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ABSTRACT

To study how the organization of information affects the way that information is interpreted, a total of 404 undergraduates in two studies (151 and 253 students, respectively) solved statistical reasoning problems based on data presented in a variety of types of graphs and tables. When assessing relative probabilities, students were equally successful at answering questions regardless of the data display type. When making data-based causal inferences, accuracy decreased and students were quite sensitive to differences in the data display. In the causal inference study, data presented in percentages produced more accurate responses than did data presented in frequencies; graphs elicited better problem-solving strategies than did contingency tables; and pie charts yielded the most consistently high accuracy of all the display types. Results support the claims that graph interpretation is distinct from graph decoding, and that the graph interpretation skill is not simply a function of the graph (or table) type, but rather is a complex interaction between the data display format, the type of problem to be solved, and the problem solver's facility with the reasoning underlying the particular problem type. Results therefore suggest that a major source of difficulty in graph and table interpretation lies in the translation of both the problem and the data display into appropriate and compatible mental representations. Numerous figures and tables present study findings, and there is a nine-item list of references. (Author/SLD)

Graph interpretation: A Translation problem?

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Abstract

Undergraduates solved statistical reasoning problems based on data presented in a variety of types of graphs and tables. When assessing relative probabilities, students were equally successful at answering the questions regardless of the data display type. When making data-based causal inferences, accuracy decreased and students were quite sensitive to differences in the data display. In the causal inference study data presented in percentages produced more accurate responses than data presented in frequencies; graphs elicited better problem-solving strategies than contingency tables; and pie charts yielded the most consistently high accuracy of all the display types.

These results support the claims that graph interpretation is distinct from graph decoding, and that graph interpretation skill is not simply a function of the graph (or table) type, but rather is a complex interaction between the data display format, the type of problem to be solved and the problem-solver's facility with the reasoning underlying the particular problem type. These students had relatively little difficulty using tables and bar graphs and frequency data to solve probability problems, but had considerable (yet variable) difficulty using the same types of data displays when solving causal inference problems. The students were adept at comparing ratios in the probability task, but generally less successful at comparing ratios in the causal inference task.

In order to solve these problems, people must decide which of the quantities in the data display are relevant to the problem at hand and how these quantities should be combined to solve the problem. When someone is uncertain about what's relevant, s/he may look to the data display to guide their problem solving. In this case, excess information in the data display may add to the difficulty of the problem. When someone is adept at a particular type of reasoning, s/he knows how to identify and ignore irrelevant information in the data display.

These studies indicate that although these students can decode graphs and tables, can compose and compare ratios, the format of the data display influenced their ability to solve some problems. The results of these studies suggest that a major source of difficulty in graph and table interpretation for these students lies in the translation of both the problem and the data display into appropriate and compatible mental representations.

Objectives

With the growing use of graphs and tables to convey information in books and lectures, students' skill at interpreting these displays is increasingly important to their education. Media reliance on graphical representations of statistical information indicates that these skills have lifelong value. Graph interpretation is an essential component of statistical problem solving skill.

Greeno (1987) and Schoenfeld (1986, 1987) have argued that instructional representations influence students' acquisition of concepts. In the context of statistical reasoning, both inside the classroom and out, the manner in which quantitative information is presented may also affect people's ability to use mathematical concepts. In order to solve such problems, both the problem statement and the relevant information in the graphical display must be translated into appropriate and compatible mental representations before one can begin to apply algebraic or statistical procedures. The ability to appropriately translate or interpret a graphical display depends partly on one's translation of the problem statement and, under some circumstances, the translation of the problem statement may be influenced by the nature of the available data.

The goal of this research is to examine how the organization of information affects the way that information is interpreted. The studies reported here explore the translation problem in graph comprehension and identify some of the factors influencing success or failure at translating the graphical information display into mental models that support problem solving.

Perspectives

Previous research on graph interpretation discussed elementary graphical perception processes and memory processes in graph comprehension. However the graphs used in these studies typically do not contain data: The areas on the graph do not represent barrels of oil or incidence of malaria, they are simply unlabeled shapes on the page. This work has emphasized the discriminability of symbols and perception of the sizes of areas on graphs. Summarizing this body of research, Cleveland (1985) classified the perceptual tasks in visual decoding of a graph, but the issue of using graphs to communicate information or using graphs to solve problems remains to be addressed. Visual decoding is a necessary component of graph interpretation, but it isn't sufficient. One graphical display may reveal a variety of interesting relationships among the data; however, but skills alone won't tell readers which of those relationships is pertinent to their interests.

Interpreting graphically presented information requires more than abstract graph reading skills, or the ability to locate various pieces of information in a given type of information display. Problem solving based on data in graphs and tables also requires that the reader know what pieces of information are needed to solve the problem. Accessing an appropriate mental model is one way of "deciding" what information to seek. This requires the reader to select or construct an appropriate mental model based on the information available in memory, in the problem and, possibly, in the graph as well.

Problem solving with tabular or graphically presented information also requires a translation of the problem and the data into terms consistent with the mental model. The translation is analogous to the process used for arithmetic story problem solving, in which a narrative about Chris and Pat and the number of marbles they own is translated into the equation $3 + 2 = \underline{?}$, if the question is about the total number of marbles, or $3 - 2 = \underline{?}$, if the question is about the difference between the numbers of marbles owned by each child. Thus, the translation of a given type of graph, e.g. a bar graph, will differ according to the kind of question being asked about the data in the graph.

Building on the work of Pinker (1981) and Kosslyn (1985, 1989), McKnight and Fisher (1991) have developed a theory of graph comprehension with a variety of memory processes. These include accessing an appropriate mental model for the graphical stimulus and problem situation;. This mental model guides further attention and perception to pull information from the graph. Finally, this information is fit to the mental model to serve as the core of the representation needed for cognitive processing to accomplish the task. This model suggests that graph comprehension will vary depending on the reader's choice of an appropriate mental model for the graphical stimulus and problem situation. The suitability of the mental model will determine its usefulness at guiding the extraction of information from the graph.

A General Model of Data Based Problem Solving

First, translate the problem statement and the data display into compatible mental representations, and choose a strategy for solving the problem. This includes determining which pieces of information are needed and how they'll be combined.

Next, decode the graph or table -- seek out those pieces of information -- and then combine the information in accordance with the strategy chosen.

Finally, translate the results back into the terms of the original problem statement.

The present studies explore the translation problem in graph comprehension by investigating the relationship between problem solving and type of graphical display for two kinds of statistical reasoning problems. The probability judgement is one for which students are likely to possess good mental models; the less familiar causal judgement is likely to require construction of a mental model.

Method

Undergraduates in introductory psychology classes participated voluntarily by completing pencil and paper tasks in a group testing situation. Each student received several problems of one type, all illustrated with the same kind of graph or table. Statistical information was represented in either contingency tables, bar graphs or pie charts: some were based on frequency data and some on percentage data. Students were assigned randomly to problem type and display type. Study 1 included 151 students aswering probability questions. Study 2 included 253 students answering questions about cause.

Study 1 Probability Judgement

The probability questions asked about populations on each of three islands, for example:

	Homeowners	Renters
Island D	1000	500
Island E	250	750
Island F	1250	1250

You are trying to sell renter's insurance and homeowner's insurance by dialing phone numbers selected at random from each island's telephone directory.

On which island is a single call most likely to contact a renter?

In the probability judgement condition, there were four display types: two kinds of frequency tables (with and without marginal totals) and two kinds of bar graphs (stacked and side-by-side). Approximately 40 students responded to each display type, and each student answered the same four questions. Examples of the four data display types used in this study are shown on the following page.

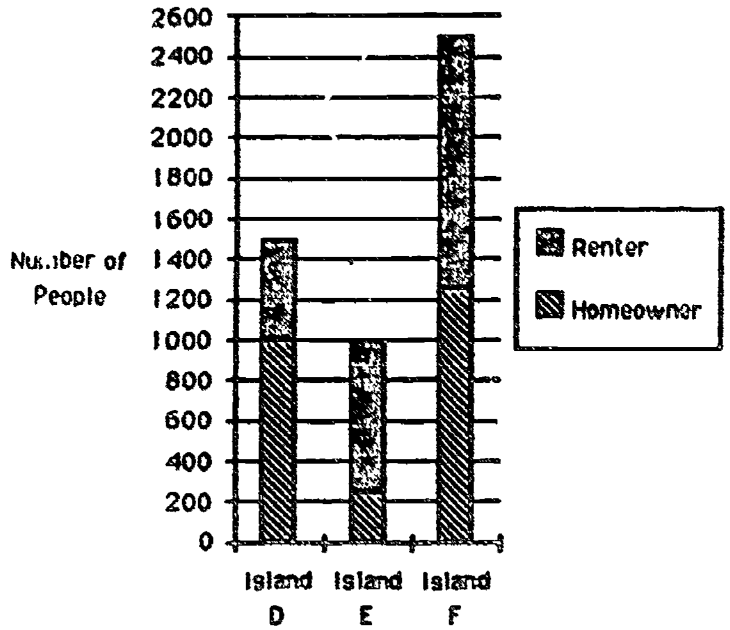
In order to base the probability judgment on covariation information, an individual must compose a ratio of renters to total population for each island, and then determine which of the three ratios is the largest. An alternative (faulty) strategy might involve selecting the island with the greatest absolute number of renters. This strategy would be less computationally demanding and might be chosen by someone who did not understand the principle of random sampling.

Students solved the probability problems regardless of the information display. Accuracy ranged from 81% correct for frequency tables with marginal totals, to 89% correct for stacked bar graphs. There was no effect of display type on the frequency of correct answers ($F_{(3,147)} = .7142$, $p = .5450$). These results suggest that most of the students were able to access (or construct) an adequate mental model, translate the problem statment, extract the relevant information from any of the display types, compare the ratios, and reach a correct conclusion.

	Homeowners	Renters
Island D	1000	500
Island E	250	750
Island F	1250	1250

You are trying to sell renter's insurance and homeowner's insurance by dialing phone numbers selected at random from each island's telephone directory.

On which island is a single call most likely to contact a renter? ____



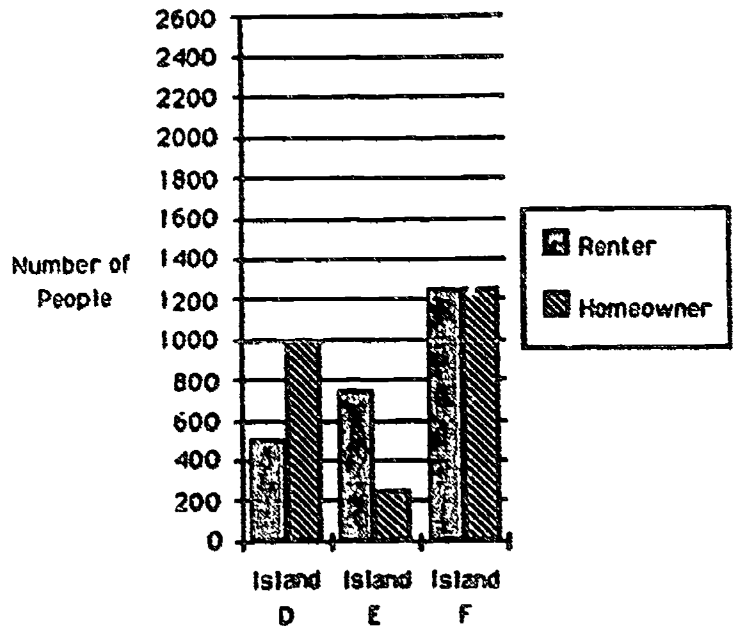
You are trying to sell renter's insurance and homeowner's insurance by dialing phone numbers selected at random from each island's telephone directory.

On which island is a single call most likely to contact a renter? ____

	Homeowners	Renters	Total
Island D	1000	500	1500
Island E	250	750	1000
Island F	1250	1250	2500
Total	2500	2500	5000

You are trying to sell renter's insurance and homeowner's insurance by dialing phone numbers selected at random from each island's telephone directory.

On which island is a single call most likely to contact a renter? ____



You are trying to sell renter's insurance and homeowner's insurance by dialing phone numbers selected at random from each island's telephone directory.

On which island is a single call most likely to contact a renter? —

Study 2 Causal Inference

The causal judgement study (Dibble & Shaklee, 1991) asked for a causal inference about the effect of sun (or shade) on leaf spots, for example:

> Spacemen decided to collect information to discover the effect of shade on leaf spots for eight different kinds of space plants. For each type of plant, the spacemen put some plants in the shade and some in the sun. Each problem below shows what happened to the leaves of those plants in each lighting condition.
>
> Plant name: HIX
>
> | | plants in Sun | plants in Shade |
> |---|---|---|
> | Have Spots | 50% | 89% |
> | No Spots | 50% | 11% |
>
> Considering the information shown, what should the spacemen conclude about the effect of sun on leaf spots for hix plants? (Circle one)
>
> A. Sun causes spots on leaves.
> B. Sun prevents spots on leaves.
> C. Sun has no effect on leaf spots.

In the causal task, there were five display types: two kinds of tables (containing frequencies or percentages), two kinds of stacked bar graphs (containing frequencies or percentages), and pie charts. There were approximately 60 students in each of the five groups. Each student judged eight problems, including four pairs of comparable positive and negative relationships between sun and leaf spots.

For one problem pair, the strategy diagnostic problems, judgements would be inaccurate if based on cause-present outcomes alone. In order to base the causal judgment on covariation information, an individual needs to compose a ratio of the likelihood of leaf spots on plants in the sun (cause present outcomes), and compare it to the likelihood of leaf spots in the shade (cause absent outcomes). The problem pairs are described in the table below:

Problem Types

DIAGNOSTIC

	Cause Present	Cause Absent
	Sun	**Shade**
Spots	50%	89%
No Spots	50%	11%

	Cause Present	Cause Absent
	Sun	**Shade**
Spots	50%	11%
No Spots	50%	89%

11_89

	Cause Present	Cause Absent
	Sun	**Shade**
Spots	11%	89%
No Spots	89%	11%

	Cause Present	Cause Absent
	Sun	**Shade**
Spots	89%	11%
No Spots	11%	89%

33_72

	Cause Present	Cause Absent
	Sun	**Shade**
Spots	33%	72%
No Spots	67%	28%

	Cause Present	Cause Absent
	Sun	**Shade**
Spots	72%	33%
No Spots	28%	67%

89_50

	Cause Present	Cause Absent
	Sun	**Shade**
Spots	89%	50%
No Spots	11%	50%

	Cause Present	Cause Absent
	Sun	**Shade**
Spots	11%	50%
No Spots	89%	50%

Examples of the five data display types used in the causal inference study are on the next page, with graphs of the results on the following page.

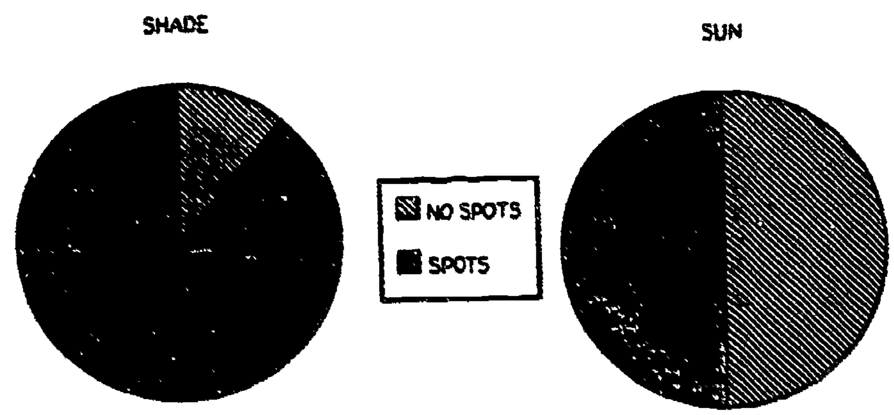
Study 2

Examples of display types

Spacemen decided to collect [illegible] spots for eight different kinds of space plants. For each type of plant, the spacemen put some plants in the shade and some in the sun. Each problem below shows what happened to the leaves of those plants in each lighting condition.

Considering the information shown, what should the spacemen conclude about the effect of sun on leaf spots for hix plants? (Circle one)

Plant Name: HIX



A. Sun causes spots on leaves.

B. Sun prevents spots on leaves.

C. Sun has no effect on leaf spots.

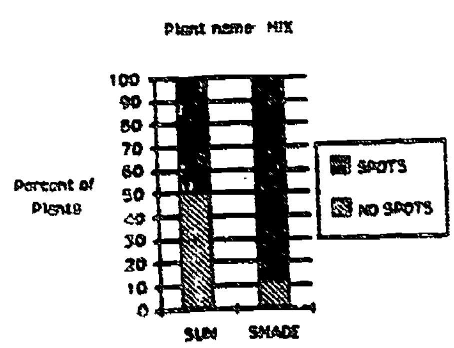
Table (%)

	plants in Sun	plants in Shade
Have Spots	50%	89%
No Spots	50%	11%

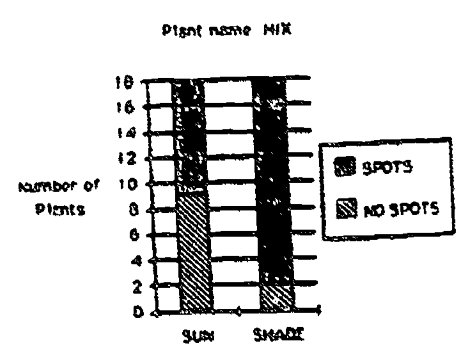
Table Frequency

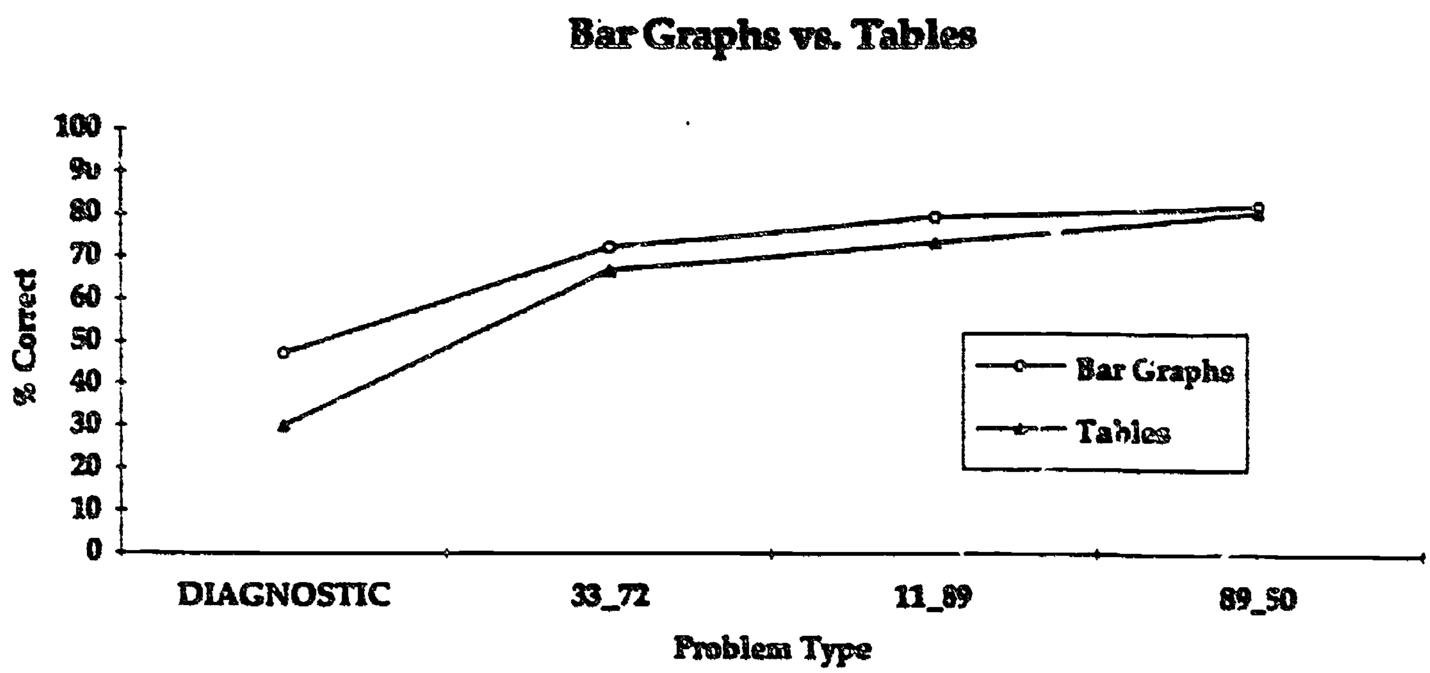
	plants in Sun	plants in Shade
Have Spots	9	16
No Spots	9	2

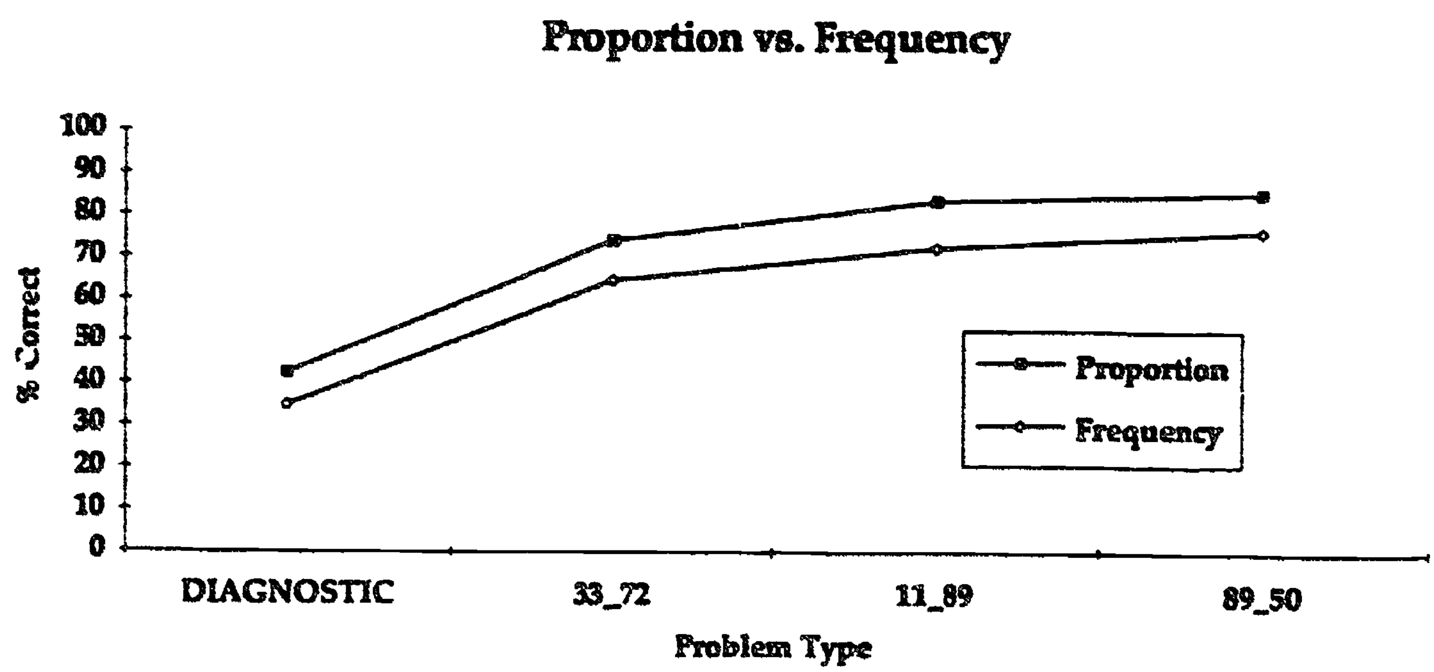
Bar Graph (%)

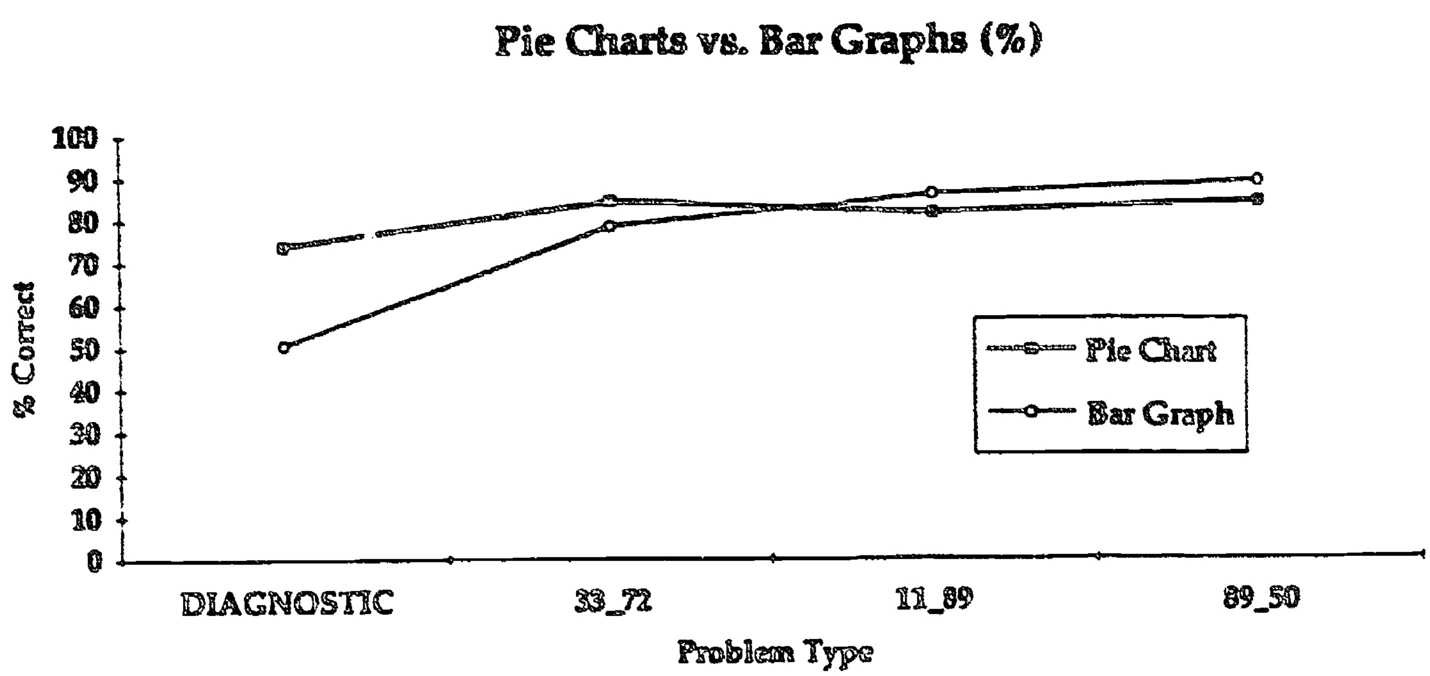


Bar Graph Frequency




Bar Graphs vs. Tables
100
90
80
70
60
50
40
30
20
10
0
% Correct
Bar Graphs
Tables
DIAGNOSTIC
33_72
11_89
89_50
Problem Type


Proportion vs. Frequency
100
90
80
70
60
50
40
30
20
10
0
% Correct
Proportion
Frequency
DIAGNOSTIC
33_72
11_89
89_50
Problem Type


Pie Charts vs. Bar Graphs (%)
100
90
80
70
60
50
40
30
20
10
0
% Correct
Pie Chart
Bar Graph
DIAGNOSTIC
33_72
11_89
89_50
Problem Type

Causal judgement accuracy was generally poor relative to accuracy in the probability judgement task. Causal judgement task accuracy varied and depended heavily on display type. Across all eight problems, accuracy was poor for tables relative to graphs (63% vs. 71%, $F_{(1, 314)} = 6.92$, $p = 0.009$), poor for frequency data in comparison with proportional data (62% vs. 72%, $F_{(1,314)} = 9.14$, $p = 0.002$), and strikingly good for pie charts (81%). Though the pie chart results were no more accurate across all eight problems than the bar graphs with percentages, there was a significant interaction between problem type and display type for this comparison: on the strategy diagnostic problems, pie charts led to significantly higher accuracy than bar graphs with percentage data ($F_{(1,151)} = 8.71$, $p = 0.000$)

Previous research (Shaklee & Elek, 1988) has shown that a common error in statistically based causal reasoning is focussing on event outcomes when the cause is present and ignoring them when the cause is absent, e.g. someone asked about the effect of sun on leaf spots might note the proportion of spotted plants in the sun and fail to attend to the proportion of spotted plants in the shade. For two of the causal problems, this strategy would lead to an error, and for these more difficult strategy diagnostic problems the above patterns were especially strong, ranging from 19% correct in the frequency table condition to 81% correct in the pie chart condition; table vs. graph: 25% vs. 37%; frequency vs. proportion: 25% vs. 36%. In general, students receiving the pie charts had little difficulty solving the causal problems, with an average accuracy across problems of over 80%, comparable to the results in the probability judgment study.

The Role of the Data Display

Although the display types in the causal inference study were physically comparable to the display types in the probability judgement study, and though both problem types required students to compose and compare ratios, students' ability to use the data in the displays varied considerably between problem types and also among display types. An explanation for this may lie in the nature of the various translation problems presented by these tasks.

In the presumably more familiar probability judgment task the students were insensitive to variations in the information display, whereas in the statistically based causal inference task they were very sensitive to such differences. In the causal study, the strategy diagnostic problems showed a greater effect of display type. These findings support the idea that students who are uncertain about how to solve the problem are relying on information in the graphical display to help them translate, or interpret the problem statement.

Bar graphs show the data as two ratios, whereas tables require the students to compose those ratios for themselves. This did not matter in the probability judgement study, but in the causal judgement study students were significantly more accurate when judging bar charts rather than tables. The fact that the difference was greatest for the strategy diagnostic problems indicates that bar graphs tended to elicit better problem-solving strategies than tables. For non-diagnostic problems, faulty strategies, e.g. ignoring cause absent outcomes, may still lead the student to a correct conclusion.

Causal judgements are significantly more accurate for percentage data than for frequencies. This suggests that composing and comparing two ratios may have been difficult for some students. Because improvement was as strong for the non-diagnostic problems as for the strategy diagnostic problems, it is unlikely that percentage data affected choice of problem solving strategy. Providing data in percentages may have reduced the computational demands for some students in the causal study. Note, however, that many students in the probability study successfully composed and compared <u>three</u> ratios!

Causal judgement accuracy was greatest for students judging data in pie charts. This effect was especially strong for the strategy diagnostic problems. Both bar graphs and pie charts depict the data in ratios, yet pie charts were even <u>more</u> likely to elicit use of an improved problem solving strategy. If, in fact, the students are looking to the data display for clues toward translating the problem statement, the pie chart has the advantage of offering information about the two ratios, and virtually nothing else. The bar graph with percentages contains (superfluous) numbers on the Y-axis, which students may have attempted to incorporate in their solutions. One apparent effect of the pie chart was to raise students' awareness that statistical causal reasoning involves comparison of outcomes when the cause is present <u>and</u> absent.

But why is it that students in the probability task can decode and interpret the graphs, compose and compare ratios, and yet students in the causal task have trouble with seemingly similar mental operations? The results of these two studies also suggest that graph and table comprehension is a context dependent skill. The interpretation of graphical (and tabu!ar) displays appears to be closely linked to facility with the kind of reasoning called for by the problem, i.e., possession of a suitable mental model. The process of making probability judgements, even in a statistical context, is likely to be more familiar to these students than the process of statistically based causal inference. The students are able to adequately translate the probability question and decide what to do. Though the majority of these students have the graph-reading sub-skills to decode the graphs, and the computational skills to compose and compare ratios, many students in the causal study apparently did not know how to bring these skills to bear on the problems at hand. They were unable to access a mental model adequate to guide their translation of the problem statements, and apparently attempted to use the data display to guide their translation of the problems.

When students understand the problem and know exactly what information they need in order to solve it, they can locate that information and ignore other details in the data display. This could be the case in in the probability study, in which most of the students appear to be accessing a suitable mental model for representing the problem and the data. When the students are less certain about what the problem requires, as in the causal judgement task, they may look to the graphical display to find information that will help them select or construct an appropriate mental model. If the display is rich in information, as in the case of the frequency table, it isn't very useful for this purpose and can lead to confusion. If, however, the display contains the bare minimum of information needed, e.g. the pie chart, it may serve as a useful guide to translation of the problem statement. If this analysis is correct, we would expect to see the effect of display type disappear for people who are adept at data-based causal inference.

Additional Considerations

The probability questions described above call for a familiar judgement -- likelihood -- in the reasonably familiar context of populations. The more difficult causal judgment was framed in a relatively less familiar context of factors influencing leaf disease in hypothetical space plants. This leaves open the possibility that the differences in sensitivity to information display type is influenced by differences in the semantic context of the problems, as well as by the differences in the type of reasoning called for by the problem.

The probability questions also differ from some of the causal questions with respect to the relative magnitude of the numbers involved in each data set. This difference does not exist for the causal data expressed in percentages or in pie charts. However, the small sample sizes in the frequency tables & frequency bar graphs may have influenced some students' willingness to base causal inferences on these data.

Summary

The function of quantitative graphics is to inform. Graphics organize information in ways that facilitate, impede or distort information processing. Graphs and tables can summarize information and call attention to certain patterns or relationships within the data. The match between the patterns relevant to the problem and the relationships emphasized by a particular display type influence whether the viewer is informed, confused or deceived with respect to a specific statistical issue. Different displays of the same information may elicit from the viewer different strategies for solving the same problem,. Or, if a given strategy is used consistently, some information displays may facilitate or impede extraction of information needed for that strategy. The viewer's familiarity with the statistical problem , with the semantic context and with the relationships within the data will also influence the usefulness of the different data displays.

Some Implications for Instruction

Decoding graphs does not equal interpreting graphs. Decoding skills are necessary but not sufficient for using graphs and tables to make statistical inferences.

When someone is uncertain about what's relevant, excess information in the data display may add to the difficulty of the problem. When someone is adept at a particular type of reasoning, s/he knows how to identify and ignore irrelevant information in the data display.

Where statistical reasoning is concerned, it doesn't make sense to talk about learning to interpret a particular type of graph, e.g. a bar graph. Graph interpretation is a function of the reasoning required by the problem at hand, thus we have high accuracy for interpreting bar graphs in the probability judgement study, and relatively low accuracy interpreting bar graphs in the strategy diagnostic component of the causal inference study.

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