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Visualizations for Science Education: A Baseline View

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Abstract

This STAR report aims to report on the scholarship around visualizations for science education. The discussion in this report differs as compared to other STAR reports in that it references concepts and themes that are not necessarily considered the most recent published, but otherwise considered foundational research in the community. This report aims to set a baseline of discussion for which future STAR reports on this topic can build on.

1. Introduction

The European Association of Computer Graphics has a long tradition of the concept of a State-of-the-Art (STARs) "report" submission as part of their Euro graphics conference on computer graphics [1]. A STAR report is a comprehensive overview of the up-to-date re-search on a computer graphic topic of interest. These reports can vary in topics (e.g., spatial mapping, volume rendering, etc.) around issues relating to visualization techniques, methods, etc. in a number of different domains.

Visualizations for science education have a long research history in the fields of Human Computer Interaction (HCI) and Learning Sciences but not in the Information Visualization (InfoVis) community. Why has the community not taken up this discussion? While these types of visualizations are at many times representation-ally simpler, their conceptual framing and visual encoding can be just as complex as visualizations reported on in current InfoVis research.

I will look at four topics with in this area of research; 1) Sense making through visualization [2]; 2) External versus internal representations [3]; 3) Knowledge integration through dynamic visualizations [4] and 4) The use of multiple representations in learning contexts [5].

1.1. Sense Making Through Visualization

Climate visualizer [2] is one of the foundational research studies on visualization and science education in the field of learning science. It investigated how students make sense of scientific visualizations within learning activities — especially during analysis and annotation phases. This study is circa 1995 in which the authors used a CD-ROM based tool that allowed high school students to view climate data (Figure 1) coupled with map representations (provided by the National Meteorological Center (NMC)).

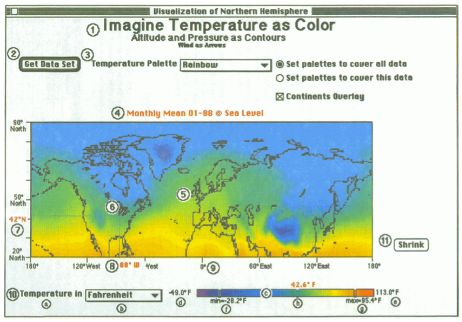

Figure 1: *Climate visualizer interface [2].*

The authors emphasize domain scientists, use the same climate representations in their everyday practice as the students in the study. They also claim that the process of integrating visualizations into science learning activities is the same process in which scientists integrate visualizations in their research. The core of this integration is about sense making around the visualization and about appropriating science practice [2, p. 203].

Gordon et al. make the specific reference to the importance of visual encoding of the representation with a deconstruction. This type of discussion is commonly held in the visualization community:

> First, color is used evocatively to indicate varying magnitudes, where our prior associations with these colors correctly anticipate their use. Second, an abstract quality, namely temperature, is illustrated visually. Third, the spatial distribution of the data is indicated through the use of space in the visualization, thus not requiring separate references to connect temperature values to spatial locations,

> as would be required by tabular data. Fourth, the data have been processed through models achieving an even distribution or gridding of data values. [2, p. 204]

Visual encodings contain sociological attributes of cognition and perception that are common among cultures and that the assemblage of visual elements (e.g., tables, labels, diagrams, etc.) in a scientific visualization is inscribed in the practices of science [2]. These inscriptions are externalized and have a weight or material that becomes a powerful tool within the practice. The impact of this study is that it supports the notion that digital manipulation of scientific visualizations and its integration into learning are key to science learning because they allow students to embody the practice of scientists. This idea of embodiment is one of the corner stones of Human Computer Interaction (HCI). In Paul Dourish's groundbreaking text on embodied interaction, he defines embodiment as "possessing and acting through physical manifestation in the world." [6, p. 100] and says, "Embodied practical action is the source of meaning. We find the world meaningful with respect to the ways in which we act within it." [6, p. 125]. In other words, the modality of physical movement and gesture may be one of our primary sources of meaning making. Where the concept of embodied learning refers to an approach where students or other learners are engaged in physical or tangible interactions with their environment, in isolation or in a social context, in such a way that their movements encapsulate or reflect (i.e., embody) the concepts that are targeted by the instructional design. For example, in embodied astronomy, one student might be asked to walk around another, while simultaneously spinning around, emulating the Earth's movement around the sun [7].

In case of Gordon et al. [2], the embodied action was about manipulating the data digitally on a computer through mouse movement. This manipulation was in a context of a scientific investigated as a student or scientist has an embodied practical action – an action that creates meaning. One of the main points I think the authors make is that these embodied actions have encodings, just like the representation does and that the interplay of visual and embodied encodings create meaning for the student or the scientist within a particular context. The next section will discuss how those encodings are integrated into a form of internal knowledge.

1.2. External Versus Internal Representations

In 1996 Roger and Scaife proposed a new outline of graphical representation research. At the time they stated "We point out, however, that little is known about the cognitive value of any graphical representations, be they good old fashioned (e.g. diagrams) or more advanced (e.g. animations, multimedia, virtual reality)." [3, p. 185]. Furthermore "Our analysis reveals a fragmented and poorly understood account of how graphical representations work, exposing a number of assumptions and fallacies." [3, p. 185]. The authors propose an analytic framework that looks at graphical representation from the point of view of internal and external cognitive representations. This draws upon research from cognitive science research from Norman [8] which defines this as "knowledge in the head" (internal) and "knowledge in the world" (external). Moreover Norman argues:

> Because behavior can be guided by the combination of internal and external knowledge and constraints, people can minimize the amount of material they must learn, as well as the completeness, precision, accuracy, or depth of the learning. [8, p. 163]

Rogers and Scaife (1996) argue that in order to understand how people discriminate elements, visual encodings, and spatial distribution when using graphical representations in learning, problem solving, and inference contexts there needs to be an analytic process that enables this type of research. Using representational types such as images diagrams, animations, and virtual reality the authors synthesized the cognitive literature and abstract three over riding attributes of internal external representations; One, computational offloading or the length at which external representations reduce the amount of cognitive effort in solving information problems such as geometric diagrams; Two, re-representation or the ability for different external representations to make problem solving easier with various forms of abstraction, e.g., reading a clock with Arabic numerals versus Roman numerals; Three, graphical constraining or the length at which graphical representations are able to constraint elements and the mapping between the elements in the representation to the problem or goal the visualizations is trying to solve. For instance, some maps that overlay route in formation might hide other topographical elements that are not relevant to the problem con text.

Within their discourse Rogers and Scaife address the importance of how designers can determine the type (e.g., diagrams, text, multi-media, etc.) of external representation that needs to be used for the task or problem that needs to be solved. The authors summarize some concepts designers of graphical representations should be aware of:

> Diagrams, animations and virtual reality can in their respective ways all make salient certain aspects of a display. A design objective, therefore, should be to facilitate perceptual parsing and inferencing, through directing attention to key components that are useful or essential for different stages of a problem-solving or a learning task. [3, p. 23]

The authors conclude that these different classes of graphical representation align with Norman's ideas of internal and external cognition in which the visualization aids in the concept of "computational offloading" or having embed rules (e.g., tables, graphs, etc.) in the representation that allows the user to free up cognitive space for other tasks. Gordon et al. [2] discuss these same concepts as sociological attributes of the visual encoding.

Before Rogers and Scaife, Ware et al. [9], reported on the notion of "Behavioral Animation" in which data is mapped to a behavioral model, i.e., animating a school of fish swimming. In turn this mapping becomes a visual language in which it expresses the data set, or structure of the visualization to the user. One of the key differences between Ware and Rogers is the discussion of cognition. Ware only goes as far as conceptualizing the tasks and goals users attend to while exploring the structure of the data, e.g., "Abstracting Task. The user seeks to get views of the data at different level of abstraction, e.g. by moving be-tween different level of details or changing the visualization method." [9]. These are lower level activities compare to that of "perceptual processing" which Rogers and Scaife discuss, but still none the less important.

Liu and Stasko [10] addressed the lack of research in the area of internal-external representations within the InfoVis community. They argue that more research around this topic would give InfoVis practitioners more of an understanding in the cognitive actions users perform when interacting with visualizations. To a non-cognitive scientist the idea of an internal representation and its relationship to an external representation could be a bit con-fusing. The authors distilled the work of Rogers et al. and many others into the idea of "Mental Models", which is not a new but distill in a form InfoVis researchers find relevant and useful. Their definition of mental models follow the line of: 1) external systems exhibit structural and behavioral properties which are encoded in mental models; 2) the data has a semantic and schematic properties that are also encoded in mental models; and 3; working memory can be used to reason and simulate interaction in a visualization through a mental model.

The next section will build on these ideas by discussing attributes of dynamic visualizations or animation in science learning contexts.

1.3. The Use of Dynamic Visualizations in Science Education

In more recent work Linn and Ryoo [4] studied how dynamic visualizations make scientific phenomena accessible to middle school learners. They designed a study that compared the use of dynamic and static visualizations in inquiry learning activities investigating phenomena around photosynthesis (Figure 2).

The study randomly assigned two hundred students either the static or dynamic visualization condition. The authors claim in general that both static and dynamic visualizations allow students to integrate abstract ideas of the scientific phenomena into prior knowledge. However, they found evidence that students with the dynamic condition were significantly more successful in articulating the concepts of photosynthesis energy transfer and chemical reaction processes than students with the static condition. In addition, students with the dynamic condition demonstrated a greater ability to link and integrate their knowledge with other concepts around the topic:

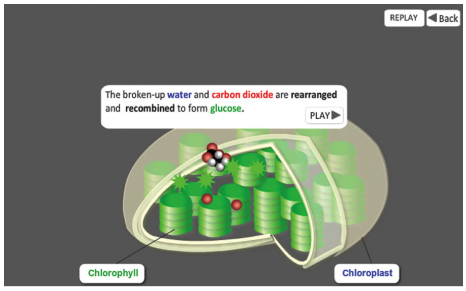

Figure 2: *Dynamic visualization of the photosynthesis process [4].*

> When students can explore how the molecules move and interact with each other during energy transformation in the dynamic version, they gain more insight into energy transformations in photosynthesis and make more connections between energy ideas in photosynthesis than when they navigate between discrete illustrations . . . They have the potential to communicate unobservable events that are difficult to infer from textbook illustrations [4].

Furthermore, they claim that both types of visualizations do not work automatically by themselves; there must be scaffolding and instruction around them. One important aspect they came claim why dynamic visualizations work better than static visualizations is that dynamic visualizations at their core employ the use of coordinated multi-representations simultaneously which help students reference corresponding attributes between different representations [11]. The next section will discuss the use of multiple representations in science visualization

1.4. Multiple Representations

Ainsworth [12] proposes a framework named DeFT for Design, Functions, Tasks that integrates the multiple 'external' representations in learning contexts using learning research. This framework arises from the evidence that multiple representations do not always provide benefits when learning new ideas and concepts. The author states that DeFT has three characteristics that connect to learning contexts; one, the design parameters that are unique to multi-representational learning environments; two, functions that support learning in multi-representational environments; and cognitive tasks that students perform while learning with multiple representations.

Within the work, the author iterates through each characteristic and sub-characteristic in great length discussing how it supports cognitive tasks for learning, however, I believe one of the main points can be simply stated as:

> MERs are designed to allow learners to construct a deeper understanding of a do-main. This goal provides designers with hard choices. If users fail to translate across representations, then abstraction and extension cannot occur. Learners find it difficult to translate over-representations that are superficially dissimilar, but if made too easy, for example, by providing representations that do not provide sufficiently different views on a domain, then abstraction of in-variances does not occur. However, if the system performs all the translation activities for students, then students are not afforded the opportunity to actively construct this knowledge for themselves. [12]

This implies that designers of MERs must be aware of the representational 'fidelity', how abstract or detailed the visualization appears. Fidelity in terms of graphical representations is an interesting topic in which many researchers are investigating. Wilson et al [13] studied the use of flat, 2-dimensional graphics in the WhyVille simulation game, and found that high levels of realism are not necessarily required to promote deep learning. Finally, Son and Goldstone [14] investigated the fidelity of computer graphics in helping students learn the principle of competitive specialization. They studied intuitive descriptions, and com-pared them with idealized graphical versions as well as concrete graphical versions. The finding was that idealized graphics led to better conceptual understanding and transfer.

1.5. Conclusion

The crux of this literature is about integrating human cognition and human perception with visual representations. While the papers used within this report are not the most current as far as publication date, they are current as far the topic. This is a small representative sample. A number of the papers cited within this report come from the learning sciences be-cause its scholarship is grounded in the domains of human cognition, psychology, education, and technology. Liu and Stasko [10] addressed the need for InfoVis scholars to under-stand the interplay of cognitive processes at work when users engage with visualizations. They developed a framework based on the notions of mental models, internal representations, and external representations as a way to make these ideas accessible to InfoVis re-search. This is a great step towards integrating these domains the breath of future research that will come out of it.

1.6. References

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