The effect of graphical format and instruction on the interpretation of three-variable bar and line graphs

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February 16, 2018

Abstract

We present a study that investigates how graph format and training can affect undergraduate psychology students' ability to interpret three-variable bar and line graphs. A pre and post-test design was employed to assess 76 students' conceptual understanding of three-variable graphs prior to and after a training intervention. The study revealed that significant differences in interpretation are produced by graph format prior to training; bar graph users outperform line graph users. Training also resulted in a statistically significant improvement in interpretation of both graph formats with effect sizes confirming the intervention resulted in substantial learning gains in graph interpretation. This resulted in bar graph users outperforming line graph users pre and post training making it the superior format even when training has occurred. The effect of graph format and training differed depending on task demands. Based on the results of this experiment, it is argued that undergraduate students' interpretations of such three-variable data are more accurate when using the bar form. Findings also demonstrate how a brief tutorial can result in large gains in graph comprehension scores. We provide a test which can be used to assess students understanding of three-variable graphs and the tutorial developed for the study for educators to use.

Introduction

Analysing and interpreting quantitative data is a key skill taught in all scientific undergraduate degree courses because the ability to work with data is a fundamental activity in the sciences [1]. Although different skills are important for students to master, one vital skill in the development of scientific inquiry is the ability to work with quantitative data [2]. The expectation that people should be able to read and interpret basic data has progressed to an expectation that individuals can actively work with the data and manipulate information depending on the nature of scientific inquiry [3]. Active interpretation of data requires skills which allow a reader to make inferences from given data, find trends, criticise data and use data to support and evaluate claims. Therefore proficiency in data literacy in today's information age is a necessary pre-requisite to scientific inquiry skills [1].

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The expanding utilisation of visual presentation of information in science, the media and regular daily life depends on the presumption that charts and graphs are straightforward to the viewer, due to the human capability of recognising a pattern and inferring the quantitative relationship being depicted [4]. However, reading scientific graphs requires more than encoding of pattern [5] and when progressing beyond the interpretation of simple pattern relationships [6, 7], the utility of the representation will depend on an interaction between the individual's graphical literacy, the graph format used and whether the format supports the task the reader is required to engage in [8, 9, 10, 11, 12, 13].

Although many experienced graph users take their abilities for granted, the knowledge and skills required are far from trivial and require considerable training and practice to be mastered [3, 9, 14]. A large body of research investigating graph reading ability has revealed that novice students misinterpret scientific graphs and that most errors can be traced to a deficit in perceptual and conceptual understanding of how the visualisation represents information [4, 5, 15]. For example, a consistent and ubiquitous finding in the physics education literature [16] is that students exhibit misconceptions such as interpreting graphs literally (as pictures) and 'slope-height' confusion where students incorrectly assume a greater slope implies a higher value.

Similar findings concerning consistent misconceptions have been found with graphs representing data from experimental designs depicting the effect of a one or more independent variables on a dependant variable. These type of experimental designs are very prevalent in psychology; a subject where students are required to learn the fundamentals of experimental design and statistical analysis of one or more independent variable on a dependant variable. These designs are known as "factorial research designs".

Factorial research designs

Factorial research designs are widely used in all branches of the natural and social sciences as well as in engineering, business and medical research. The efficiency and power of such designs to reveal the effects and interactions of multiple independent variables (IVs) or factors on a dependent variable (DV) has made them an invaluable research tool and, as a consequence, the teaching of such designs, their statistical analysis and interpretation lies at the core of all natural and social science curricula.

The simplest form of factorial design is the two-way factorial design, containing two factors, each with two levels, and one DV (for example the differences in wellbeing (DV) between men and women (IV_1) as a function of high and low exercise regimes (IV_2)). Statistical analysis of these designs most often results in a 2×2 matrix of mean values of the DV corresponding to the pairwise combination of the two levels of each IV. Interpreting the results of even these simplest of designs accurately and thoroughly is often not straightforward however, but requires a significant amount of conceptual understanding—for example the concepts of 'simple', 'main' and 'interaction' effects [9]. Like most statistical analyses, interpretation can be eased considerably by representing the data in diagrammatic form [17, 18, 19]. Data from two-way factorial designs are most often presented as either three-variable line or bar graphs—variously called 'interaction' or 'ANOVA' graphs. Examples of such bar and line graphs (taken from the experiments reported here) are shown in Figure 1. Consistent with findings in the domain of physics, research investigating these three-variable graphs reveals a systematic bias in interpretation centred on two-variables with a deficiency of interpretation concerning the third variable.

Although the graphs displayed here are relatively simple (depicting the relationship between three variables) research has consistently revealed that the majority of graph viewers will struggle to interpret them accurately when the information is depicted in line graph format [5, 15, 20]. Despite relatively minor differences between the two types of graphs experimental studies have revealed that line graph users were significantly more likely to misinterpret or be unable to interpret the data represented than bar graph users [15]. In previous research we hypothesised that these observed differences result from a combination of two factors: (a) the inadequate knowledge structures and procedures of some novice users and (b) Gestalt principles of perceptual organisation [21] that made data points and their relationships more visually salient in the bar graphs, thereby making their interpretation, particularly by novices, much more detailed and accurate [15, 20].

Specifically, the visual salience of the lines in the line graphs drew attention to them and readers could associate the line pattern to the legend via a colour matching process. However, the line connecting the data points made the identification and interpretation of the specific data points relating to the variable plotted on the x axis more difficult. These errors were less likely to be found in bar graph interpretations because each data point is represented by a unique, readily identifiable bar. To test this notion we designed a novel line graph design [15] to offset the bias present in traditional line graphs. Data points were coloured and matched to their corresponding variables by placing a colour patch next to the associated variable on the x axis. Consistent with the analysis once this novel colour match line graph shared similar anchoring principles as the bar graph format performance was equivalent for both graph formats [15].

One potential implication of these findings is that three-variable data of this type may be more effectively taught to undergraduate students in the form of bar graphs than with the more traditional line graphs (or the modified graph design of the colour match graph). Based on previous findings it would appear that bar graphs are superior to line graphs when presenting statistical information to a student population. A possible longer term implication may be that this recommendation is more generally applicable to other forms of data.

The Effect of training on statistical reasoning

There still remains however an important question regarding the robustness of this effect and whether training can produce any discernible benefits. Although research has been conducted demonstrating that design modification [15, 22] and cognitive scaffolding [23] can boost accuracy and quality of interpretation, no studies which we are aware of have investigated the effect of direct training on comprehension of three-variable bar and line graphs and how training may potentially interact with graph format.

Additionally, although working with visual representations of data is considered to be an essential skill in scientific reasoning and there is an increasing demand in the literature for these skills to be taught [3] we could not find any tutorial guiding students on how to interpret three-variable Cartesian co-ordinate graphs or graphical tests which assessed comprehension of these types of graphs. Graph comprehension is a complex task [14] so it is often the case that novices will not benefit from the purpose of the visualisation, or worse the representation will increase misconceptions and erroneous interpretations of data [20]. Dreyfus and Eisenberg (1990, p. 33) argue that: "Reading a diagram is a learned skill; it doesn't just happen by itself. To this point in time, graph reading and thinking visually have been taken to be serendipitous outcomes of the curriculum. But these skills are too important to be left to chance" [14].

A systematic review of the literature [3] concluded that graph interpretation and construction had to explicitly be taught in order for graduate students to develop scientific inquiry skills in data handling and interpretation. The level of skill needed to appropriately interpret data from graphs depends on the task demands on the user. These task demands have traditionally been classified as elementary, intermediate and advanced [1, 3] in the literature and increasing sophistication of skills is associated with higher educational achievement. Elementary reasoning is the simplest and requires the user to simply read the data by locating specific information from the graph. For example, a point reading question for the graph in Figure 1a would be "How much CO_2 do Quebec plants which are chilled uptake?" The graph user is then expected to read the information from the graph and accurately locate that the CO_2 uptake is 50 units.

Intermediate reasoning involves identifying the relationship between variables and trends being depicted in the graph. For example an intermediate reasoning question for the graph in Figure 1a would be "Describe how the treatment affects each plant type?". The user is then expected to describe the relationship between variables, a step up from reading information off such as point reading. An example of an intermediate interpretation is: "In the case of chilled treatment both plants take up the same amount of CO_2 but for non-chilled treatment Mississippi takes up a lot more CO_2 than Quebec". Advanced reasoning involves extrapolating from the data such as generalising to a population, making a prediction based on the trend or a comparison of trends and variable groupings [1, 3]. In factorial research designs advanced reasoning involves identifying main effects of each independent variable (e.g., for the graph in Figure 1b, "Overall fasting results in a much higher glucose uptake than not fasting") and if there is an interaction effect present. An example of an interpretation of an interaction effect in the graph in Figure 1b is "When you are fasting relaxation training slightly increases glucose uptake. When you are not fasting relaxation training slightly decreases glucose uptake. Therefore the effect of relaxation training on glucose uptake reverses depending on whether fasting occurred or not".

In previous research we have demonstrated that novices may be able to provide interpretations of the graphical pattern but do not have the knowledge structures to be able to explicitly identify main and interaction effects (indeed it is only in an expert sample such advanced reasoning occurs [9, 20]. In addition, we also found that novice students struggle with elementary interpretation if they cannot relate the pattern to the variables the pattern represents [9, 20]. It is crucial therefore that the rules of graphical representations are taught or even basic reasoning may be difficult for a non-expert audience of graph users. To address this need for training this paper describes an experimental intervention where students were taught how to interpret these graphs depicting results of factorial research designs. In order to assess graph comprehension prior to training and after training, pre- and post-tests designed to measure graph reading ability were also developed. Both measures are described in more depth below.

It may be the case that a high rate of error in graph interpretation emerges in the absence of appropriate and explicit instruction. If so, the conclusion to be drawn would be that explicit and rigorous teaching of line graph interpretation is essential in statistics to prevent it being hampered by the potentially confusing features of the format. Alternatively, it is possible that the visual salience of the lines in line graphs is so high that its effect on interpretation is still found after explicit training has occurred. If this is the case, then it may be wise to conclude that such data would be best taught and communicated in bar graph form. The key questions this study aims to address are:

1. Is one particular graph format more appropriate than another for students in Further and Higher Education?

2. What effect (if any) does a training intervention have on students' ability to reason with graphical information?

3. How does the effect of graph format and training differ depending on task demands?

4. Is there an interaction effect between graph format and training?

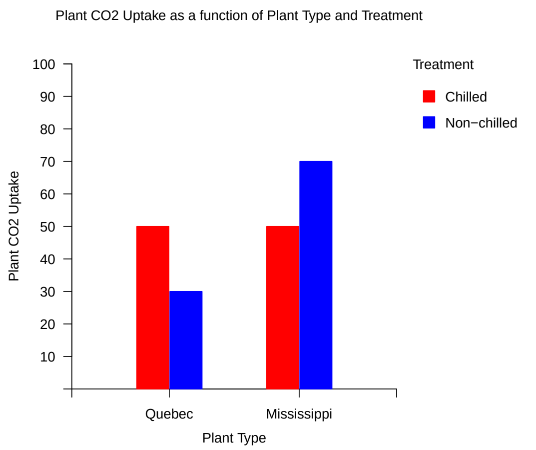
Method

Participants

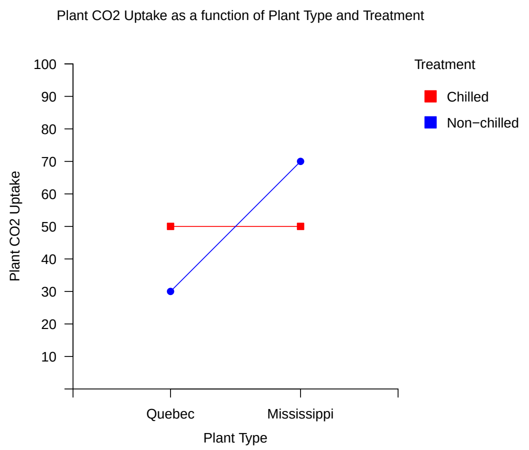
Participants were 80 foundation level undergraduate psychology students at the University of Huddersfield with 40 participants in each graph condition. There were 36 participants who completed both the pre and post-test in the line graph condition and 40 participants who completed both in the bar graph condition making the overall sample size 76.

Materials

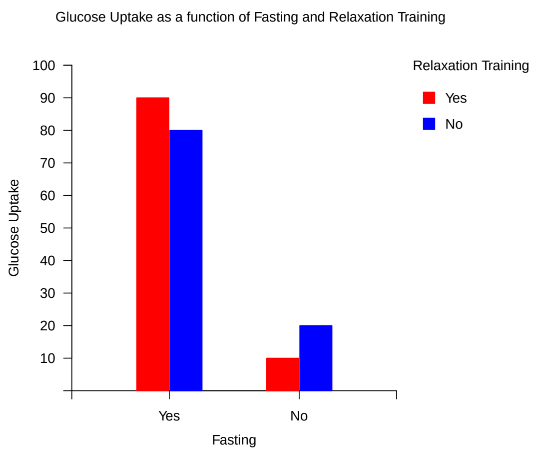
Two tests were constructed using two data sets that produced two pairs of bar and line graphs. These graphs were informationally equivalent in that no information can be inferred from one that cannot be inferred from the other and each can be constructed from the information in the other [19]. In



(a) Bar graph – pre-training



(b) Line graph – pre-training



(c) Bar graph – post-training

(d) Line graph – post-training

Figure 1: Factorial graph stimuli used in the pre-training and post-training tests

addition, all features were identical between the two graph formats apart from the pattern in the centre connecting the data points. The graphs for the session 1 test are shown in Figures 1a and 1b while those for session 2 are shown in Figures 1b and 1d[1].

The variables in the graphs used for the test were chosen so that no prior knowledge of the domain or relationships would influence interpretation. The values of the conditions were devised to present and test the fundamental items of knowledge required to produce an appropriate knowledge structure or schema for each graph and to produce patterns that would test the various hypotheses under investigation. The questions in both questionnaires were essentially identical, with only minor changes in wording to account for the different graph formats. The questions were devised to examine students' knowledge of relevant concepts at an elementary, intermediate and advanced level. Elementary questions (questions 1–4) probed for knowledge of independent and dependent variables, correct identification of causal relationships and point reading questions. The maximum score for these set of

[1]The pre-test is available at http://peebles.sdfeu.org/heapn/q1b.pdf and the post-test is available at http://peebles.sdfeu.org/heapn/q2l.pdf

questions was 9.

These questions were followed by questions 5–12 which required intermediate reasoning. Specifically the questions required a simultaneous consideration of the two independent variables to establish the effect on the dependant variable, e.g., mean values, minimum and maximum values etc.). The maximum score for these set of questions was 16. Advanced reasoning involved questions which probed knowledge of main effects, an interaction effect and ability to be able to consider every combination of the levels of each IV on the DV (questions 13–15). The maximum score for these set of questions was 6. Both sessions 1 and 2 graphs showed a possible main effect of the independent variable plotted on the x-axis and an interaction effect.

Similar to the test, a tutorial was also developed as an instructional intervention to teach students how to interpret these three-variable graphs (one for line graphs and the other for bar graphs). The information in both tutorials was essentially identical, with only minor changes to account for the different graph formats. The tutorial mirrored the test of graphicacy and covered basic to advanced skills in graph reading and statistical information extraction. Therefore the tutorial begins with elementary instruction, such as where the independent and dependant variables are plotted, how to associate pattern to variables, etc. then progresses onto intermediate reasoning (how to simultaneously consider the effect of two IV's on a dependant variable, how to transform data to provide mean scores etc.) and advanced instruction which focussed on how to establish whether a main effect and an interaction effect is present[2].

For the purpose of the experiment the tutorial was delivered as a 25 minute presentation (in a lecture theatre, during a first year cognitive psychology class) by the two authors who practised delivery prior to the experiment and read off standardised scripts to ensure consistency between conditions.

Design and procedure

The study consisted of three elements; a pre-test, an instructional intervention and a post-test 2 weeks later. A mixed design was employed to assess the effect of graph format and instruction on graph comprehension. An independent group design was employed to assess the effect of graph format, with different participants being given bar or line graphs. The test was a repeated measures design where participants completed both the pre-test and the post-test.

The test was in either bar or line graph form and was randomly distributed to students which resulted in random allocation to each experimental condition (bar or line graph). They were then immediately given a 25 minute lecture on graph interpretation at the same time by each respective author in separate lecture rooms. We chose this setting (lecture hall where students attend teaching sessions) to increase the validity of the learning material and the learning environment. However, employing elements of a field study meant that counterbalancing of graphs was not possible in the pre and post-test design.

The lecture was simply a presentation delivered of the tutorial produced. Students were informed that they needed to remember whether they were assessed using the bar or line graph format. A period of 14 days separated the two tests after which the students completed the second test, again in class. The students informed the authors the graph condition they had been allocated to, and the authors did a check of pre and post-tests to ensure they were completed by the same person.

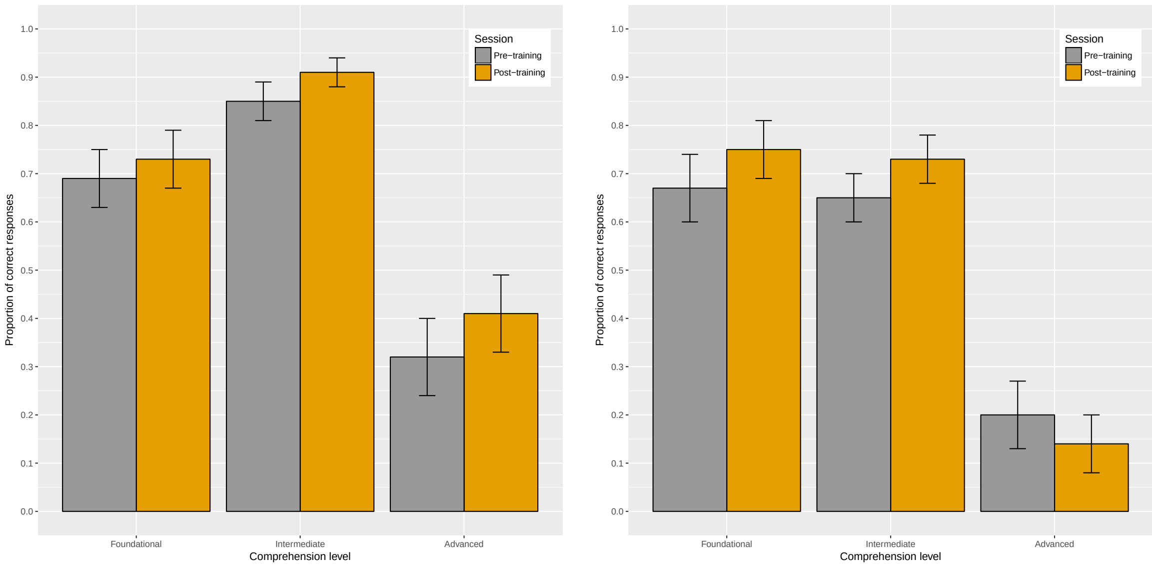
Scoring

Each question was scored as correct or incorrect by the author. Where questions had multiple response options (e.g., name the independent variable(s)) negative marking was employed to control for guessing and to prevent inflation in scores. The maximum overall score which could be obtained on the test is a score of 31.

[2] The tutorial is available at: http://peebles.sdfeu.org/heapn/heapn-tutorial.swf.

Results

The results are discussed in terms of effect size as well as statistical significance which allows for a meaningful consideration of the results in an educational context. Descriptive analysis (Figure 1) reveals bar graph users outperform line graph users before and after training, with the one exception being the post-test scores assessing foundation reasoning whereby performance is very similar in both groups. Therefore this format is superior to the line graph format for depicting three-variable data sets. Training itself improves performance although the benefit differs depending on task demand. Therefore the improved effect of training interacts with task demands, improvement in intermediate reasoning is more pronounced than improvement in foundation or advanced reasoning. Variance is similar in both conditions apart from when intermediate reasoning is being assessed, in which case variance is much higher in the line graph condition compared to the bar graph condition. Therefore, in a student sample performance is better when the bar graph format is used and there is more consistency in performance when intermediate reasoning is required if this format is used.



(a) Bar graph condition

(b) Line graph condition

Figure 2: Proportion of correct responses for each comprehension level and testing session, bar and line graph conditions. Error bars indicate 99% confidence intervals.

A mixed method ANOVA determined that test scores differed significantly as a function of graph format, $F(1, 74) = 14.613, p < .001, \eta_p^2 = .165$, and this difference is large—bar graph users scored on average 17% higher than line graph users. Training also resulted in statistically significant improvement, $F(1, 74) = 15.230, p < .001, \eta_p^2 = .171$, and the effect size is also large, indicating a substantial benefit from the educational intervention. There was no interaction effect between graph format and training, $F(1, 74) = 0.033, p = .855, \eta_p^2 = 0.0$.

To establish whether improvement from training differed as a function of task demands and graph format, paired samples t-tests were conducted using a Bonferroni corrected alpha of 0.017. These revealed that in the line graph condition there was a statistically significant improvement from pre to post-test when foundation reasoning is assessed ($p = .009$) and when intermediate reasoning is assessed ($p = .01$) but not when advanced reasoning is required ($p = .134$).

In the bar graph condition training did not produce significant gains in foundation reasoning ($p = .177$) but produced significant improvement in intermediate reasoning ($p = .007$). The adjustment of the alpha level results in training not producing a statistically significant improvement in advanced reasoning ($p = .022$).

Discussion

The experiment presented in this article provides insight into how graph format, task demands and training in graph interpretation affects the comprehension of three-variable bar and line graphs. The experiment revealed three key findings which have important implications for graphical display design and educational recommendations for which graph format to use when presenting data from statistical analyses.

First, informationally equivalent bar and line graphs are not computationally equivalent for students in higher education. Bar graph users are more likely to correctly interpret information than line graph users prior to any training. This effect is stable, irrespective of task demands. This finding has now been replicated using different methods to assess comprehension including verbal protocols, written responses and question answer tasks of the type used in this study [15, 20]. The effect size is large and indicates that 17% of variation in performance on the test can be accounted for by graph format, consistent with previous findings that novice students perform substantially better when the representation they work with is in bar form. The increased benefit of training for bar graph users means that this format still surpasses the line format post-training (Figure 1).

Secondly a brief training intervention designed to improve graph comprehension results in a marked improvement when the results are considered in the context of a one off tutorial in graph interpretation lasting 25 minutes. The effect size is large, indicating that the educational intervention resulted in significant improvement, especially in the line graph condition. Training results in improvements in foundation reasoning when data is presented in the line graph form but not in bar graph form. This is consistent with previous findings that novice students struggle with elementary reasoning when data is presented in the line graph form but not the bar form. Specifically novice users struggle to correctly associate the pattern in the centre to variables plotted on the axes [15, 20, 24]. Once this simple matching process has been taught through the tutorial a significant improvement emerges in foundation and intermediate reasoning when using the line graph form.

Advanced reasoning requires a long time to develop [9]; novices are unlikely to have the knowledge structures to assist them in identifying main effects and interaction effects [15, 20]. However, the improved performance in the bar graph condition extends to advanced reasoning indicating some benefit from the tutorial. Therefore the component of the tutorial providing instruction on advanced reasoning would require additional study, although study can be tailored around the individual student's test score using our pre and post tests. The video can also be treated as a hyperlink so components of the tutorial can be targeted for re-study such as components involving advanced reasoning.

Summary and recommendations

Bar and line graphs are some of the most commonly used graphical formats for presenting data from some of the most commonly used statistical tests in the social sciences [25]. Our research findings demonstrate that degree level students perform better when using bar graphs than when using line graphs. The effect of graph format is substantial even without training. It is reasonable to assume that further training would result in instruction accounting for a greater variance in performance.

Training results in improvements in reasoning with both graph formats. Therefore, the recommendations are clear: students should use bar graphs when interacting with visual displays depicting quantitative data and a brief tutorial can improve reasoning with this format to a considerable extent. Higher education institutions can use our tutorial to provide such training whilst teaching statistics as part of the psychology degree program. The training can be tailored around the sophistication of skills. For example, a student may find one off instruction is sufficient for them to be able to manage elementary reasoning, but repeated practise would be necessary to develop advanced skills such as identifying holistic trends such as main effects and interaction effects. We also provide a test of graphicacy for HEI's to assess students' reasoning with graphs presenting results of experimental designs.

Acknowledgements

This research was supported by a grant from the UK Higher Education Academy Psychology Network.

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