Teaching Middle School Students to Reason with Visual Representations in Science

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Perspectives and Purpose

As part of the 21st Century Center on Cognition and Science Instruction, we have modified 3 textbooks/modules each from both traditional and inquiry-based middle-school science curricula, using principles regarding reasoning with diagrams and other visual representations. We describe why and how we have modified the 6 curricular units, with the goal of framing the next 4 presentations.

Visual representations such as diagrams, flow charts, tables, photographs, maps, and timelines are ubiquitous in science texts and tests. Science textbooks at the middle school, high school, and undergraduate level typically feature one visual representation per page; about one-half of the items on state, national, and international science assessments include a visual representation. Ample evidence exists that students across all of these age groups have low comprehension of visualizations, whether measured by performance on assessment items (Unsworth & Chan, 2010), think-aloud protocols (Cromley, Snyder-Hogan, & Luciw-Dubas, 2010), eye movement studies (Hannus & Hyona, 1999), or other methodologies. Despite the ease with which experts comprehend visualizations and despite rhetoric about “visually literate” youth, many readers either skip visualizations entirely, skip large portions of the visualization (e.g., reading only a few labels but skipping the caption), are distracted by less-important information (Sanchez & Wiley, 2004), and fail to draw critical inferences (Butcher, 2005; Hegarty ???). Visualizations such as schematic diagrams, photographs, maps, and tables are a cultural invention of the modern era, and have become more colorful and more plentiful in textbooks with the advent of new printing technologies. Furthermore, textbooks do not explain how to understand these representations, and teachers assume that students already know how do so, so they do not teach them (McTigue & Croix, 2010). Because these are cultural inventions, it is no surprise that students might benefit from explicit instruction in how to comprehend visualizations (Seufert, Schutze, & Brunken, 2009). Very little research has studied the effectiveness of instruction to improve diagram comprehension. The little intervention research to date has focused on either a) helping students link specific segments of text to the relevant portion of the diagram, b) draw their own diagrams as a way to learn the scientific content (i.e., drawing to learn). Other avenues for intervention might be c) teaching students to draw inferences (self-explanation training) or d) teaching students the conventions used in diagrams.

In the present work, we focus on this last approach to improving comprehension of visualizations—teaching conventions that are unique to visualizations, such as captions, arrows, color keys, labels, columns and rows in tables, and numerical scales. In our research, we are investigating whether attending to and understanding these conventions is necessary and/or sufficient for higher (inferential) levels of comprehension of visualizations.

Our Conventions of Diagrams (COD) intervention maps most closely to the representation-specific skills in recognizing relevant information component in Larkin and Simon's (1987) theory, a portion of the referential connections component in Narayanan and Hegarty (1998)'s theory (students must read arrows, labels, captions, etc. in order to make the referential connections within a portion of a diagram), and the image comprehension skills component of Mayer's (2005) theory.

Our modifications directly instruct students in conventions of diagrams, which are highlighted in theories of diagrammatic reasoning (Larkin & Simon, 1987; Narayanan & Hegarty, 1989; Mayer, 2005). Larkin and Simon's (1987) theory of diagrammatic reasoning asserts that when a diagram is superior to a text with identical propositional content, this is due to three factors related to searching, matching, and inference. Larkin and Simon argued that when diagrams and text are informationally equivalent, they are computationally non-equivalent because: 1) Diagrams arrange information spatially, which can simplify the process of searching for specific information used to solve a problem; 2) Since parts are grouped, spatial arrangement can simplify recognition of relevant information; and 3) Spatial inferences are easier in a diagram than in linear text. With regard to the design of diagram comprehension interventions, Larkin and Simon's theory suggests that students need to know what to search for in a diagram, need domain-specific search skills, need domain- and representation-specific skills in recognizing relevant information (and ignoring irrelevant information), need sufficient visual working memory skills, and need domain-specific spatial inference skills.

Narayanan and Hegarty (1998) built a theory of diagrammatic reasoning on Hegarty's (Hegarty, 1992; Hegarty & Just, 1993; Hegarty & Sims, 1994; Sims & Hegarty, 1997) eye movement studies with mental animation of static pulley-and-rope systems. They argued that the reader has to first recognize the objects that are schematically represented, then simultaneously make connections within (representational connections) and between (referential connections) representations to construct a static mental model. Representational connections include relationships between parts (e.g., the connection between a piston and a hinged rod) and activating prior knowledge about parts (e.g., their purpose, materials of which they are made). Referential connections include relationships between a part and its textual label or two corresponding parts in different images. If the diagram depicts a process involving movement, the reader must determine the causal path, and then construct a dynamic mental model via inference and mental animation. With regard to the design of diagram comprehension interventions, Narayanan and Hegarty's theory suggests that students need visual recognition skills, prior knowledge about the parts of a system, skills at making referential connections, following a causal path, and mental animation. As in Larkin and Simon (1987), this theory also implies the need for inference skills, but Narayanan and Hegarty broaden this out beyond spatial inference to include all types of inference.

In Mayer's (2005) theory of multimedia learning, readers initially process text separately from diagrams and form two representations: one textual and one visual. In Mayer's model, the verbal model and the pictorial model are first fully formed (i.e., both the picture and text are understood), each within a limited capacity working memory system (i.e., auditory working memory and visual working memory). Only after each mental model is formed does the crucial step of integration occur, in which referential connections are formed between the two models and prior knowledge. With regard to the design of diagram comprehension interventions, Mayer's theory calls for text comprehension skills, image comprehension skills, adequate auditory and visual working memory capacity, and referential connection skills.

Overall, we see the visualizations intervention as a low-level treatment that provides several prerequisites for comprehending diagrams, but we do not intend it to address higher-level processes such as inference. In other words, we designed the study with the expectation that knowledge about conventions of diagrams might be necessary but not sufficient for comprehending the diagrams themselves.

Methods and Data

Here, we describe the principles driving our modifications and some practical aspects of the modification processes. Our modifications consist of instruction in conventions of diagrams that 6th-8th grade science teachers give verbally at strategic moments during their regular instruction. Teachers follow their districts' pacing guides in terms of which pages of the textbook are covered each day; when they have finished presenting a portion of the textbook—typically one page—and they reach a visualization, they stop and give a brief explanation or ask students to complete an exercise. In some cases (e.g., in using columns, rows, and the intersection of columns and rows in tables), we have created PowerPoint presentations which teachers use to explain the conventions.

We begin instruction with one convention per image (e.g., the caption), and gradually increase the number of conventions per image. Students have opportunities for practice; they identify conventions (e.g., naming labels, captions), create their own captions, and teachers scaffold whole-class discussion of student answers.

Types of Instructed Conventions. Below, we briefly describe our modifications for 7 types of conventions: arrows, captions, color, enlargements, labels, scale, and table columns and rows.

Arrows. Teachers explain to students that arrows can show change, forces, or movement. For example, in the modified curricula arrows are used to show how wind erodes particles from rock, how a base pair is changed in a DNA mutation that causes sickle cell anemia, and how one step in the process of photosynthesis yields oxygen as a waste product and glucose for the plant cell. Verbal explanations, PowerPoints, student exercises (e.g., draw in an arrow that was removed), and warm-ups are all used to teach students to pay attention to and make sense of arrows in diagrams.

Captions. Teachers remind students to read the caption in order to get the main idea of the visualization. Despite the aphorism that "a picture is worth a thousand words," most pictures could be used to make a number of different points, and the caption makes clear the intended use of the visualization. Captions can point the reader's attention to certain features of the visualization (e.g., erosion on stream banks), name the objects shown (e.g., a spiral bacterium, a cube of one-meter dimension carried by a man), explain the main idea (e.g., a fault in a rock face), and define abbreviations and/or uses of color. Most of our explanations remind students to read the caption before looking at the diagram, and to always read the caption.

Color. In our explanations, we distinguish between true color (e.g., a green leaf vs. a brown leaf in fall) and false color (e.g., "purple" mitochondria in a schematic diagram or "pink" virus particles in a scanning electron micrograph). Themes across these explanations include: the prevalence of staining in photomicrographs, consistent (or inconsistent) use of color across multiple diagrams (e.g., the cytosine base in DNA or RNA is always shown as blue), and the importance of focusing on areas of color in photographs that are pointed out in the caption (e.g., paying attention to white flowers vs. purple flowers—but not to the green stems and leaves). Most of these explanations are delivered verbally by teachers; students have the opportunity in in-class discussion and in warm-ups to identify cases of true and false color.

Enlargements. Many scientific visualizations show a whole object at one scale and an enlargement of some portion of the object at a much larger scale (e.g., a whole rock and an enlargement showing the crystalline structure within that same rock). While different textbooks may use different visual conventions to represent enlargements, but each textbook does have a convention for showing enlargement, and these are taught to students. Our methods for teaching enlargements are focused on teacher explanation—verbally or through demonstrations with a magnifying glass—and students also practice using these in warmups and exercises. Enlargements also touch on issues of scale (see below).

Labels. Most diagrams and some photographs label individual parts (e.g., a pistil and stamen within a flower) and also include numbered steps in a sequence (e.g., steps in protein synthesis) which we call explanatory labels. As noted above, students often skip these entirely, even though they contain important information and explanations. Most of our instruction occurs through teacher explanation; in some cases for a warmup or exercise we remove a label and ask students to write in the missing label.

Scale. Related to misconceptions, students have a great deal of trouble grasping the extremely small physical scale of cells and atoms and the extremely large scale of tectonic plates. Likewise, they have difficulty grasping the enormous forces at work in geology—physical forces and temperatures so large that they can bend rocks weighing millions of tons over distances measured in miles, can liquefy rocks, and as shown in the recent events in Japan, cause waves of more than 25 feet in height which can destroy entire cities in minutes. These difficulties with scale and misconceptions about scale are specifically addressed in our materials in the teacher explanations, warm-ups and other exercises.

Table columns and rows. Students need to use tables both to find the intersection of a row and column (a search process) and also to look for trends across tables. For example, a table may show the different characteristics of pea plants (e.g., pea color) and the multiple traits (e.g., green and yellow peas) investigated by Gregor Mendel. As with other features, teachers were asked to show students how to find the appropriate column, row, and their intersection in a search or summarization task; these types of tasks are also embedded in warm-ups and exercises.

Professional development. Teacher professional development (PD) for the project is delivered during initial 3-day intensive summer sessions and ongoing PD sessions which teachers attend every 2-3 weeks. Both initial and continuing PD emphasize all four types of modifications—visualizations, contrasting cases, misconceptions, and repeated assessment. With regard to visualizations training in the initial PD sessions, we review the literature on students' poor diagram comprehension, review the types of modifications made, and also ask teachers in one exercise to create their own explanations of the conventions used in 3 representations. Pilot teachers who have implemented the modifications in their own middle school classrooms provide powerful, first-hand experience about students' unexpected difficulties with the visualizations and also the benefits of direct instruction in conventions for improving students' comprehension of the visualizations.

Results

Here, we summarize the modifications made to three FOSS (Earth History, Diversity of Life, and Weather and Water) and Holt (Inside the Restless Earth; Cells, Heredity, and Classification; and Introduction to Matter) curricula. Each curriculum modification is embedded in a teacher guide of approximately 500 pages, which presents verbal or visual explanations of how to understand various conventions. These modifications range from reminders to inspect and read all parts of the visual representation, to explanations of what different conventions may mean (e.g., arrows as showing change in a single object vs. different organisms in evolutionary time), practice in using the conventions, and spaced practice (quizzes with discussion).

Scholarly significance

These cognitive-science-based modifications represent a middle ground between using commercially-published curricula *as is* and wholesale *rewriting* of curriculum. Our modifications provide classroom teachers with a coherent curriculum that is based in principle of cognitive science. These include the modifications of visual representations discussed above, as well as contrasting cases (developed by a team at the University of Pittsburgh), work around student knowledge and misconceptions, and spaced testing (led by the University of Pennsylvania team). Subsequent presentations will show how the implementation of these modified curricula by trained teachers have had an impact on middle school students' learning of science.

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