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Improving Decision Making Skill Using an Online Volcanic Crisis Simulation: Impact of Data Presentation Format

Elizabeth J. Barclay,[1] Carl E. Renshaw,[1,a)] Holly A. Taylor,[2] and A. Reyan Bilge[2]

ABSTRACT

Creating effective computer-based learning exercises requires an understanding of optimal user interface designs for improving higher order cognitive skills. Using an online volcanic crisis simulation previously shown to improve decision making skill, we find that a user interface using a graphical presentation of the volcano monitoring data reduces the effectiveness of the exercise compared to an informationally equivalent text-based data presentation format. Results are consistent with earlier work demonstrating that the over-automation of quantitative analyses in computer-based learning reduces their effectiveness in improving higher order skills. Additional research is critically needed to clarify the conditions under which user interfaces can be optimized for ease of use while not sacrificing the exercises' effectiveness in improving higher order cognitive skills. © *2011 National Association of Geoscience Teachers*. [DOI: 10.5408/1.3543933]

INTRODUCTION

Designing effective computer aided instruction (CAI) exercises (i.e., those that improve critical thinking skills) requires the delineation of specific instructional methodologies and user interfaces that positively impact higher order cognition. Much of the existing emphasis on computer user interface design is on increasing the "usability" of software—a concept that emphasizes the ease of learning, efficiency of use, as well as user satisfaction (Butler, 1996; Green and Payne, 1984; Hornbaek, 2006; Nielsen, 1994; Rubens *et al.*, 2005). An important question that arises, however, is to what extent minimizing learning effort and speeding up performance is compatible with the objectives of educational CAI software that is meant to engage the user and to effectively convey the desired concepts (Ormrod, 1995). For example, in previous work (Renshaw *et al.*, 2000) we have shown that while automating quantitative analyses in a CAI exercise reduces completion time, it also reduces its educational effectiveness; the exercise more effectively improves student mastery of the complex task of dimensional analysis when they perform the underlying algebraic analyses themselves rather than having the computer do the algebraic analyses automatically. These results indicate that students need to fully understand the underlying analyses before the core conceptual ideas become clear, an idea known as "scaffolding," referring to the idea that students build new knowledge upon existing knowledge (Brown *et al.*, 1989). However, the appropriate level of automation is population dependent. Automating basic algebraic tasks for students proficient in these skills may decrease learning time without a corresponding loss of effectiveness (Renshaw *et al.*, 1998).

The idea that less automation leads to greater learning is consistent with previous work showing that user interfaces optimized for ease of use and minimal cognitive effort are not always effective for learning purposes (Svendsen, 1991; Trudel and Payne, 1995). These studies suggest that the more mental effort exerted in understanding a concept, the better it is learned (Ormrod, 1995; Salomon, 1979). This conclusion is consistent with the cognitive theory of generative learning and supporting studies that find greater learning is achieved when knowledge is actively generated using, at least in part, existing knowledge (e.g., Slamecka and Graf, 1978; Wills *et al.*, 2000; Wittrock, 1989).

However, the conclusion that greater mental effort results in better learning does not necessarily hold with respect to the graphical representation of data. For example, we have shown that students trained using CAI to interpret three-dimensional data using color-coded maps have greater understanding of the underlying data than those trained to use traditional monochrome contour maps requiring greater mental effort to interpret (Taylor *et al.*, 2004). These results suggest that effective graphical presentation of data may facilitate its interpretation while decreasing cognitive effort.

From the CAI user interface design perspective, the automation of algebraic tasks and the presentation of data in graphical form are similar in that both reduce the time required to complete the exercise and hence increase software usability. However, from a cognitive perspective, algebraic manipulations and the interpretation of graphical data require different cognitive resources. Thus, it is not surprising that their incorporation into CAI software differentially impacts an exercise's effectiveness in improving higher order cognition. In one case, increasing usability by automating algebraic analyses *reduced* student learning, but in another case increasing usability by enhancing the graphical representation of data *increased* student understanding. These results highlight a critical uncertainty in the optimal CAI software design: it is essential that we understand how different approaches to enhancing usability impact the software's effectiveness in improving higher order cognition.

Here we investigate the optimal user interface design for presenting scalar data in an online CAI interactive simulation of a volcanic hazard designed to improve decision-making skill. As appears to be the case for three-dimensional (e.g., spatial) data, it may be that presenting scalar data graphically enhances student understanding of the data and thus

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[1] Department of Earth Sciences, Dartmouth College, Hanover, New Hampshire 03755-3571, USA

[2] Department of Psychology, Tufts University, Medford, Massachusetts 02155, USA

[a)] Author to whom correspondence should be addressed. Electronic mail: Carl.Renshaw@dartmouth.edu. Telephone: 603-646-3365. FAX: 603-646-3922.

improves the exercise's impact on higher order skills. Alternatively, the greater cognitive effort required to interpret scalar data presented in a simple text-based format may promote a fuller understanding of the data, leading to better learning and greater impact on higher order cognition.

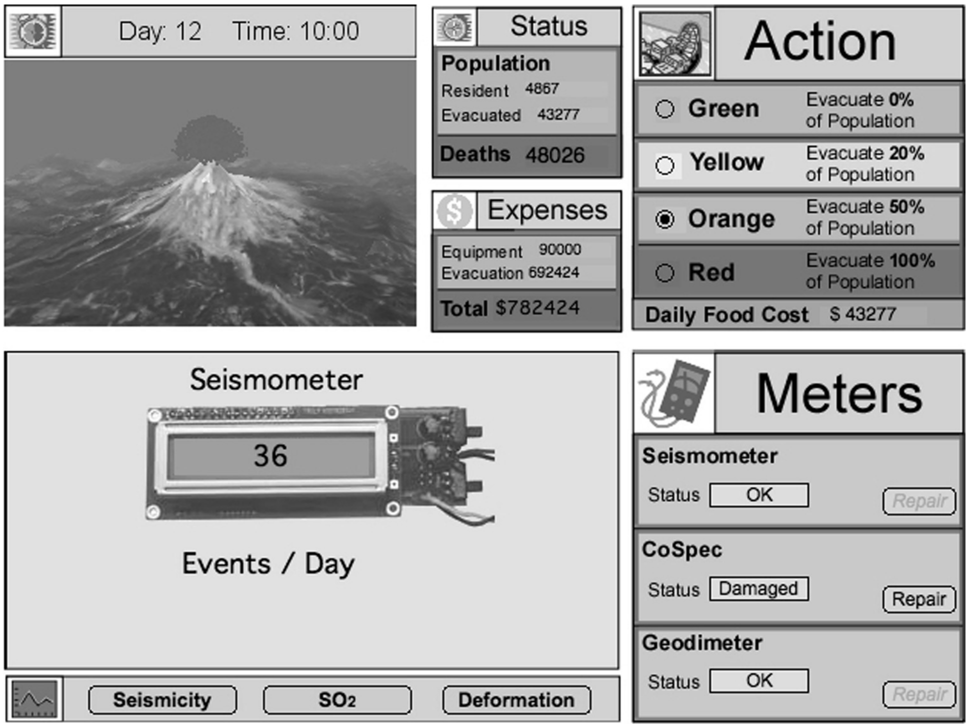
The online CAI simulation used here previously has been shown to improve decision making skill (Taylor *et al.*, 1997). Below we give an overview of the simulation and review the methodology used to assess its impact on student decision-making skill. We then describe how the data presentation format in the simulation was modified. The impact of the different data presentation formats in the simulation on student decision-making skill was then assessed using the same methodology used previously and the results compared to determine the impact of data presentation format on the CAI simulation's effectiveness in improving decision making.

BACKGROUND

Eruption

In the CAI laboratory *Eruption*, students take on the role of a volcanologist who must purchase equipment, interpret scalar data (instrument readings), and decide whether a village should be evacuated (Fig. 1). *Eruption* was originally developed by volcanologists at the State University of New York at Buffalo (Sheridan *et al.*, 1993). As part of the work presented here, the *Eruption* code was updated and ported to a web-based format now freely available at http://www.dartmouth.edu/~earthsci/eruption. The fundamental design objective of the simulation is to require students to use scientific data in decision making. In the role of a volcanologist, students obtain information from three instruments commonly used to monitor volcanoes: a geodimeter, a correlation spectrometer (cospec), and a seismometer. The geodimeter provides information about ground deformation; the cospec about gas emissions; and the seismometer about earthquake frequency. In the simulation, as in reality, information from these instruments is imperfectly correlated with volcanic eruptions, making instrument readings related to different probability estimates of eruption. The correlations between instrument readings and eruption probability can be framed either positively or negatively based on how the outcome is described. For example, a cospec reading of 400 tons SO_2/day can be associated with a 60% chance of eruption (a negative framing because an eruption is a negative outcome) or a 40% chance that the volcano remains dormant (a positive framing because continued dormancy is a positive outcome).

Prior to using *Eruption*, students determine the correlation between instrument readings and volcanic activity by analyzing a previous period of volcanic unrest. The volcanic activity in the simulation itself and that presented for the previous period of unrest is synthesized based on documented sequences from various volcanoes around the world. Students see the synthesized volcanic activity for the previous period of volcanic unrest summarized in a table comparing instruments readings to observations of volcanic activity taken every 12 h for a 25 day period. Volcanic activity is consistently framed either positively (e.g., the volcano did or did not remain "dormant") or negatively (e.g., the volcano did or did not "erupt"). From these data, students develop a correlation table for each instrument, with each table classifying the specific instrument's readings into three ranges representing low, intermediate, and high readings (e.g., cospec readings of <400 tons SO_2/day, 400–750 tons/day, and >750 tons/day, respectively). For each range of readings, students calculate the probability, based on the historical record, that the volcano remains dormant over the next 12 h if the data are



Day: 12 Time: 10:00

Status
Population
Resident 4867
Evacuated 43277
Deaths 48026

Expenses
Equipment 90000
Evacuation 692424
Total $782424

○ Green Evacuate 0% of Population
○ Yellow Evacuate 20% of Population
● Orange Evacuate 50% of Population
○ Red Evacuate 100% of Population
Daily Food Cost $ 43277

Seismometer
36
Events / Day

Seismometer
Status OK
CoSpec
Status Damaged
Geodimeter
Status OK

FIGURE 1: Text-based version of the *Eruption* simulation.

positively framed, or the probability that the volcano erupts over the next 12 h if the data are negatively framed. We refer to the framing of the correlation tables as the "*Eruption* framing," i.e., the framing of the exercise, to distinguish it from the "volcanic hazard scenario framing," described below, that is used to measure decision-making skill.

Assessing Decision Making Skill

The educational objectives of *Eruption* are to serve as a vehicle for introducing various techniques used to monitor volcanic hazards and to improve student decision-making skill. Here we focus on the later objective and begin by reviewing the methodology for assessing decision-making skill.

When making decisions, people grant differential importance to available information. Various factors, including how the information is presented, can influence this weighting. A phenomenon known as the "framing effect" illustrates the influence of context on decisions (e.g., Tversky and Kahneman, 1982). For example, framing a medical decision either in terms of survival or mortality affects the choice between two procedures (McNeil *et al*., 1982), even when the alternate frame can be determined. Thus the likelihood of an individual agreeing to undergo a risky operation differs depending on whether they are told that they have a 95% chance of surviving the operation (positive framing) versus a 5% chance that they will die (negative framing) (Tversky and Kahneman, 1982). The inconsistency in decision making due to framing is a robust effect observed across a variety of contexts ranging from medicine (McNeil *et al*., 1982) to law (McCaffery *et al*., 1995) to finance (Tversky and Kahneman, 1986) to environmental hazards (Taylor *et al*., 1997) and across different populations including different ages and levels of education (Taylor *et al*., 1997; Tversky and Kahneman, 1986) and nationalities (McNeil *et al*., 1982). Only when the alternate framework is specifically presented does the discrepancy in decision behavior disappear (Jou *et al*., 1996). Inconsistent and poor decisions arise in part because individuals fail to consider alternate frameworks.

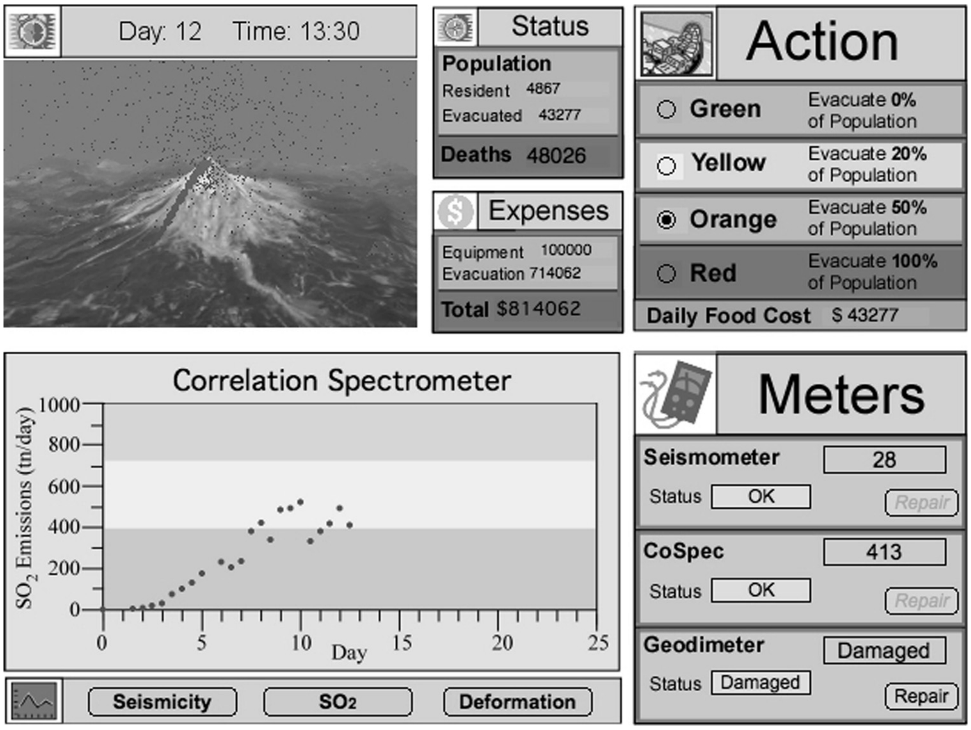
Since the consideration of alternate frameworks is an essential component of good decision making, we argue that a person's sensitivity to framing is one measure of their decision-making skill. We emphasize that this strategy for assessing decision making skill does not require the definition of a "correct" decision, only the assertion that a "good" decision is one that is consistent and independent of the way data have been framed.

In previous work we documented inconsistent decisions due to problem framing in a variety of environmental problems across a spectrum of populations ranging from high school students to geoscience professionals (Taylor *et al*., 1997). Of particular interest here are the framing effects associated with a volcanic hazard problem based on the political policy scenario used by Quattrone and Tversky (1988). We refer to this problem as the "volcanic hazard scenario." The positively framed version of this scenario is:

> Batuna, a small nation on a volcanic island, wishes to improve their ability to predict volcanic eruptions. The nation has one hundred million dollars ($100M) to invest in two prediction systems. A decision on how the $100M will be distributed between two systems must be made. Both systems have been shown to be equally accurate at predicting eruptions.
>
> Field studies indicate that the first prediction system is in working order 91% of the time whereas the second technology is in working order 97% of the time.
>
> How much of the $100M would you spend for each system? The total amount spent on both program should add up to $100M.
>
> The negatively framed version of this scenario is identical except for the second paragraph, which is presented as
>
> Field studies indicate that the first prediction system randomly breaks down 9% of the time, while the second prediction system breaks down 3% of the time.

Taylor *et al*. (1997) showed that undergraduates enrolled in introductory geoscience courses at the State University of New York at Buffalo and Tufts University allocated, on average, twice as much money to the first system when the question was positively framed compared to when the question was negatively framed; the allocation of funds between the two systems was nearly equal in the positive framing, but 3:1 in favor of the more reliable system in the negative framing. Although demographic data were not collected, the students in these classes were drawn from across the institutions and likely are representative of the overall demographics of these schools: nearly all of the participants were likely within a few years of 20 years old, predominantly Caucasian, and more or less equally distributed between genders. As noted above, however, framing effects are robust across demographics and context. For example, Quattrone and Tversky (1988), using a structurally similar problem addressing crime rates given to undergraduates at Standard University and the University of California at Berkeley, also found that the allocation students made between the two alternatives was more even when the question was positively framed. They ascribe this framing effect to what they term the "ratio-difference principle" which states that the perceived impact of any fixed absolute difference between two amounts increases with their ratio. Thus the difference between 3% and 9% (ratio: $9/3=3$) is perceived as greater than the difference between 91% and 97% (ratio: $97/91 \sim 1$), even though the absolute difference (6%) is the same in both cases. Thus the allocation of funds between the two systems is more even in the positive framing (ratio ~ 1) because there is less perceived difference between the two systems than in the negative framing (ratio $= 3$).

To assess the impact of *Eruption* on student decision-making skill, as measured by their sensitivity to framing effects, Taylor *et al*. (1997) gave a questionnaire including the volcanic hazard scenario to 270 high school students from western New York after they completed the *Eruption* exercise. Half of the students used the computer-based version of *Eruption*, half used an informationally equivalent paper-based version. Responses to the volcanic hazard scenario among high school students who used the paper-based version of *Eruption* were similar to those of high school students who had never used either version of *Eruption* in that the



Day: 12 Time: 13:30

Status

Population

Resident 4867

Evacuated 43277

Deaths 48026

Expenses

Equipment 100000

Evacuation 714062

Total $814062

Action

○ **Green** Evacuate **0%** of Population

○ **Yellow** Evacuate **20%** of Population

● **Orange** Evacuate **50%** of Population

○ **Red** Evacuate **100%** of Population

Daily Food Cost $ 43277

Meters

Seismometer 28

Status OK

CoSpec 413

Status OK

Geodimeter Damaged

Status Damaged

FIGURE 2: Graphic-based version of the *Eruption* simulation.

responses of both groups showed a significant framing effect [paper-based users: $F(1, 269) = 14.033$, $MSe = 351.028$, $p < 0.001$]. In contrast, no significant sensitivity to framing of the volcanic hazard scenario was present among those who had used the computer-based *Eruption* [computer-based users: $F(1, 147) = 0.30$, $MSe = 1241.95$, $p = 0.58$]. Unprompted comments among students using the computer-based *Eruption* demonstrate their explicit recognition of the alternative framings during their decision making: many noted that an X% probability of surviving was equal to a (100-X)% probability of dying. Comments of this ilk were not observed with students using the paper-based version.

Modifications to *Eruption*

The central task of students using the *Eruption* exercise is to obtain information from three instruments used to monitor volcanoes and, based on this information, decide to what extent a community threatened by the volcano should be evacuated. Our objective is to determine how the presentation format of the scalar instrument data impacts the exercise's effectiveness in improving decision-making skill.

Accordingly, we explore two different approaches for conveying the instrument readings. In the text–based presentation format version, the current instrument readings appear as numerical values (Fig. 1). The student must compare these values to each instrument's correlation table to determine the likelihood of imminent volcanic activity. In the graphics-based presentation format version, the instrument data appear on a color-coded graph depicting the instrument reading over time (Fig. 2). Shading on the graph divides the instrument readings into three ranges, low, intermediate, and high, corresponding to the correlation table ranges, making it readily apparent to which range each data point belongs. Data labels for both presentation formats are identical, e.g., in both cases seismicity is quantified in units of events per day, etc. Aside from the data presentation format, the two versions of *Eruption* are identical.

METHODS

To assess the relative impact of the two versions of *Eruption* on decision making, 129 undergraduates from Dartmouth College completed the online, web-based *Eruption* exercise and a postexercise questionnaire including the volcanic hazard scenario. The students completed the exercise and questionnaire either as part of a regularly scheduled laboratory associated with an introductory geoscience course or as an optional out-of-class assignment as part of an introductory course on natural hazards. Demographic data were not collected, but as the courses draw students seeking to fulfill their science distribution requirement from across the institution, the demographics of the participants are likely similar to those of the institution as a whole: nearly all of the participants were likely within a few years of 20 years old, predominantly Caucasian, and more or less equally distributed between genders.

The study used a 2 (*Eruption* frame: positive, negative) × 2 (data format: text, graphical) × 2 (volcanic hazard scenario frame: positive, negative) between-participant design. Students were randomly assigned to each condition, either based on lab section (introductory geoscience courses) or individually (optional out-of-class assignment). In all cases, prior to using *Eruption* students received a short lecture introducing the equipment used to monitor volcanic hazards and an explanation of why data from these instruments are related to the volcanic activity. The lecture also included an introduction to *Eruption* and a demonstration of its use.

TABLE I: Means, standard deviations (in parentheses) for amount of money (in millions of dollars) allocated to program A as a function of *Eruption* interface, *Eruption* frame, and volcanic hazard scenario frame. Numbers of students in each condition also provided.

	Graphics-based Interface		Text-based Interface	
Eruption frame	Positive	Negative	Positive	Negative
Positive hazard Frame	27.3 (15.5)	34.5 (22.6)	33.7 (16.3)	25.2 (14.2)
	N = 10	N = 15	N = 24	N = 16
Negative hazard frame	36.1 (20.9)	22.5 (16.9)	29.1 (18.7)	26.8 (12.8)
	N = 14	N = 15	N = 20	N = 15

RESULTS

The analysis consisted of a univariate analysis of variance (ANOVA) using the dollar amount the student allocated to the first prediction system as the dependent variable (see Table I). The data met the assumptions for using a parametric ANOVA. Analyses revealed a significant interaction between Eruption frame, data presentation format, and volcanic hazard scenario frame [$F(1, 121) = 4.52$, $\text{MSe} = 1387.51$, $p < 0.05$]. Follow-up simple effects (Kirk, 1982; Maxwell, 1990; Winer *et al.*, 1991) explored the locus of this interaction by examining interactions between *Eruption* frame and volcanic hazard frame separately for the two data formats. These follow-up analyses revealed no significant interactions for students who used the text-based format [$F(1, 121) = 0.566$, $\text{MSe} = 307.31$, $p > 0.05$] but among the students who used the graphics-based format a significant interaction remained between *Eruption* frame and volcanic hazard frame [$F(1, 121) = 4.622$, $\text{MSe} = 307.31$, $p < 0.01$; see Fig. 3]. Thus the decision making of those students who used the graphics-based version of *Eruption* is less skilled in the volcanic hazard scenario in the sense that their decisions are influenced by the framing of the volcanic hazard scenario whereas the decision making in the volcanic hazard scenario of students who used the text-based presentation format is invariant to the framing of the scenario. This is shown in Fig. 3 which compares the funds allocated to the first (less reliable) system in the volcanic hazard scenario as a function of scenario frame. Among students who used the graphics-based version of *Eruption* [Fig. 3(a)], the funds allocated to the first system is sensitive to the framing of both *Eruption* and the volcanic hazard scenario. In contrast, the allocation of funds to the first system among students who used the text-based version of *Eruption* is not sensitive to either the framing of *Eruption* or the hazard scenario.

DISCUSSION

Factors Impacting Volcanic Hazard Scenario Decisions

The significant interaction between data presentation format, *Eruption* frame, and volcanic hazard scenario frame demonstrates that data presentation format impacts *Eruption*'s success in improving decision making. Indeed, only students who used the text-based data presentation format subsequently made decisions in the hazard scenario invariant to information framing, either of the scenario or *Eruption* itself. As stated previously, this invariance to information format results in better information-based decisions.

In contrast to the responses of students who used the text-based presentation format, responses to the volcanic hazard scenario among students who used the graphics-based format varied as a function of *Eruption* framing. Among this group, participants who used the negatively framed version of *Eruption* (i.e., interpreted instrument readings in terms of probability that the volcano erupts) showed a bias in the allocation of funds between the two systems in the hazard scenario similar to that shown by participants who had never used either version of *Eruption*; both groups allocated funds more equitably between the two systems when the hazard scenario was positively framed (system reliability described in terms of percent of time system is in working order). This bias toward more equitable fund distribution in the positive frame is the same bias observed by Quattrone and Tversky (1988) among undergraduates at Stanford University and the University of California at Berkeley when asked to respond

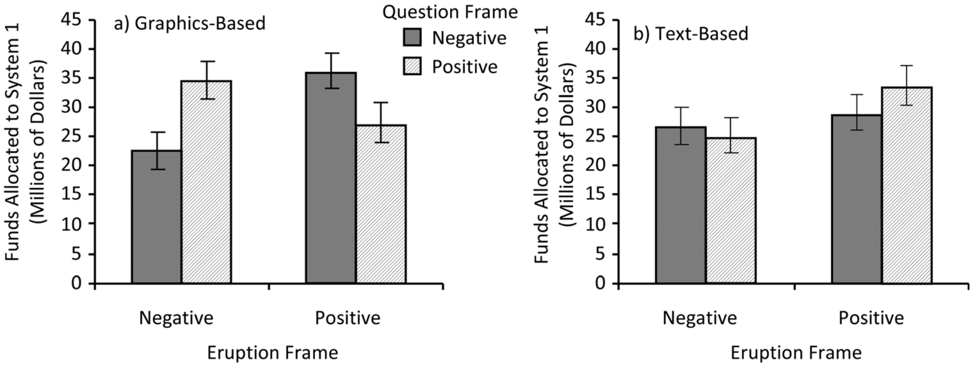


FIGURE 3: Comparison of funds allocated to the first (less reliable) system in the volcanic hazard scenario as a function of *Eruption* frame and scenario (question) frame.

to a structurally similar decision problem addressing crime rates. In both cases the bias may be attributable to the ratio-difference principle that, for problems structurally similar to the volcanic hazard scenario, tends to reduce the perceived difference between the two systems in the positive frame, encouraging a more equitable allocation of funds between the two systems.

Interestingly, the allocation of funds in the volcanic hazard scenario is reversed among those participants who used the positively framed graphics-based version of *Eruption* (i.e., interpreted instrument readings in terms of probability that the volcano remains dormant); they allocated their funds less equitably in the volcanic hazard scenario when it was positively framed. For some reason this group is relatively risk averse, more strongly preferring the more reliable monitoring system (system 2) even when the perceived difference between the two systems is minimized using the ratio-difference principle. We speculate that in framing both *Eruption* and the volcanic hazard scenario positively, the participant may assess the volcanic hazard not in terms of the likelihood of an eruption, but rather in terms of the likelihood that the current status will be maintained (i.e., that the volcano remains dormant). From this perspective, the current status (dormancy) may be viewed as an achieved gain that would be lost if an eruption occurs. It is well established that people have a greater tendency for risk aversion when assessing risk from the perspective of losing an achieved gain (Kahneman and Tversky, 1984). In contrast, participants switching from a positively framed version of *Eruption*, where the focus is on maintaining dormancy, to a negatively framed hazard scenario, where the focus is on the likelihood of an eruption, are forced to switch their perspective from that of maintaining an achieved gain (dormancy) to that of mitigating a loss (an eruption). Just as people have a greater tendency for risk aversion on the domain of gains, they similarly have a tendency for risk seeking in the domain of losses (Kahneman and Tversky, 1984).

Impact of Data Presentation Format

Regardless of the psychophysics underlying their decision making, the impact of the different scalar data presentation formats is clear; students who used the text-based data presentation format of *Eruption* made more skilled decisions in the volcanic hazard scenario in the sense that their decisions were invariant to framing effects. This indicates that the text-based presentation format has a greater impact on the reducing the sensitivity to framing than the graphics-based presentation format.

While both the text-based and graphics-based interfaces were informationally equivalent, the ease of accessing this information was significantly greater in the graphics-based version in at least two respects. First, when a data point is plotted graphically, it's vertical location provides an immediate visual clue as to which range of readings the point belongs to; low, intermediate, or high (Fig. 2). In contrast, users of the text-based interface must compare the numeric value from the instrument to the limiting values in the low, intermediate, and high ranges for that data type in their risk tables. We note that the limiting values between the different ranges are different for each type of instrument. For example, a seismometer reading of 10 (earthquakes per day) corresponds to a relatively low risk of imminent eruption whereas a geodimeter reading of 10 (cm) corresponds to a very high risk of imminent eruption. Second, as the simulation proceeds, the graphics-based presentation format provides easy visual access to previous instrument readings (Fig. 2). This historical information is only available in the text-based version if the participant remembers, writes down, or graphs previous instrument readings. For these reasons we argue that the interpretation of the instrument readings is easier with the graphics-based format. Despite its enhanced usability, the graphics-based data presentation is less effective in improving subsequent decisions.

The greater effectiveness of the text-based presentation format is consistent with previous work demonstrating that user interfaces optimized for ease of use and minimal cognitive effort are not always effective for learning purposes (Svendsen, 1991; Trudel and Payne, 1995) and is consistent with our previous work demonstrating that a computer-based laboratory exercise was more effective when students were required to exert more cognitive effort by performing the underlying algebraic analyses themselves rather than having them done automatically by the computer (Renshaw *et al.*, 2000). However, this conclusion is inconsistent with our other previous findings demonstrating that students trained using CAI to interpret three-dimensional data using color-coded maps have greater understanding of the underlying data than those trained to use traditional monochrome contour maps requiring greater mental effort to interpret (Taylor *et al*., 2004).

Data classification, algebraic manipulations, and the interpretation of spatial data are distinct cognitive activities and thus it is not surprising that enhancing the usability of CAI software by enhancing each of these activities differentially impacts the exercise's effectiveness in improving higher order cognition. From a software design perspective, however, it would be helpful to have some guidelines, which can be generalized, that apply to all these activities and indicate conditions under which software usability can be increased without sacrificing its impact on higher order skills.

Taken together, the results from our CAI investigations indicate that cognitive effort, by itself, is not a sufficient criterion for determining learning effectiveness. We argue that the key consideration in controlling learning effectiveness is not total cognitive effort, but instead how the effort is reduced. Both in *Eruption* and in our quantitative analysis laboratory, cognitive effort was reduced by eliminating essential components of the analysis—the classification of the data into appropriate risk categories and the underlying algebraic components. The hope in both cases was that the resulting laboratory exercise might help participants focus their attention on the core conceptual ideas without the distraction of the quantitative details. Instead, we found that students need to understand the underlying analyses before the core conceptual ideas become clear.

In contrast, the enhancement of three-dimensional maps with color coding, although reducing the cognitive effort required to understand the map, does not *eliminate* the essential step of interpreting the data. Instead, the color-coded maps *assisted* participants in completing an essential task. Color can be a natural quantifier, is intuitively linked to some concepts, and can be easy to learn and remember. This is not to say that color always aids conceptual interpretations; it can sometimes lead to misinterpretations (Tufte, 1990). We conclude that in designing an optimal user interface for computer-assisted learning it is possible the simultaneously reduce cognitive effort and improve learning effectiveness, but only if the design changes assist students in completing essential tasks rather than eliminate the tasks by automation.

This conclusion is consistent with research examining the role of working memory in learning. Working memory is a hypothesized memory system for temporarily managing information used for complex cognitive tasks such as learning, reasoning, and comprehension (Baddeley, 2003). The system has separate processing mechanisms for verbal and visuospatial information, the phonological loop and visuospatial sketchpad, respectively. Assisting participants in completing an essential tasks by providing information in multiple formats maximizes their use of working memory resources, thus appearing to increase the flexibility of a learner's experience and to be particularly effective at freeing up cognitive resources for deeper information processing (Paivio, 1990; Pass *et al.*, 2003; Van Merriënboer *et al.*, 2003). In fact, there is evidence that such partitioning aligns directly with deeper processing in a fairly intuitive way: integrating spatial and verbal information is in and of itself a form of deeper processing (Mayer, 1997; Mayer and Moreno, 2002). This is particularly true when an information type is particularly well suited to an information format, for example spatial data (Brunyé *et al.*, 2008; 2006). In the present study, the graphic presentation of the volcanic instruments appealed only to the visuospatial processes of working memory.

CONCLUSIONS

Among users of the CAI laboratory *Eruption*, there is a significant interaction between data presentation format, *Eruption* framing, and volcanic hazard scenario framing. When separated based on presentation format, the interaction only remains for the graphics-based presentation format, indicating that is has less of an impact on reducing sensitivity to framing effects in decision making than the text-based data presentation format. The graphical data presentation appears to result in a less effective educational exercise, perhaps due to the reduction in cognitive effort required to understand the instrument readings or by engaging only visuospatial working memory processes. However, we suggest that cognitive effort, by itself, is not a sufficient criterion for determining learning effectiveness. Because students need to understand the underlying analyses before the core conceptual ideas become clear, in designing optimal user interfaces for CAI software, efforts to reduce cognitive effort and improve learning effectiveness must focus on design changes that assist students in completing essential tasks rather than eliminating the tasks by automation.

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REFERENCES

Baddeley, A., 2003, Working memory: Looking back and looking forward: Nature - Neuroscience Reviews, v. 4, p. 829–839.

Brown, J.S., Collins, A., and Duguid, P., 1989, Situated cognition and the culture of learning: Educational Researcher, v. 18, p. 32–42.

Brunyé, T.T., Taylor, H.A., and Rapp, D.N., 2008, Can you say that again: Repetition and integration in procedural multimedia learning: Appl. Cognitive Psychology, v. 22, p. 877–895.

Brunyé, T.T., Taylor, H.A., Rapp, D.N., and Spiro, A., 2006, Multimedia presentation of procedures: Influences on memory for structure and content: Appl. Cognitive Psychology, v. 20, p. 917–940.

Butler, K.A., 1996, Usability engineering turns 10: Interactions, v. 3, p. 59–75.

Green, T.R.G., and Payne, S.J., 1984, Organization and learnability in computer languages: Int. J. Man.-Mach. Stud., v. 21, p. 300–311.

Hornbaek, K., 2006, Current practice in measuring usability: Challenges to usability studies and research: Int. J. Hum.-Comput. Stud., v. 64, p. 79–102.

Jou, J., Shanteau, J., and Harris, R.J., 1996, An information processing view of framing effects: The role of causal schemas in decision making: Memory & Cognition, v. 24, p. 1–15.

Kahneman, D., and Tversky, A., 1984, Choices, values, and frames: American Psychologist, v. 39, p. 341–350.

Kirk, R.E., 1982, Experimental design: Procedures for the behavioral sciences: Belmont, CA, Wadsworth.

Maxwell, S.E., 1990, Designing experiments and analyzing data: A model comparison perspective: Belmont, CA, Wadsworth.

Mayer, R.E., 1997, Multimedia learning: Are we asking the right questions?: Educ. Psychologist, v. 32, p. 1–19.

Mayer, R.E., and Moreno, R., 2002, Aids to computer-based multimedia learning: Learning and instruction, v. 12, p. 107–119.

McCaffery, E.J., Kahneman, D.J., and Spitzer, M.L., 1995, Framing the jury: Cognitive perspectives on pain and suffering awards: Virginia Law Review, v. 81, p. 1341–1420.

McNeil, B.J., Pauker, S.G., Sox, H.C., and Tversky, A., 1982, On the elicitation of preferences for alternative therapies: New England Journal of Medicine, v. 306, p. 1259–1262.

Nielsen, J., 1994, Heuristic evaluation, *in* Nielsen, J., and Mack, R.L., eds., Usabilityinspection methods: New York, NY, Wiley.

Ormrod, J.E., 1995, Human learning: Upper Saddle River, NJ, Prentice Hall.

Paivio, A., 1990, Mental representations: New York, NY, Oxford University Press.

Pass, F., Renkl, A., and Sweller, J., 2003, Cognitive load theory and instructional design: Recent developments: Educ. Psychologist, v. 38, p. 1–4.

Quattrone, G.A., and Tversky, A., 1988, Contrasting rational and psychological analyses of political choice.: American Political Science Review, v. 82, p. 719–736.

Renshaw, C.E., Johnson, G.D., and Kvale, K., 2000, A laboratory exercise to determine dinosaur speeds using dimensional analysis: J. Geosci. Educ., v. 48, p. 342–346.

Renshaw, C.E., Taylor, H.A., and Reynolds, C.H., 1998, Impact of computer-assisted instruction in hydrogeology on critical thinking skills: J. Geoscience Education, v. 46, p. 274–279.

Rubens, W., Emans, B., Leinonen, T., Skarmeta, A.G., and Simons, R.-J., 2005, Design of web-based collaborative learning environments. Translating the pedagogical learning principals to human computer interface: Computers & Educ., v. 45, p. 276–294.

Salomon, G., 1979, Interaction of media, congnition, and learning: An exploration of how symbolic forms cultivate mental skills and affect knowledge acquisition: San Francisco, CA, Jossey-Bass Inc.

Sheridan, M.F., Reitan, P., Hodge, D.S., Bursik, M.I., and Fink, J.H., 1993, Eruption!: EOS, Trans. Amer. Geophys. Union, v. 74, p. 82–83.

Slamecka, N.J., and Graf, P., 1978, The generation effect: Delineation of a phenomenon: Journal of Experimental Psychology: Human Learning and Memory, v. 4, p. 592–604.

Svendsen, G.B., 1991, The influence of interface style on problem solving: Int. J. Man.-Mach. Stud., v. 35, p. 379–397.

Taylor, H.A., Renshaw, C.E., and Choi, E., 2004, The effect of multiple formats on understanding complex visual displays: J. Geosci. Educ., v. 52, p. 115–121.

Taylor, H.A., Renshaw, C.E., and Jensen, M.D., 1997, Effects of computer-based role-playing on decision making skills: J. Educational Computing Research, v. 17, p. 147–164.

Trudel, C.-I., and Payne, S.J., 1995, Reflection and goal management in exploratory learning: Int. J. Hum.-Comput. Stud., v. 42, p. 307–339.

Tufte, E.R., 1990, Envisioning information: Cheshire, CT, Graphics.

Tversky, A., and Kahneman, D., 1982, The framing of decisions and the psychology of choice, *in* Hogarth, R., ed., New directions for methodology of social and behavioral science: Question framing and response consistency: San Francisco, CA, Jossey-Bass, p. 3–20.

Tversky, A., and Kahneman, D.J., 1986, Rational choice and the framing of decisions: J. Business, v. 59, p. S251–S278.

Van Merriënboer, J.J.G., Kirschner, P.A., and Kester, L., 2003, Taking the load off a learner's mind: Instructional design for complex learning: Educ. Psychologist, v. 38, p. 5–13.

Wills, T.W., Soraci, S.A., Chechile, R.A., and Taylor, H.A., 2000, "Aha" effects in the generation of pictures: Memory & Cognition, v. 28, p. 939–948.

Winer, B.J., Brown, D.R., and Michels, K.M., 1991, Statistical principles in research design: New York, McGraw-Hill.

Wittrock, M.C., 1989, Generative processes of comprehension: Educational Psychologist, v. 24, p. 345–376.