An experimental investigation of consistency of explanation and graph representation

Journal

Proceedings of the Annual Meeting of the Cognitive Science Society, 34(34)

ISSN

1069-7977

Authors

Kanzaki, Nana
Miwa, Kazuhisa

Publication Date

2012

Peer reviewed

An experimental investigation of consistency of explanation and graph representation

Nana Kanzaki (kanzaki@cog.human.nagoya-u.ac.jp)
Graduate School of Information Science, Nagoya University, Japan

Kazuhisa Miwa (miwa@is.nagoya-u.ac.jp)
Graduate School of Information Science, Nagoya University, Japan

Abstract

Many previous studies of graph comprehension have confirmed that information gleaned from a graph is greatly influenced by its representation. When explaining data with a graph, writers/researchers must generate graphs whose representation is consistent with the explanation contents. In the current study, we defined those who engage in academic activities using graphs on a daily basis as expert graph users and investigated whether they and undergraduates (non-experts) can adaptively generate a consistent graph with explanations from the viewpoint of the consistency of the contents and graph representation. Experiment 1 indicated that expert graph users adaptively generate a graph whose structure is consistent with the explanation contents. On the other hand, Experiment 2 suggests that undergraduates cannot do so. But in Experiment 3 undergraduates were supported by selecting graphs from provided candidates, but there was a limited concordance between the type of explanation and graph representation.

Keywords: Diagrammatic representation; Graph; Explanation.

Introduction

Many previous studies confirmed that using diagrams is effective for understanding information. In a pioneering psychological paper, Larkin & Simon (1987) theoretically demonstrated the efficacy of using diagrams while solving a problem and suggested that diagrammatic representation simplifies access to relative information more than sentential representation does, and transforms the cognitive processes into more efficient ones.

Norman (1991) pointed out that task difficulties depend on such visual representation as figures and tables and promote problem solving performance. He also suggested that a cognitively consistent correspondence between internal representation and external world is crucial.

In this study, we experimentally investigated the consistency of the contents of the explanations and the representations of graphs for the explanation. Kosslyn (2006), who marshaled psychological findings about graph design, argued that graph representation must be examined, especially based on the human cognitive system for effectively conveying information. And also, Hegarty(2011) mentioned the importance of cognitive science to design visual-spatial displays.

Graphs, which are pictures that convey logical relationships among numbers for a specific purpose, include line graphs, bar graphs, step graphs, and pie charts. Specific examples of graph usage are demonstrated in the *Publication Manual of the American Psychological Association* (2001).

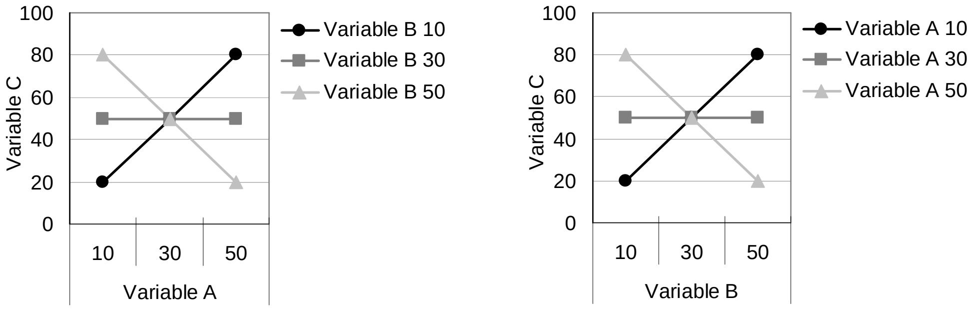
Experimental studies of graph comprehension confirmed that the information from a graph is greatly influenced by its representation. Graphs can be represented in various forms. Different representations generated from an identical data set elicit different interpretations of the graphs. For example, in studies of inferences from bar and line graphs, viewers are more likely to describe x-y trends when viewing line graphs than bar graphs (Zacks & Tversky, 1999; Shah, Mayer, & Hegarty, 1999). Peebles and Cheng (2003) suggested that the comprehension time of certain information differs depending on the graph structure.

Although many studies on graph comprehension have been conducted, graph generation is also an important issue. In the current study, we deal with the issue of arrangements of variables on graphs when generating them. Shah and Carpenter (1995) confirmed that x-y trends were comprehended easily, although z-y trends were comprehended with difficulty using three-variable line graphs (e.g., Carpenter & Shah, 1998; Kanzaki & Miwa, 2011). The reason may be that visual chunks are constructed for every line in a line graph, and the graph is interpreted based on each chunk.

Consider the case indicated in Table 1 where a line graph is depicted from the data that consist of two independent Variables, A and B, and one dependent variable, Variable C. Two types of graphs are considered. One is a graph in which Variable A is put on the x-axis and Variable B on the z-label (Figure 1(a)), and on the other Variable B is put on the x-axis and Variable A on the z-label (Figure 1(b)). According to Larkin & Simon (1998), these two graphs are informationally equivalent but computationally different; they are equivalent because they are constructed from identical data sets, but they are different since different chunks are constructed in each of the graphs and the information may be read in different ways. When explaining

Table 1: Variable C vs. Variables A and B.

		Variable B		
		10	**30**	**50**
Variable A	**10**	20	50	80
	30	50	50	50
	50	80	50	20



(a) (b)

Figure 1: Graphs made from Table 1.

the data of Table 1, one of two alternative graphs must be generated whose structure is consistent with the explanation.

Consider a more specific situation in which we must adjust independent Variable B with an uncontrollable change of Variable A to intentionally control the quantity of dependent Variable C. When explaining how to manage Variable B in this situation, the explanation is classified into two types from the viewpoint of the representation of Variable A. In one explanation, Variable A is described discretely. In this classification, the explanation is generated for each level of Variable A, such as “when Variable A is at …, you should set Variable B to ...” In the other explanation, Variable A is described continuously. In this classification, the explanation reflects whether its value is larger than a specific value, such as “when Variable A is larger than ..., set Variable B to …”, or from the viewpoint of a continuously changing variable A, such as “according to the increase of Variable A.”

When two independent variables are placed on a line graph, one variable is commonly put on the x-axis and the other on the z-label. In such a situation, it is contemplated that the variable on the x-axis is regarded as a continuous variable, and the one on the z-label is regarded as a discrete variable because the x-axis is represented as a continuous factor and the z-label as a discrete factor.

Kosslyn (2006) noted that “the continuous rise and fall of a line is psychologically compatible with the continuous nature of an interval scale. . . Time, temperature, and amount of money are measured using an interval scale.” Additionally, Kanzaki & Miwa (2011) suggested that an explanation based on each line increases the comprehension of a line graph because a chunk of each line is generated (e.g., Carpenter & Shah, 1998; Shah & Carpenter, 1995). These studies indicate that a variable on the z-label in a line graph is regarded as a discrete variable.

The above investigations propose a hypothesis, where in a normative graph, an independent variable is put on the x-axis when the variable is regarded as a continuous variable in the explanation; in contrast, an independent variable is put on the z-label when it is regarded as a discrete variable.

If this hypothesis is correct, we predict the following when we must explain how to adjust independent Variable B, with the uncontrollable change of independent Variable A to control the quantity of dependent Variable C:

1. Participants who treated Variable A as a continuous variable in their explanation put it on the x-axis (Figure 1(a)).

2. Participants who treated Variable A as a discrete variable in their explanation put it on the z-label (Figure 1(b).

In the current study, expert graph users participated in Experiment 1, whom we defined as those who daily engage in academic activities using graphs. Our first objective is to confirm whether such experts adaptively generate graphs that are consistent. We expected them to do so because they have much experience giving presentations with graphs and reading them in research papers.

Our second aim is to perform a similar experiment with undergraduates as novices. Undergraduates who have not received systematic training in statistics participated in our second and third experiments. We propose a hypothesis that they may have trouble generating consistent graphs when they are required to adaptively generate graphs based on understanding such highly abstract mathematical concepts as continuousness and discreteness.

Recently, various types of software have been developed for making graphs. User can automatically generate them by simply choosing some properties. In this situation, users select a graph rather than generate one. The third objective is to examine whether undergraduates can select a consistent graph when they are presented alternative candidates of consistent graphs.

Experiment 1

Experiment 1 investigated whether people who use graphs daily can adaptively generate consistent graphs when constructing an explanation with them.

We set a situation in which either “air temperature” or “humidity” was adjusted to promote the growth of “newly discovered mushrooms.” Two dependent variables, air temperature and humidity, can be treated either as continuous or discrete. An independent variable is the "amount of mushroom growth." The table used in our experiments is the same as Table 1, but Variables A, B, and C were replaced with specific factors: humidity, air temperature, and amount of growth. The shape of the line graph generated from the table is also the same as in Figure 1. These two graphs' shapes were controlled to be the same in order that the ease of constructing explanation should not be affected by the shapes of the graphs.

In our experiments, we set two situations for a particular explanation context. In one situation, participants explained how to promote mushroom growth by adjusting the humidity, where air temperature was not controllable. In the other situation, they did so by adjusting the air temperature, where the humidity was not controllable. These two situations were counter-balanced in the experimental procedure.

Method

Participants The participants in Experiment 1 were either university associate professors or doctoral students in experimental psychology. 22 researchers participated as experts. 17 had Ph. Ds. All participants had published one or more peer-reviewed academic journal papers.

Procedure The experiment was performed individually or in small groups. The participants were presented the table shown in Table 1 and given the following instructions:

"A new kind of mushroom was recently discovered whose growth greatly depends on air temperature and humidity. Its growth at specific temperatures and humidities is shown in this table."

Half of the participants were given a situation where the amount of growth was controlled by adjusting the humidity, but the temperature was not controllable. For these participants, the following instructions were given:

"You are a salesperson of mushroom seedlings. Your customers can adjust the humidity in their mushroom greenhouses, but they cannot adjust the temperature. Explain how to grow the mushrooms by adjusting the humidity with uncontrollable changes of temperature. Use a line graph in your explanation."

For counter-balance manipulation, the other half was given a situation where the humidity could not be adjusted, and temperature was replaced by humidity in the instructions.

They wrote their explanation in ten minutes and then drew a graph on an experimental sheet shown in Figure 2 in five minutes, labeling the x-axis and the z-legend by themselves.

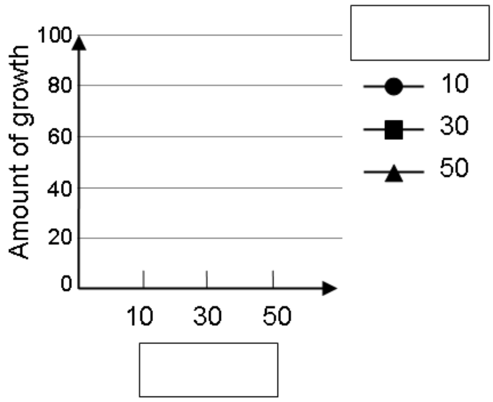


Figure 2: Graph format used in Experiments 1 and 2.

Classifying generated graphs The generated graphs were classified by the placement of an unadjustable variable in the graphs. The following were the classification criteria:

(1) *X-axis unadjustable* graph: an unadjustable variable is put on the x-axis

(2) *Z-legend unadjustable* graph: an unadjustable variable is put on the z-legend

Classifying explanations The participant explanations were classified depending on whether the unadjustable variable was described as a continuous or a discrete variable. The following were the classification criteria:

(1) C*ontinuous explanation*: an unadjustable variable is described continuously. The following are example explanations in this category for a situation where the temperature is not adjustable: "When the temperature is above 30ºC," "according to the increase of temperature," and so on.

(2) *Discrete explanation*: an unadjustable variable is described discretely. Example explanations in the same situation include, "When the temperature is at 10ºC," "when the temperature is low," and so on.

When both types of descriptions appeared in an explanation, the classification was made based on the description that was part of the conclusion. Such descriptions were usually seen in the last part of the explanation.

Results and discussions

The participants were grouped depending on whether they generated *continuous* or *discrete explanations*. Those who generated *continuous explanations* were classified as the *continuous explanation* group, and those who generated *discrete explanations* as the *discrete explanation* group. Ten of the 22 participants were categorized in the *continuous explanation* group and the other twelve in the *discrete explanation* group.

Figure 3 shows the proportions of the graphs classified into each category in the two groups.

To examine whether the structure of the generated graphs was influenced by the described explanation, a two difference in the distribution ($X^2(1, N{=}22) = 6.42$, $p < .05$).

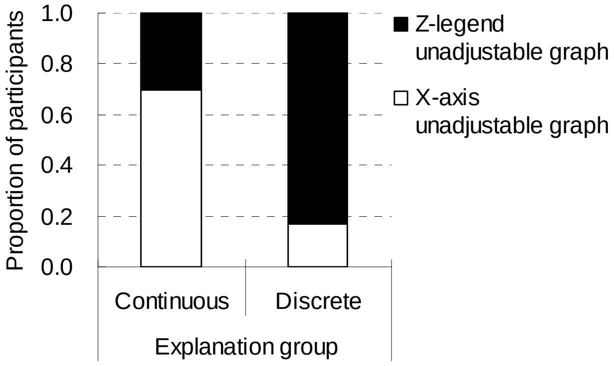


Figure 3: Proportions of participants who generated *x-axis* or *z-legend unadjustable* graphs in Experiment 1.

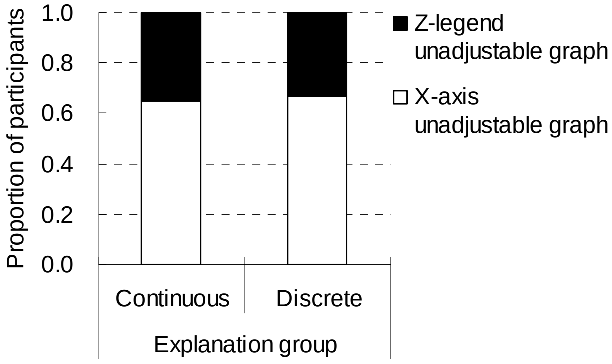


Figure 4: Proportions of participants who generated *x-axis* or *z-legend unadjustable* graphs in Experiment 2.

(*continuous* and *discrete* explanation groups) x two (*x-axis* and *z-legend* generated graphs) chi-square test was performed on their distribution. There was a significant
A residual analysis shows that both the numbers of the participants who generated *x-axis unadjustable* graphs in the *continuous explanation* and *z-legend unadjustable* graphs in the *discrete explanation* group were greater than the expected values (the residual value was 2.53). On the other hand, both the numbers of participants who generated *z-legend unadjustable* graphs in the *continuous explanation* group and *x-axis unadjustable* graphs in the *discrete explanation* group were less than the expected values (the residual value was -2.53).

This result suggests a tendency to generate specific line graphs in which an unadjustable variable was put on the x-axis when it was regarded as a continuous variable in an explanation. On the other hand, there was a tendency to generate graphs in which an unadjustable variable was put on the z-legend when it was regarded as a discrete variable. This result implies that the participants, who use graphs on a daily basis, adaptively generate graphs whose structures are consistent with their explanations.

Experiment 2

In Experiment 1, we confirmed that expert graph users adaptively generate graphs whose structures are consistent with their explanations. In Experiment 2, we performed the same investigation with undergraduates who have little experience of making graphs when explaining something.

Method

In the following, descriptions are omitted about the same procedures as in Experiment 1.
Participants 44 undergraduate Liberal Arts majors who had not completed a course in statistics participated. Half were given a situation where the growth was controlled by adjusting the humidity, but the temperature was not controllable, and for counter-balance manipulation, the other half was given a situation where the growth was controlled by adjusting the temperature, but the humidity was not controllable.
Procedure The procedure of Experiment 2 was the same as that of Experiment 1.

Results and discussions

Seventeen of the 44 participants were categorized in the *continuous explanation* group and the other 27 in the *discrete explanation* group.

Figure 4 shows the proportions of graphs classified into each category in the two groups.

To examine whether the structure of the generated graphs was influenced by the described explanation, a two (*continuous* and *discrete* explanation groups) x two (*x-axis* and *z-legend* generated graphs) chi-square test was performed on the distribution of the generated graphs. There was no significant difference in the distribution ($X^2(1, N=44) = 0.02$, *ns*). This result suggests that undergraduates cannot generate consistent graphs.

Experiment 3

In Experiment 2, we confirmed that undergraduates did not necessarily make graphs whose structure is consistent with their explanations. In Experiment 2, the participants generated graphs by themselves. But in Experiment 3, we gave them two candidates of consistent graphs and let them select one to investigate whether they could adaptively select a consistent graph from two alternatives.

Method

In the following, descriptions are omitted about the same procedures as in Experiment 2.
Participants 57 undergraduate Liberal Arts majors who had not completed a statistics course participated. 29 were given a situation where the growth was controlled by adjusting the humidity, but the temperature was not controllable, and for the counter-balance manipulation, the other 28 were given a

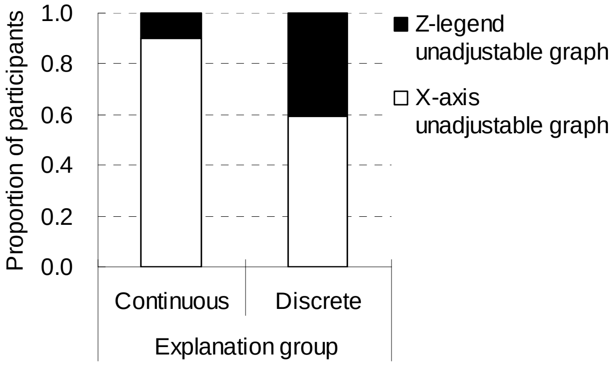


Figure 5: Proportions of participants who selected x-axis or z-legend unadjustable graphs in Experiment 3.

situation where the growth was controlled by adjusting the air temperature, but the humidity was not controllable.

Procedure The experiment was performed as part of their class assignments. The participants wrote a script for the given situation and presented the table used in Experiments 1 and 2. They were also presented two types of line graphs made from the table, such as those in Figure 1, and required to select a suitable one.

Results and discussions

Five participants were excluded from analysis because they failed to follow the instructions. 20 were categorized in the *continuous explanation* group and the other 32 in the *discrete explanation* group.

Figure 5 shows the proportions of graphs classified into each category in the two groups.

To examine whether the structure of the selected graphs was influenced by the described explanation, a two (*continuous* and *discrete* explanation groups) x two (*x-axis* and *z-legend* selected graphs) chi-square test was performed on their distribution. There was a significant difference ($X^2(1, N=52) = 5.62, p< .05$). A residual analysis shows that both the numbers of the participants who selected *x-axis unadjustable* graphs in the *continuous explanation* group and *z-legend unadjustable* graphs in the *discrete explanation* group were greater than the expected values (the residual value was 1.96). On the other hand, both the numbers of the participants who selected *z-legend unadjustable* graphs in the *continuous explanation* group and *x-axis unadjustable* graphs in the *discrete explanation* group were less than the expected values (the residual value was -1.96).

This result implies that undergraduates tended to adaptively select consistent graphs if alternatives were presented to them. However, in Experiment 3, the proportions of participants who selected *x-axis unadjustable* graphs were greater than those in the result of the expert graph users in Experiment 1. We discuss this point below.

Discussion and conclusions

In this study, we investigated whether expert graph users and undergraduates make consistent graphs from given data to construct explanations. The result of Experiment 1 confirmed that expert graph users successfully generated graphs in relation to their explanations. On the other hand, Experiment 2 showed that undergraduates failed to indicate this tendency.

We discuss the results in the light of our hypothesis proposed in the introduction by analyzing the proportions of each type of graphs in each explanation group.

In the result of Experiment 1 (Figure 3) in the *discrete explanation* group, the proportion of *z-legend unadjustable* graphs was significantly larger than that of the *x-axis unadjustable* graphs (p = .019, one-tailed Fisher's exact tests). This means that the clearly greater use of a discrete factor in the graph was due to the influence of the greater use of discrete expressions in the explanation. In other words, there was a consistency between the explanation and the graph. On the other hand, in the *continuous explanation* group, although the proportion of *x-axis unadjustable* graphs was larger than that of the *z-legend unadjustable* graphs, there was no significant difference in their proportions (p = .172, one-tailed Fisher's exact tests). Three of the ten experts in the *continuous explanation* group put the variable described as a continuous one on the z-legend, contrary to our expectation. When analyzing their explanations, two of the three generated explanations based on the slopes of the lines. For example, in the humidity unadjustable situation, "when the humidity is lower than 30%, the mushroom growth proportionally increases with the air temperature because the line slope is positive." Since a line slope is described based on each label of the z-legend, and a line slope is represented continuously in a line graph, they put the continuous variable on the z-legend. The above investigation supports that, as a whole, expert graph users adaptively generated consistent graphs both in the *continuous* and *discrete explanation* groups.

Next, we discuss the graph generation by undergraduates in Experiment 2 (Figure 4). To generate consistent graphs, we must examine what should be represented based on deep consideration of explanations (Kosslyn, 2006). Our result implies that undergraduates tend to use graphs without such consideration.

On the other hand, when selecting a graph in Experiment 3, undergraduates were given choices. Such given choices might enable them to consider the consistency of their explanation and graph representation.

As Norman (1992) noted: "to think of the problem of designing something that people will find understandable and easy to use as the same problem as writing something that other people will understand and find easy to read." The process of generating a graph for conveying information resembles the process of writing. A cognitive writing model proposed by Hayes & Flower (1980) consists of *planning, translating* (text production), and *reviewing*. Similarly, the process of generating a graph also involves *planning,* in which people discuss how to present information, *translating* (depicting), in which people depict a graph, and *reviewing*, in which people review whether the graph is appropriate for their purpose. Studies on writing point out the troubles of the *planning* phase in novices: e.g., not considering situations and objectives for explanation (Flower & Hayes, 1980) and tending to ignore planning (Carey, Flower, Hayes, Schriver, & Haas, 1989).

When selecting a graph from the candidates in Experiment 3, the undergraduates were only required to *review* a graph in the light of explanation without *planning* and *translating*. This may explain why more consistent graphs were selected in Experiment 3 than in Experiment 2.

In Experiment 3 (Figure 5), although we confirmed that the proportions of each type of graphs adaptively changed depending on the explanation contents, as a general tendency, the proportion of *x-axis unadjustable* graphs exceeded that of the *z-legend unadjustable* graphs. This tendency was also shown in Experiment 2 (Figure 4). These results suggest that undergraduates tended to put an unadjustable variable on the x-axis without considering their explanations.

In this study, we defined the normative consistency of explanation and graph representation from the viewpoint of the variable's continuousness and discreteness. Scrutiny is needed to confirm whether such graph consistency actually promotes understanding. Such investigation remains important future work.

Finally, even if the automatic generation of graphs with spreadsheet software simplifies their utilization, this study's results indicate that undergraduates still have trouble selecting consistent graphs. On the other hand, presenting candidate graphs improved the selection of consistent graphs, implying that presenting undergraduates with variations of possible graphs and having them consider the relation of what they wish to explain and the candidate graphs may be an effective method in tutoring graph construction.

References

American Psychological Association (2001). *Publication Manual of the American Psychological Association*. 5th ed., Washington, DC; American Psychological Association.

Carpenter, P. A., & Shah, P. (1998). A model of the perceptual and conceptual processes in graph comprehension. *Journal of Experimental Psychology-Applied*, **4**, 75-100.

Carey, L.J., Flower, L., Hayes, J. R., Schriver, K. A., & Haas, C. (1989). Differences in writers' initial task representations. Technical Report No. 35. (ERIC Document Reproduction Service No. ED310403)

Hayes, J. & Flower, L. (1980). Identifying the organization of writing processes. In L. Gregg, & E. Steinberg (Eds.), *Cognitive processes in writing*. Hillsdale, N.J.: Lawrence Erlbaum Associates.

Hegarty, M. (2011). The cognitive science of visual-spatial displays: implications for design. *Topics in cognitive science*,**3**, 446-474.

Kanzaki, N., & Miwa, K. (2011). Experimental investigation of effects of representations and contexts on comprehension and generation of line graphs. *Proceedings of 33rd annual conference of the cognitive science society (CogSci 2011)*, 2196-2201.

Kosslyn, S. M. (2006). *Graph Design for the Eye And Mind. New York*: Oxford University Press.

Larkin, J. H., & Simon, H. A. (1987). Why a diagram is (sometimes) worth ten thousand words. *Cognitive Science*, **11**, 65-99.

Norman, D. (1991). Cognitive artifacts. In J. M. Carroll (Ed.), *Designing interaction: Psychology at the human-computer interface*. Cambridge: Cambridge University Press, 17-38.

Norman, D. (1992). *Turn signals are the facial expressions of automobiles*. Cambridge: Perseus Books.

Peebles, D., & Cheng, P. C. H. (2003). Modeling the effect of task and graphical representation on response latency in a graph reading task. *Human Factors*, **45**, 28-45.

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

Shah, P., Mayer, R. E., & Hegarty, M. (1999). Graphs as aids to knowledge construction: Signaling techniques for guiding the process of graph comprehension. *Journal of Educational Psychology*, **91**, 690-702.

Zacks, J., & Tversky, B. (1999). Bar and lines: A study of graphic communication. *Memory & Cognition*, **27**, 1073-1079.