the typesetter will put the graph and text together: (a) Put instructions for figure placement immediately before the paragraph where results are described, especially if the paragraph is long. (b) Space the figures among the text such that instructions to place multiple figures are not presented in close succession. This may require that you use figures sparingly and present more of your results in the body of the text.

2.3.3. An article that presents a series of related experiments using the same basic experimental design and analytical methods should maintain consistent graph structures and symbol use. This consistency will allow the reader to perceive the related meaning across experiments and directly compare the data across experiments.

- Use the same type of graph across similar experiments. In other words, if a bar graph displays the data for Experiment 1, then a bar graph should display comparable data for Experiment 2.
- Use the same layout of the data in the graph across similar experiments. In other words, if a graph for Experiment 1 has "Type of Interface" on the *x* axis, then place "Type of Interface" on the *x* axis of the comparable graph for Experiment 2.
- Use the same symbols and patterns for coding the same independent variables (and levels thereof) across the graphs for different experiments.
- Use the same numerical scales on the axes across graphs from different experiments that display the same dependent variable.
- Make the critical feature that distinguishes each graph from its neighboring graphs visually prominent.
- If a study measures different dependent variables (e.g., response time, accuracy, and usability) and the reader is likely to compare the results for the different dependent variables (either to observe the same pattern of results or to observe differences), make the graphs visually similar to facilitate comparisons. Specifically, use the same type of graph (line, bar, etc.), same layout of data, same symbols and patterns for coding the independent variables, and same length and labeling for the *x* axes. In addition, keep the length of the *y* axis similar across the different graphs. (Because of differences in the values of the dependent variables, the graphs will most likely use different *y* axis scales.) Figure 9 provides an example.

2.3.4. If different graphs are intended to communicate unrelated information within an experiment or between experiments (e.g., graphs addressing different hypotheses), visual differences can be used to discourage readers

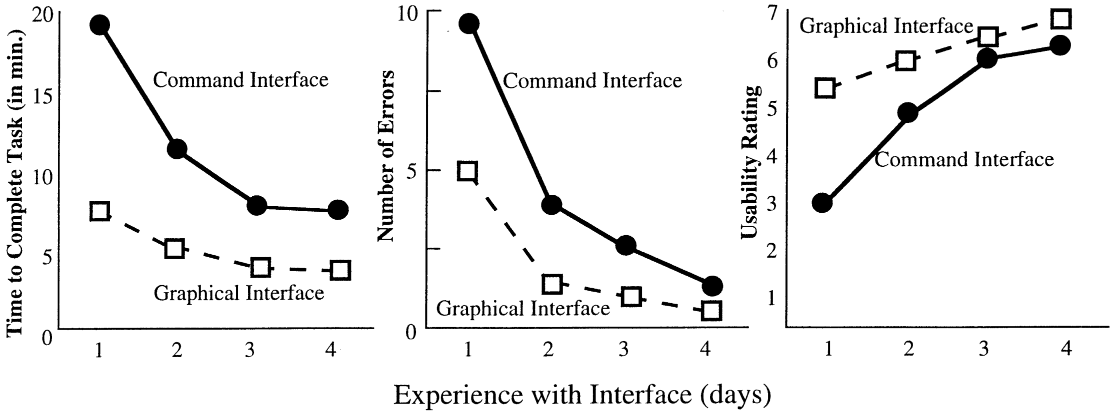


Figure 9. Three graphs in which different dependent variables are affected by the independent variables in similar ways. The graphs show the results of an imaginary experiment that manipulated the type of interface and the participants' experience with the interfaces and measured the time to complete a task, the number of errors in a session, and a rating of usability (with 1 = low and 7 = high usability). Across the three measures, the graphical user interface produces a large performance advantage initially, but the difference decreases as participants gain more experience with the interfaces.

from making comparisons that are not meaningful.

- To create visual differences that match the differences in meaning between graphs, use different types of graphs across the different conditions or experiments.
- Use different coding symbols or patterns for the independent variables across the different graphs.

2.3.5. Readers should be able to remember the data in relation to the hypothesis, theoretical point, or design implications of article.

- Design the graphs so that the most important variables for the hypothesis and/or applications are available to global perception and are most salient.
- Refer to the relevant graph or graphs in the textual discussions relevant to the hypotheses or applications.

2.3.6. Readers' memories for graphical information may be subject to various memory biases. For instance, readers tend to remember the slope of a line in a graph as closer to 45° than it actually is. Likewise, readers tend to remember a curved line in a graph as more symmetrical than it actually is.

- Textual descriptions of the critical characteristics of the data should be clear, accurate, and consistent with the visual representation in the graph.

REFERENCES

Gillan, D. J., & Lewis, R. (1994). A componential model of human interaction with graphs: I. Linear regression modeling. *Human Factors, 36,* 419–440.

Hink, J. K., Wogalter, M. S., & Eustace, J. K. (1996). Display of quantitative information: Are grables better than plain graphs or tables? In *Proceedings of the Human Factors and Ergonomics Society 40th Annual Meeting* (pp. 1155–1159). Santa Monica, CA: Human Factors and Ergonomics Society.

Larkin, J., & Simon, H. (1987). Why a diagram is (sometimes) worth 10,000 words. *Cognitive Science, 4,* 317–345.

Loftus, G. R. (1993). Visual data representation and hypothesis testing in the microcomputer age. *Behavior Research Methods, Instruments, & Computers, 25,* 250–256.

Lohse, G. L. (1993). A cognitive model for understanding graphical perception. *Human-Computer Interaction, 8,* 313–334.

Pinker, S. (1990). A theory of graph comprehension. In R. Freedle (Ed.), *Artificial intelligence and the future of testing* (pp. 73–126). Hillsdale, NJ: Erlbaum.

Simkin, D., & Hastie, R. (1987). An information processing analysis of graph perception. *Journal of the American Statistical Association, 82,* 454–465.

Stevens, S. S. (1975). *Psychophysics: Introduction to its perceptual, neural, and social prospects.* New York: Wiley.

Wickens, C. D. (1992). The human factors of graphs at HFS annual meetings. *Human Factors and Ergonomics Society Bulletin, 35*(7), 1–3.

BIBLIOGRAPHY

Readers interested in reading more about the design of graphs and on human interaction with graphs are encouraged to explore the following selected papers and books (many of which served as general source material for these guidelines).

Theories and Models of Graph Perception and Comprehension

Carswell, C. M. (1992). Reading graphs: Interactions of processing requirements and stimulus structure. In B. Burns (Ed.), *Percepts, concepts, and categories* (pp. 605–645). Amsterdam: Elsevier.

Cleveland, W. S. (1985). *The elements of graphing data.* Monterey, CA: Wadsworth.

Cleveland, W. S., & McGill, R. (1984). Graphical perception: Theory, experimentation, and application to the development of graphic methods. *Journal of the American Statistical Association, 70,* 531–555.

Gurthrie, J. T., Weber, S., & Keimmerly, N. (1993). Searching documents: Cognitive processes and deficits in understanding graphs, tables, and illustrations. *Contemporary Educational Psychology, 18,* 186–221.

Hollands, J. G., & Spence, I. (1992). Judgments of change and proportion in graphical perception. *Human Factors, 34,* 313–334.

Kosslyn, S. M. (1989). Understanding charts and graphs. *Applied Cognitive Psychology, 3,* 185–225.

Tan, J. K. H., & Benbasat, I. (1990). Processing of graphical information: A decomposition taxonomy to match data extraction tasks and graphical representations. *Information Systems Research, 1,* 416–439.

Wickens, C. D., & Carswell, C. M. (1995). The proximity compatibility principle: Its psychological foundation and relevance to display design. *Human Factors, 37,* 473–494.

Winn, W. (1994). Contributions of perceptual and cognitive processes to the comprehension of graphics. In W. Schnotz and R. W. Kulhavy (Eds.), *Comprehension of graphics* (pp. 3–27). Amsterdam: Elsevier.

Empirical Papers on Graph Reading

Barfield, W., & Robless, R. (1989). The effect of two- and three-dimensional graphics on the problem-solving performance of experienced and novice decision makers. *Behaviour and Information Technology, 8,* 369–385.

Bennett, K. B., Toms, M. L., & Woods, D. D. (1993). Emergent features and graphical elements: Designing more effective configural displays. *Human Factors, 35,* 71–97.

Carswell, C. M. (1992). Choosing specifiers: An evaluation of the basic tasks model of graphical perception. *Human Factors, 34,* 535–554.

Carswell, C. M., Frankenberger, S., & Bernhard, D. (1991). Graphing in depth: Perspectives on the use of three-dimensional graphs to represent lower-dimensional data. *Behavior and Information Technology, 10,* 459–474.

Carswell, C. M., & Ramzy, C. (1997). Graphing small data sets: Should we bother? *Behaviour and Information Technology, 16,* 61–71.

Carswell, C. M., & Wickens, C. D. (1987). Information integration and the object display: An interaction of task demands and display superiority. *Ergonomics, 30,* 511–527.

Carswell, C. M., & Wickens, C. D. (1990). The perceptual interaction of graphical attributes: Configurality, stimulus homogeneity, and object integration. *Perception and Psychophysics, 47,* 157–168.

Carter, L. F. (1947). An experiment on the design of tables and graphs used for presenting numerical data. *Journal of Applied Psychology, 31,* 640–650.

Casali, J. G., & Gaylin, K. B. (1989). Selected graph design variables in four interpretation tasks: A microcomputer-based pilot study. *Behaviour and Information Technology, 7,* 31–49.

Casner, S. (1991). A task-analytic approach to the automated design of graphic presentations. *ACM Transactions of Graphics, 10,* 111–151.

Clevelend, W. S., & McGill, R. (1985). Graphical perception and graphical methods for analyzing scientific data. *Science, 229,* 828–833.

Coury, B. G., & Boulette, M. D. (1993). Time stress and the processing of visual displays. *Human Factors, 34,* 707–726.

Coury, B. G., & Purcell, J. (1988). The bargraph as a configural and separable display. In *Proceedings of the Human Factors Society 32nd Annual Meeting* (pp. 1361–1365). Santa Monica, CA: Human Factors and Ergonomics Society.

Culbertson, H. M., & Powers, R. D. (1959). A study of graph comprehension difficulties. *A/V Communication Review, 7,* 97–110.

DeSanctis, G. (1984). Computer graphics as decision aids: Directions for research. *Decision Sciences, 15,* 463–487.

Gillan, D. J., & Neary, M. (1992). A componential model of human interaction with graphs: II. The effect of distance between graphical elements. In *Proceedings of the Human Factors Society 36th Annual Meeting* (pp. 365–368). Santa Monica, CA: Human Factors and Ergonomics Society.

Gillan, D. J., & Richman, E. (1994). Minimalism and the syntax of graphs. *Human Factors, 36,* 619–644.

Goettl, B. P., Kramer, A. F., & Wickens, C. D. (1991). Integrated displays and the perception of graphical data. *Ergonomics, 34,* 1047–1063.

Hollands, J. G. (1992). Alignment, scaling, and size effects in discrimination of graphical elements. In *Proceedings of the Human Factors Society 36th Annual Meeting* (pp. 1393–1397). Santa Monica, CA: Human Factors and Ergonomics Society.

Hurts, C. M. M. (1996). The effectiveness of configurality in statistical graphs: A task-oriented approach. In H. Zwaga, T. Boersma, & H. C. M. Hoonhout (Eds.), *Public graphics* (pp. 1–8). London: Taylor & Francis.

Jarvenpaa, S. L. (1989). The effect of task demands and graphical format on information processing strategies. *Management Science, 35,* 285–303.

Lauer, T. W., & Post, G. V. (1989). Density in scatterplots and the estimation of correlation. *Behaviour and Information Technology, 8,* 235–244.

Legge, G. E., Gu, Y., & Luebker, A. (1991). Efficiency of graphical perception. In S. R. Ellis (Ed.), *Pictorial communication in virtual and real environments* (pp. 111–130). London: Taylor & Francis.

MacGregor, D., & Slovic, P. (1986). Graphic representation of judgmental information. *Human-Computer Interaction, 2,* 179–200.

Maichle, U. (1994). Cognitive processes in understanding line graphs. In W. Schnotz & R. W. Kulhavy (Eds.), *Comprehension of graphics* (pp. 207–225). Amsterdam: Elsevier.

Meyer, J., & Shinar, D. (1992). Estimating correlations from scatterplots. *Human Factors, 34,* 335–349.

Milroy, R., & Poulton, E. C. (1978). Labelling graphs for increased reading speed. *Ergonomics, 21,* 55–61.

Nowicki, J. R., & Coury, B. G. (1993). Individual differences in processing strategy for a bargraph display. In *Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting* (pp. 1315–1319). Santa Monica, CA: Human Factors and Ergonomics Society.

Peterson, L., & Schramm, W. (1954). How accurately are different kinds of graphs read? *A/V Communication Review, 2,* 178–189.

Poulton, E. C. (1985). Geometric illusions in reading graphs. *Perception and Psychophysics, 37,* 543–548.

Powers, M., Lashley, C., Sanchez, P., & Shneiderman, B. (1984). An experimental comparison between tabular and graphic data presentation. *International Journal of Man-Machine Studies, 20,* 545–566.

Preece, J. (1983). Graphs are not straightforward. In T. R. G. Green, S. J. Payne, & G. C. van der Veer (Eds.), *The psychology of computer use* (pp. 41–56). New York: Academic.

Sanderson, P. M., Flach, J. M., Buttigieg, M. A., & Casey, E. J. (1989). Object displays do not always support better integrated task performance. *Human Factors, 31,* 183–198.

Sanderson, P. M., Haskell, I., & Flach, J. (1992). The complex role of perceptual organization in visual display design theory. *Ergonomics, 35,* 1199–1219.

Schutz, H. (1961a). An evaluation of formats for graphic trend displays – Experiment II. *Human Factors, 3,* 99–107.

Schutz, H. (1961b). An evaluation of methods for presentation of graphic multiple trends – Experiment III. *Human Factors, 3,* 108–119.

Shah, P., & Carpenter, P. A. (1995). Conceptual limitations in comprehending line graphs. *Journal of Experimental Psychology: General, 124,* 43–61.

Sparrow, J. A. (1989). Graphical displays in information systems: Some data properties influencing the effectiveness of alternative forms. *Behaviour and Information Technology, 8,* 43–56.

Spence, I. (1990). Visual psychophysics of simple graphical elements. *Journal of Experimental Psychology: Human Perception and Performance, 16,* 683–692.

Spence, I., & Lewandowsky, S. (1990). Graphical perception. In J. Fox & J. S. Long (Eds.), *Modern methods of data analysis* (pp. 13–57). Newbury Park, CA: Sage.

Spence, I., & Lewandowsky, S. (1991). Displaying proportions and percentages. *Applied Cognitive Psychology, 5,* 61–77.

Tan, J. K. H., & Benbasat, I. (1993). The effectiveness of graphical presentation for information extraction: A cumulative experimental approach. *Decision Sciences, 24,* 167–191.

Tversky, B. (1991). Distortions in memory for visual displays. In S. R. Ellis (Ed.), *Pictorial communication in virtual and real environments* (pp. 61–75). London: Taylor & Francis.

Tversky, B., & Schiano, D.J. (1989). Perceptual and cognitive factors in distortions in memory for graphs and maps. *Journal of Experimental Psychology: General, 118,* 387–398.

Washburne, J. (1927). An experimental study of various graphic, tabular and textual methods of presenting quantitative material. *Journal of Educational Psychology, 18,* 361–376, 465–476.

Wickens, C. D., LaClair, M., Sarno, K. (1995). Graph-task dependencies in three-dimensional data: Influence on three-dimensionality and color. In *Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting* (pp. 1420–1424). Santa Monica, CA: Human Factors and Ergonomics Society.

Guidelines for Graph Design (based on research in perception and cognition)

Jarvenpaa, S. L., & Dickson, G. W. (1988). Graphics and managerial decision making: Research-based guidelines. *Communications of the ACM, 31,* 764–774.

Kosslyn, S. M. (1994). *Elements of graph design.* New York: Freeman.

Guidelines for Graph Design (based on practice)

Andrews, H. P., Snee, R. D., & Sarner, M. H. (1980). Graphical display of means. *American Statistician, 34,* 195–209.

Bertin, J. (1983). *Semiology of graphics* (W. J. Berg, Trans.). Madison: University of Wisconsin Press. (Original work published 1967)

Schmid, C. F. (1954). *Handbook of graphic presentation.* New York: Ronald.

Tufte, E. R. (1983). *The visual display of quantitative information.* Cheshire, CT: Graphics Press.

Tufte, E. R. (1990). *Envisioning information.* Cheshire, CT: Graphics Press.

Tufte, E. R. (1997). *Visual explanations.* Cheshire, CT: Graphics Press.

Wainer, H. (1980). Making newspaper graphs fit to print. In P. A. Kolers, M. E. Wrolstad, & H. Bouma (Eds.), *Processing of visible language* (Vol. 2, pp. 125–142). New York: Plenum.

Wainer, H. (1984). How to display data badly. *American Statistician, 38,* 137–147.

Wainer, H., & Thissen, D. (1981). Graphical data analysis. *Annual Review of Psychology, 32,* 191–241.

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