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Extraneous information and graph comprehension: Implications for effective design choices

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Implications for effective design choices

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Abstract

Purpose – The purpose of this paper is to examine if university students could accurately extract information from graphs presented in 2D or 3D formats with different colour hue variations or solid black and white.

Design/methodology/approach – Participants are presented with 2D and 3D bar and pie charts in a PowerPoint presentation and are asked to extract specific information from the displays. A three (question difficulty) × two (graph type) × two (dimension) × two (colour) repeated measures ANOVA is conducted for both accuracy and reaction time.

Findings – Overall, 2D graphs led to better comprehension, particularly when complex information was presented. Accuracy was similar for colour and black and white graphs.

Practical implications – These results suggest that 2D graphs are preferable to 3D graphs, particularly when the task requires that the reader extract complex information.

Originality/value – For the past several decades, diagrams have been valuable additions to textual explanations in textbooks and in the classroom to teach various concepts. With an increase in technological advancements, many authors add extraneous features to their graphs to make them more aesthetically pleasing. This paper has shown, however, that 3D rendering may negatively affect graph comprehension.

Keywords Presentation graphics, Information retrieval

Paper type Research paper

Introduction

Technology has become increasingly embedded in many learning environments and, as a result, has changed the learning space considerably. The recent increase in technological learning tools has reshaped the processes and tools that educators use to teach both simple and multifaceted concepts (Hartman *et al.*, 2007). As a result of increased use of technology, software-designed visualizations are commonly used to enhance the instructional media in educational settings. For the past several decades, diagrams and graphs have been valuable additions to textual explanations in textbooks and in the classroom to teach concepts in mathematics, science, and history (Carpenter and Shah, 1998; Spence and Krizel, 1994). Research has suggested that diagrams decrease the number of cognitive processes needed to solve complex problems, in turn decreasing the time necessary to solve and understand the problem at hand (Tairab and Khalaf, 2004). Thus, using diagrams in educational settings increases both understanding and memory of taught materials (Mayer and Massa, 2003).

Technological advancements provide designers and educators with a wide variety of tools to enhance their visual displays. Software programs have made the addition of extraneous information easy and, as a result, more common. For example, with commercially available software programs, the addition of 3D perspectives to

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visualizations has become increasingly common due to ease of design (Shelley *et al.*, 2008). Although the addition of extraneous information may make a display visually appealing, research suggests, however, that this information may hinder comprehension (Fischer, 2000; Zacks *et al.*, 1998).

3D renderings have been described as the latest evolution in graphics technology and can create a more realistic environment in terms of simulation activities, as seen in driving and flight simulators (Shelley *et al.*, 2008); however, there is a tendency to arbitrarily render images in 3D solely for aesthetic purposes (Tufte, 2006). Although 3D rendering may be beneficial for simulations, research has suggested that such renderings may hinder the comprehension of visual displays, such as graphs, that are intended to communicate specific mathematical and proportional information (Zacks *et al.*, 1998). In addition to 3D formats, colour enhanced visual materials have also become easier and much less expensive to produce electronically (Shah and Freedman, 2003). For example, the default setting for graphical displays in both PowerPoint and Excel is a 3D colour graph (Shelley *et al.*, 2008) but research focusing on the effects of colour is mixed. Although Tufte (1983) argued that chart junk, including redundant colour information, distracts attention from the primary information in visual displays, Kossylyn (1994) suggested that the inclusion of colour reduces the number of eye movements necessary to compare the elements in visual displays. Given the ease with which extraneous information can be added to visual displays, it is important to clarify when this information is and is not effective in enhancing comprehension. Gaining a better understanding of the features that enhance comprehension of visual displays will enable better designs that maximize readability.

Theories of graph perception and cognition

Empirical theories of graph comprehension can be categorized as focusing on bottom-up and top-down processing. Bottom-up processing involves the perception of simple graph elements (Cleveland and McGill, 1984) and top-down processing focuses on cognitive factors, including the role of short-term memory and graph reading experience (Kosslyn, 1994; Pinker, 1990). According to graph cognition researchers, comprehension involves decoding the visual patterns, determining the relationship between the patterns and the quantitative information they represent, and associating the referents of the concepts to the functions (Carpenter and Shah, 1998). Therefore, graph interpretation is the result of the complex interaction between the top-down and bottom-up processes.

Pinker (1990) suggested that the process of graphical cognition involves two processes: the formation of a visual description and the subsequent formulation of a graph schema. The graph schema is an overall framework for graph reading that develops from prior knowledge and experience with graphs. In the initial stages of graphical analysis, information in the graph is analyzed by the visual system and, during these initial stages, all visual stimuli are processed similarly. In the subsequent stages of visual cognition, the graph reader must construct a "structural description" of the graph wherein the graph elements and their interrelationships are identified, and the graph schema is activated. When the graph schema is activated, the reader draws on his or her graphical knowledge to select an appropriate interpretation of the display (Pinker, 1990).

Trickett and Trafton (2004) incorporated both perceptual and cognitive theories to identify several different tasks required of a graph reader. They argued that these tasks involve either perceptual or spatial processing. Perceptual processing involves making direct or explicit comparisons of graph elements and requires simply reading values directly from the graph (for example, is Bar A higher than Bar B?). If a reader is asked to compare points that are separated by other elements or asked to compare between different graphs, a more complex strategy, involving the spatial transformation of graphed elements, is necessary. This task involves spatial processing because the reader must mentally manipulate graph elements in order to make comparisons among elements.

Extraneous information and graph readability

Graphic designers are able to render a graph easily in either 2D or 3D. In some instances, a 3D graph contains information about three different variables thereby making the addition of depth information necessary to convey the intended meaning. For example, a scatterplot that depicts three different variables must be presented in 3D to fully express the data. However, in many instances, the addition of a third dimension is purely aesthetic and does not convey meaningful information about the variables (Zacks *et al.*, 1998). Zacks *et al.* examined the effect of dimensionality on the accuracy of height judgments and memory for bar graphs. In a preliminary study, they compared the effect that extraneous depth information and neighbouring graphical elements had on height estimation. A follow-up study examined if the effects observed in the first study were maintained in memory. The results from these studies indicated that the addition of any extraneous information lowered accuracy.

Does the use of colour in a graphical display increase comprehensibility as well as visual appeal? Colour can reduce the number of eye movements necessary to extract relevant information. For example, when a graph contains multiple variables, using colour can reduce cognitive load by allowing the reader to easily discriminate between different variables. Cleveland and McGill (1984, 1985) examined the effect of colour on size judgements of geographic regions and found that certain highly saturated colours may cause overestimations of size. Benbasat and Dexter (1985) further examined the influence of colour and information system (e.g. table or line graph) on decision making. Their results indicated that responses were made more quickly and accurately when multi-colour graphs were presented. Thus, based on the available research on colour graphs, how the addition of colour influences comprehension is not clear.

Tufte (1983, 2006) argued that, although extraneous information is added to make displays more interesting, these features can be distracting and often do not convey meaningful information. To date, there is little research focusing on the comprehension of visual displays that contain extraneous features. Given that scientific diagrams are both beneficial and common, the inclusion of extraneous information in visual displays needs further investigation.

Methods

Given the trend toward aesthetically enhancing diagrams, the ease with which extraneous features can be added and the reliance on diagrams in educational settings, it is important to empirically determine if extraneous information influences the comprehension of multifaceted concepts (Shah and Freedman, 2003). As such, the overall goal of this study was to determine if particular aesthetic features that are commonly used in electronic software programs provide any benefit to the comprehension of graphical displays. An additional goal was to provide researchers and educators with a more comprehensive understanding of the components which increase the effectiveness of visual displays.

Participants

A total of 22 participants, 11 male and 11 female, participated in the study. The overall mean age of participants was 23.0 years (female $M = 25.5$ years; male $M = 21.0$ years). Most participants had not taken any previous statistics classes (on average, participants had completed 0.4 classes).

Procedure

After being briefly introduced to the experimental procedure, participants were seated at a computer and told to work at their own pace to complete the questions presented. Both bar graphs and pie charts were presented on the screen in Microsoft PowerPoint. Each of the graphs was presented in either 2D or 3D and in colour or black and white. A total of 16 graphs were presented three times and each presentation was paired with a question that varied in difficulty. The simplest type of question was a read-off task, which required the identification of an individual value. The intermediate level of question difficulty was a spatial transformation task, which required the person to integrate two or more variables. The most difficult type of question required the reader to interpret the data or predict a trend. Additional questions to determine which graphs the participants preferred and which graphs they thought were more scientific were included at the end of the test. In total, participants were presented with 48 graphs. Reaction times were determined by time, in seconds, spent on each question as recorded by Microsoft PowerPoint.

Results

A three (question difficulty) × two (graph type) × two (colour) × two (dimension) repeated measures ANOVA was performed to determine how comprehension and reaction time were affected by the addition of colour and dimension. Graph comprehension was defined as the number of questions that were answered correctly for each type of graph comprehension question. For ease of interpretation, the scores were converted to percentages. Reaction time was defined as the number of seconds taken to answer each question.

Graph comprehension accuracy

There were statistically significant main effects for graph type ($F(1, 20) = 16.37$, $p < 0.0001$, $\eta^2 = 0.46$), dimensionality ($F(1, 20) = 36.20$, $p < 0.05$, $\eta^2 = 0.64$), and question type ($F(2, 40) = 13.38$, $p < 0.05$, $\eta^2 = 0.40$). Mean (M) accuracy was higher when pie charts were presented ($M = 86.1$ per cent as compared to $M = 76.7$ per cent when bar charts were presented). As expected, accuracy was higher for 2D graphs ($M = 86.3$ per cent, standard error of the mean – SEM = 2.1 per cent) than for 3D graphs ($M = 76.64$ per cent, SEM = 2.5 per cent). These findings confirm previous research (Fischer, 2000; Zacks *et al.*, 1998) that suggests that accuracy is lower when 3D graphs are presented. Accuracy was highest for read-off questions ($M = 89.8$ per cent, SEM = 1.0 per cent). The spatial transformation questions (intermediate level of difficulty) were more difficult with a mean accuracy of 85.3 per cent (SEM = 3.0 per cent). Accuracy was lowest on the most difficult questions that required participants to predict future trends and interpret the overall meaning of the graph ($M = 69.2$ per cent, SEM $= 4.6$ per cent). Further *post hoc* tests on question type indicated that accuracy was higher on easy and intermediate questions and was significantly lower on difficult questions.

Interestingly, the main effect of colour was not statistically significant ($F(1, 20) = 3.02$, $p > 0.05$, $\eta^2 = 0.131$). Overall, average accuracy was 79.7 per cent (SEM $= 2.6$ per cent) when colour graphs were presented and 83.1 per cent (SEM $= 2.0$ per cent) when black and white graphs were presented.

There was a statistically significant interaction between graph type and dimensionality, $F(1, 20) = 7.74$, $p < 0.05$, $\eta^2 = 0.28$. As can be seen in Figure 1, accuracy for both graph types was significantly lower when presented in 3D. This effect was most pronounced when bar graphs were used; accuracy was significantly higher when the graph was presented in 2D ($M = 83.7$ per cent, SEM $= 2.3$ per cent) and was lower when the same graph was presented in 3D ($M = 69.6$ per cent, SEM $= 3.1$ per cent). When pie charts were used the overall accuracy was 89 per cent (SEM $= 2.4$ per cent) for 2D pie charts and 83.5 per cent (SEM $= 2.9$ per cent) for 3D pie charts.

There was also a statistically significant interaction found between dimensionality and question difficulty, $F(2, 40) = 6.75$, $p < 0.05$, $\eta^2 = 0.25$ (Figure 2). *Post hoc* tests

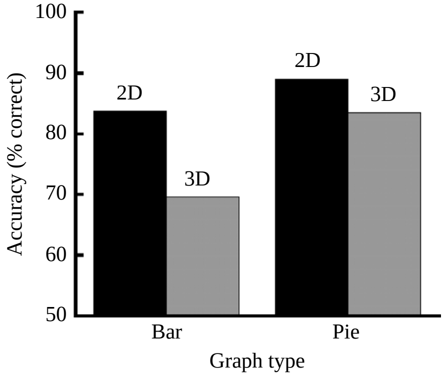

Figure 1.
The effects of graph type and dimensionality on comprehension

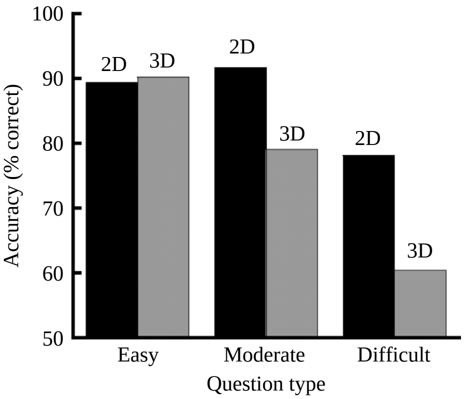

Figure 2.
Levels of graph comprehension for 2D/3D graphs

revealed that on read-off questions, accuracy was similar for 2D and 3D graphs and, participants could accurately answer these questions regardless of whether they were presented in 2D ($M = 89.3$ per cent) or 3D ($M = 90.2$ per cent) graph. On questions requiring a spatial transformation, there was a statistically significant difference that depended upon whether the graph was 2D ($M = 91.6$ per cent) or 3D ($M = 79.0$ per cent). Finally, on interpretation questions, participants had higher accuracy when they were presented with 2D graphs ($M = 78.1$ per cent) and lower accuracy when 3D graphs ($M = 60.4$ per cent) were presented.

There was a statistically significant three-way interaction between graph type, dimensionality, and question difficulty, $F(2, 40) = 3.326, p < 0.05, \eta^2 = 0.143$. As can be seen in Figure 3, for bar graphs, accuracy on easy questions was similar regardless of whether a 2D or 3D graph was presented but accuracy on moderate and difficult questions was significantly lower when 3D graphs were presented. When presented with pie charts, accuracy on easy and moderate difficulty questions was similar regardless of whether the graph was 2D or 3D. When difficult questions were presented, accuracy was significantly lower when the graph was 3D.

Reaction time differences

To determine if participants spent more time analyzing pie or bar charts, the reaction time of participants was also examined using a three (question difficulty) × two (graph type) × two (dimension) × two (color) repeated measures ANOVA. There were statistically significant main effects for question type ($F(2, 40) = 60.01, p < 0.0001, \eta^2 = 0.75$), graph type ($F(1, 20) = 6.66, p < 0.05, \eta^2 = 0.25$), dimension ($F(1, 20) = 8.33, p < 0.05, \eta^2 = 0.29$), and colour ($F(1, 20) = 12.89, p < 0.05, \eta^2 = 0.40$). As was expected, participants had significantly lower reaction times when they were required to answer read-off questions ($M = 33.68$ seconds, SEM = 2.38 seconds) and spent more time answering spatial transformation ($M = 49.93$ seconds, SEM = 4.04 seconds) and interpretation questions ($M = 62.79$ seconds, SEM = 5.07 seconds). Overall, reaction time was lower when bar graphs were presented ($M = 47.1$ seconds, SEM = 3.61 seconds) and higher for pie charts ($M = 50.5$ seconds, SEM = 3.86 seconds). Thus, although accuracy was higher for pie charts this could be because participants spent more time reading the pie charts and dedicated less time to reading bar charts.

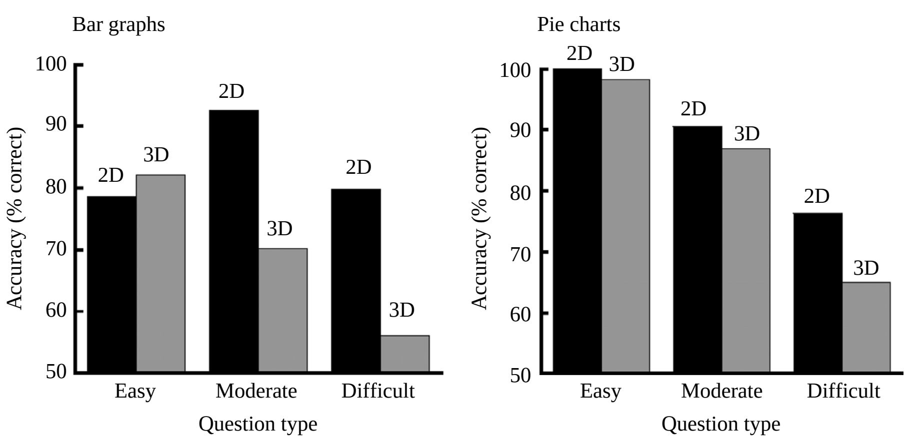

Figure 3.
Effects of dimension, question type, and graph type on comprehension

As expected, reaction time was highest for 3D graphs ($M = 50.9$ seconds, SEM $= 3.63$ seconds) and was lowest for 2D graphs ($M = 46.7$ seconds, SEM $= 3.86$ seconds). Thus, participants spent more time reading 3D graphs and their accuracy for these types of graphs was lower which suggests that the addition of a third dimension makes a graph more difficult to read and interpret. Reaction time for colour graphs was higher ($M = 50.85$ seconds, SEM $= 3.49$ seconds) and decreased when black and white graphs ($M = 46.74$ seconds, SEM $= 3.86$ seconds) were used.

There was a statistically significant interaction between graph type and dimensionality, $F(1, 20) = 18.19$, $p < 0.0001$, $\eta^2 = 0.476$. When bar graphs were presented, the differences in reaction time for 2D graphs ($M = 47.63$ seconds, SEM $= 3.76$ seconds) and 3D graphs ($M = 46.62$ seconds, SEM $= 3.57$ seconds) were not significantly different. However, when pie charts were presented there were statistically significant differences between 2D pie charts ($M = 45.85$ seconds, SEM $= 4.14$ seconds) and 3D pie charts ($M = 55.10$ seconds, SEM $= 3.92$ seconds).

The interaction between dimensionality and difficulty was also statistically significant, $F(2, 40) = 7.98$, $p < 0.001$, $\eta^2 = 0.285$. As can be seen in Figure 4, when participants had to answer read-off questions, reaction time was similar regardless of whether the graph was 2D or 3D. When questions were moderate or difficult, reaction time was significantly lower when 2D graphs were used.

Discussion

The hypothesis that 3D-rendered graphs would interfere with graph comprehension was supported. The presence of different levels of graph comprehension difficulty was also supported. From these theoretical assumptions, it follows that levels of comprehension should be affected differently by extraneous information. This is, in fact, what we found for 3D graphs, in which the effects of accuracy and reaction time were particularly evident on the more difficult graph comprehension questions. These results support previous research findings by Cleveland and McGill (1984, 1985) and Rangecroft (2003). Since the most difficult questions require conceptual understanding of implicit information, these results indicate that participants had difficulty understanding the overall concepts represented by 3D graphs. Overall, the results of

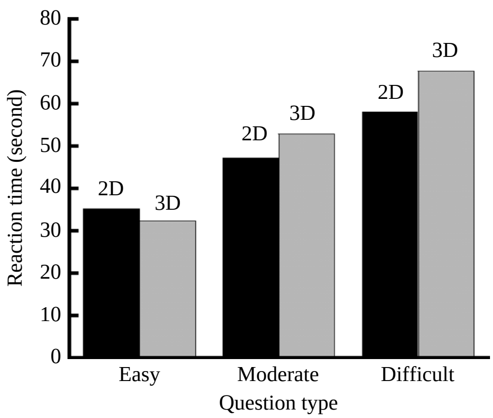

Figure 4.
Effects of question type and dimensionality on reaction time

this study indicate that the addition of 3D perspectives to graphs depicting two variables affects accuracy and reaction time negatively. Thus, 3D graphs may not be effective when the reader is required to extract the overall meaning of graphed information.

Kosslyn (1994) stated that colour could lead to higher graph reading accuracy if added carefully and in a way that is meaningful; however, the results reported here have not established a conclusive role for colour enhancements in graphical displays. In the current study, graph comprehension accuracy was similar for colour and black and white graphs. At first glance, this does not support the hypothesis that colour will enhance the readability of a display. However, it is possible that all of the graphs used in this study contained enough colour information (different hues to indicate distinguish between the variables) to allow the reader to discriminate between the variables equally. Future studies examining the effects of colour information on comprehension should focus on the interactions between such variables (Cleveland and McGill, 1984).

It is possible that the addition of colour may be inconsequential for graph comprehension but may affect the initial perception of the graph. Preliminary physiological results using event-related potentials suggested that participants respond more quickly to graphs with colour information. Furthermore, these differences were more pronounced in posterior sites, which are known to be involved in elementary perceptual tasks (Stewart, 2007). Previous researchers have focused on graph perception (Cleveland and McGill, 1984, 1985), rather than graph comprehension (Trickett and Trafton, 2004). It is possible that these processes are differentially affected by the addition of colour. Further research focusing specifically on comprehension is necessary to conclusively determine the affect of colour.

Trafton and Trickett (2004) and Hunter *et al.* (2007) all suggested that there are three different types of reading skills: read-off; spatial transformation; and interpretation/prediction. The results of this study further support the idea that there are different graph reading skills and the addition of features, such as dimensionality, can affect each of these skills differently. Easy questions were not significantly affected by dimensionality, however, difficult questions were. Performance on questions that involved simple extraction of information directly from the graph showed higher accuracy and lower reaction times. Questions that required spatial transformation, on the other hand, showed lower accuracy and higher reaction time. When required to interpret the overall meaning of a set of graphed data, there were further accuracy decreases and reaction time increases.

Several questions were included to examine which types of graphs the participants found easiest to read, which graphs they preferred reading, and which graphs were most likely to appear in a scientific journal. When asked about their bar graph preferences, 95 per cent of participants reported that the 2D graphs were easiest to read. In spite of this, 71 per cent reported that the 3D colour graph looked the best and 62 per cent reported that this graph would most likely appear in a scientific journal. Preferences were similar when participants were asked about what types of pie charts they preferred. Overall, 90 per cent thought that a 2D pie chart was easier to read but approximately 72 per cent reported that a 3D pie chart would be more likely to appear in a scientific journal.

General conclusions

Given that there has been an increase in the use of 3D rendering and colour in educational materials, further research should focus on how to use them optimally. With an increase in technological advancements many authors add 3D perspectives and colour to their graphs to make them more aesthetically pleasing. This study has shown, however, that both of these additions affect graph comprehension and increase reaction time. The current results strongly suggest that 3D rendering not intended to carry meaningful information interferes with students' comprehension of graphical displays, particularly for difficult information. Although accuracy was similar for colour and black and white graphs, there were reaction time differences that should be further explored. Finally, although students preferred 3D colour graphs, as this study demonstrated, this preference does not necessarily translate into improved comprehension. Given these findings, it is important for educators and software designers to focus on both aesthetic characteristics and the message that they want to convey.

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