Creating Visual Explanations Improves Learning

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Abstract

Diagrams and other visual explanations are widely used in instruction, in media, in presentations, in public places, and more because they communicate effectively and improve learning and performance. They use space and elements in space to represent meanings more directly than purely symbolic words. Can creating visual explanations also promote learning? In two studies, students were taught a STEM phenomenon. Half created visual explanations and half created verbal explanations; afterwards their knowledge was tested. Those who had created visual explanations performed better in a post-test than those who created verbal explanations. Visual explanations provide a check for completeness and coherence as well as a platform for inference, notably from structure to process.

Keywords: learning; visual explanation, diagrams, external representation; structure; function; process; complex system; STEM; spatial ability.

Introduction

Dynamic systems such as those in science and engineering are notoriously difficult to learn. Mechanisms, processes, and behavior of complex systems present particular challenges. Learners must master not only the components and structure of the system but also the behavior, process, and causality of the system (function), which may be complex and frequently invisible. Although the teaching of STEM phenomena typically relies on visualizations, learning is typically revealed in language. Visualizations have many advantages over verbal explanations for teaching; can creating visual explanations promote learning?

Benefits of Visualizations

The power of visualizations comes from representing meaning more directly and naturally than purely symbolic words. Visualizations map elements and relations of systems that are inherently spatial to elements and relations on a page, as in maps and architectural plans. They also map elements and relations of systems that are metaphorically or conceptually spatial to a page, as in diagrams, charts, and graphs (e. g., Tversky, 2011). Visualizations can readily depict the parts, shapes, and configurations of a system. Language can describe spatial properties and arrays but because the correspondences of meaning to language are purely symbolic, constructing mental models from descriptions is far more effortful and error prone (e. g., Hegarty and Just, 1993; Glenberg and Langston, 1992). Depicting the operations of a system, its causal mechanisms, and how it changes over time is more challenging. Arrows are widely produced and comprehended as representing a range of kinds of changes over time, though which kind of change can be ambiguous (e.g., Heiser and Tversky, 2006). Visualizations not only represent structural and some behavioral properties directly, they also serve as an excellent platform for inferences, for example, spotting trends in graphs, imagining traffic flow or seasonal changes in light in architectural sketches (e. g., Tversky and Suwa, 2009), and determining the consequences of movements of gears and pulleys in mechanical systems (e.g., Hegarty and Just, 1993).

Generating Visual Explanations

Learning is improved when students are active learners, for example, while generating their own explanations (e.g., Johnson & Mayer, 2010; Van Lehn, Jones, & Chi, 2009; Wittrock, 1990). Mayer and colleagues have conducted several experiments that have shown a learning benefit of generative activities in domains involving invisible components, including electric circuits (Johnson & Mayer, 2010), lightning formation (Johnson & Mayer, 2009), and the chemistry of detergents (Schwamborn et al., 2010). Although studies have not directly compared the effects of generating visual vs. verbal explanations, the results of several studies with partial comparisons suggest that generating visual explanations could be more effective than generating verbal ones (e. g., Ainsworth, Prain, & Tytler, 2011; Gobert & Clement, 1999; Schneider, Rode, and Stern, 2010). Creating visual explanations confers extra benefits over and above the benefits of using them for comprehension. Creating a visual explanation provides a check for completeness; are all the parts there? Creating a visual explanation provides a check for coherence; do the relations among the parts make sense? Finally, as for learning, visual explanations provide intuitive platforms for inference, especially inferences from structure to function. The benefits of creating visual explanations, completeness, coherence, and inference, are the benefits that accrue from constructing formal models of phenomena, with the extra advantages that come from the visuospatial mapping of parts, structure, and function.

Present Experiments

Two experiments directly compared student learning after creating visual or verbal explanations of STEM phenomena, a bicycle pump or chemical bonding, conducted in the course of regular activities in science classes. In both cases, students created explanations after the lessons were completed. Spatial ability was assessed; previous research has revealed that those high in spatial or mechanical ability perform better on learning STEM concepts (e. g., Hegarty & Just, 1993; Leutner, Leopold, & Sumfleth, 2009; Tversky, Heiser, and Morrison, 2013).

Explaining the Workings of a Bicycle Pump

Method

Participants Participants were 127 (59 female) 7th and 8th grade students, ages 12-14, enrolled in an independent school in New York City.

Materials Each participant was given the Vandenberg-Kuse Mental Rotation Test (MRT) (1978), a 12-inch Spalding bicycle pump, a blank 8.5 x 11 sheet of paper, a 16 question post-test.

Procedure On the first of two non-consecutive school days, participants completed the MRT as a whole-class activity. On the second day, participants were given the pump with instructions to try to understand how it worked. This segment was untimed. Participants were allowed to manipulate and take apart the pump. Next, students were asked to explain the workings of the bicycle pump, either verbally on paper or visually. After completing the explanation, participants were given a post-test that had 8 structural and 8 functional true/false questions.

Coding Explanations

Coding for Structure and Function. A maximum score of twelve points was awarded for the inclusion and labeling of six structural components: chamber, piston, inlet valve, outlet valve, handle, and hose. Information was coded as functional if it depicted or described the function/movement of an individual part, or the way multiple parts interact. There was no maximum imposed on the number of functional units.

Coding of Essential Features. Both kinds of explanations were coded for the inclusion of information essential to its function according to a four-point scale (adapted from Hall, Bailey, & Tillman, 1997). One point was given if both the inlet and the outlet valve were clearly present in the drawing or described in writing, one point was given if the piston inserted into the chamber was shown or described to be airtight, and one point was given for each valve if they were shown or described to be opening/closing in the correct direction.

Coding Arrows and Multiple Steps. For the visual explanations, three uses of arrows were coded and tallied: labeling a part or action, showing motion, or indicating sequence. For both visual and verbal explanations, the number of discrete steps was coded.

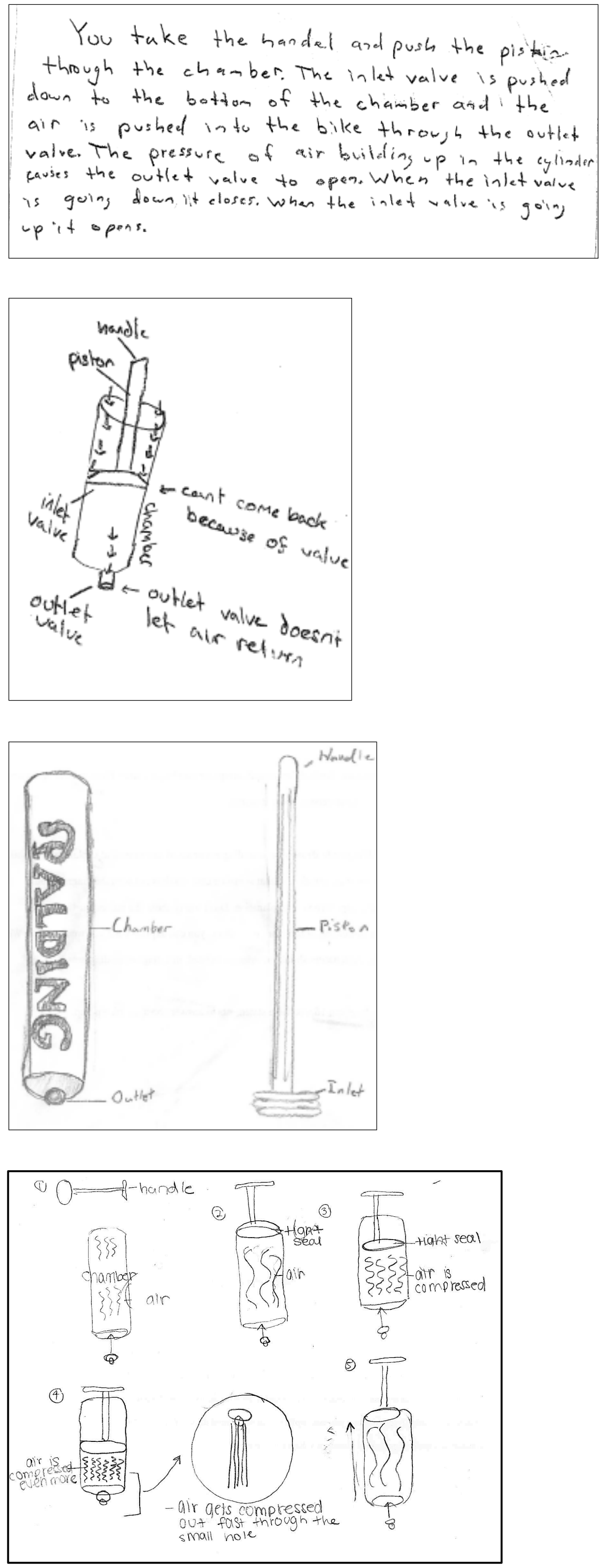

Figure 1: Examples of visual and verbal explanations.

Results

Spatial ability. The mean score on the MRT was 10.56, with a median of 11. Males scored significantly higher (M = 13.5, SD = 4.4) than females (M = 8.8, SD = 4.5), F(1, 126) = 19.07, p<.01, a typical finding (Voyer, Voyer, and Bryden, 1995). Participants were split into high or low spatial ability by the median.

Explanations: Structure and Function. Both visual and verbal explanations contained from two to ten structural components. Visual explanations contained significantly more structural components (M= 6.05, SD = 2.76) than verbal explanations (M = 4.27, SD = 1.54), F(1, 126) = 20.53, p<.05. The number of functional components did not differ between visual and verbal explanations. Interestingly, 67% of the visual explanations contained some verbal information.

Essential Features. Visual explanations contained significantly more essential information (M = 1.78, SD = 1.0) than verbal explanations (M = 1.20, SD = 1.21), F(1, 126) = 7.63, p<.05. Inclusion of essential features correlated positively with post-test scores, r = .197, p<.05).

Multiple Steps. The number of steps used by participants ranged from one to six. Participants whose explanations, whether verbal or visual, contained multiple steps scored significantly higher (M = .76, SD = .18) on the post-test than participants whose explanations consisted of a single step (M = .67, SD = .19), F(1, 126) = 5.02, p<.05.

Post-test Scores. Creating a visual explanation selectively helped low spatial participants. The interaction between spatial ability and explanation type was significant F(1, 124) = 4.094, p<.01. Low spatial participants who created visual explanations had significantly higher scores (M = .716, SD = .121) than low spatial participants who generated verbal explanations (M = .609, SD = .145). (Scores are reported as proportion correct). The facilitation of visual explanations for low spatial students was especially pronounced in the subset of questions that assessed knowledge of function; scores for visual explanations (M = .678, SD = .122) were significantly higher than those for visual explanations (M = .502, SD = .194), F(1,126) = 9.498, p<.05, see Figure 2.

Discussion

In the first experiment, students learned the workings of a bike pump from interacting with it. Half then produced verbal explanations and half visual explanations, followed by a test of knowledge. The visual explanations contained more information than the verbal ones, both more structural information and more of the core, essential information. Even though creating explanations occurred after learning, creating a visual explanation improved scores for low spatial participants more than creating a verbal explanation, especially for the functional knowledge that is more difficult (e. g., Tversky, et al., 2013). This finding mirrors many studies in which diagrams in teaching selectively help low spatial students. The bike pump was a relatively simple system, and overall performance was high, perhaps not allowing more subtle findings to appear. The second study investigates the role of visual explanations for a more difficult set of concepts.

The quality of the explanations predicted overall learning. Specifically, including more of the essential features and showing multiple steps correlated with good performance.

These findings have clear implications for teaching. Creating visual explanations should be an effective way to improve performance, especially of low spatial students. Creating visual explanations can be guided toward the features that augment learning, for example, encouraging students to focus on the essential information and suggesting that they show every step. The coding system shows that visual explanations can be objectively evaluated for feedback to students or grading. In addition, visual explanations provide valuable feedback to instructors as to what students do and do not comprehend.

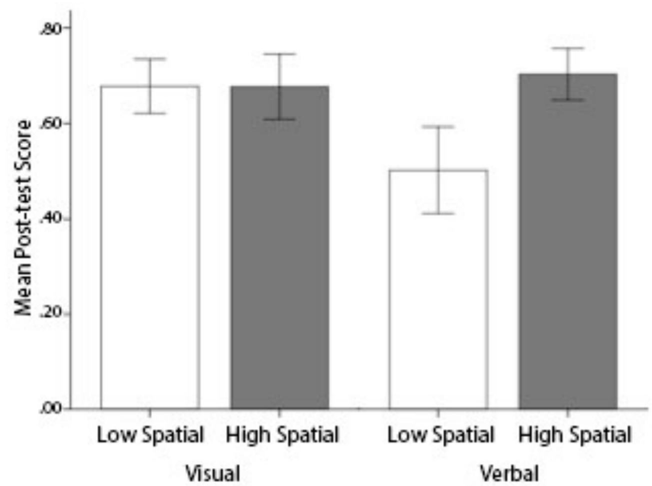

Figure 2: Post-test scores by explanation type and spatial ability.

Explaining Chemical Bonding

The first experiment showed that creating a visual explanation of STEM mechanics improves learning for students with low spatial ability more than creating a verbal explanation. However, understanding the workings of a bicycle pump is relatively easy. The next study investigates learning chemical bonding, a more challenging set of phenomena. For this, creating a visual rather than verbal explanation is expected to aid students of low as well as high ability. The next study also asks whether creating an explanation per se can increase learning in the absence of additional teaching by administering two post-tests of knowledge, one after learning but before creating an explanation and one after creating an explanation. Does the act of integrating and consolidating knowledge serve learning even in the absence of study or teaching?

Method

Participants Participants were 126 (58 female) 8^{th} grade students, ages 13-14, enrolled in an independent school in New York City.

Materials The class lesson on chemical bonding consisted of a video that was 13 min, 22 sec. The video began with a brief review of atoms and their structure, and introduced the idea that atoms combine to form molecules. Next, the lesson showed that location in the periodic table reveals the behavior and reactivity of atoms, in particular, the gain, loss, or sharing of electrons. Examples of atoms, their valence shell structure, stability, charges, transfer and sharing of electrons, and the formation of ionic, covalent, and polar covalent bonds were discussed.

Participants were given a blank 8.5 x 11 sheet of paper. Both immediate and delayed post-tests consisted of seven multiple-choice items and three free-response items.

Procedure On the first of three non-consecutive school days, participants completed the MRT as a whole-class activity. On the second day, participants viewed the recorded lesson on chemical bonding. They were instructed to pay close attention to the material but were not allowed to take notes. Immediately following the video, participants had 20 min. to complete the immediate post-test; all finished within this time frame. On the third day, the participants were randomly assigned to either the visual or verbal explanation condition. They were told to either visually or verbally explain how atoms bond and how ionic and covalent bonds differ. See Figure 3 for examples. After completing the explanations, students were given the second post-test, different from the first.

Coding Explanations

As evident from Figure 3, the visual explanations were individual inventions; they neither resembled each other nor those used in teaching. Most contained language, especially labels and symbolic language such as NaCl.

Structure and Function. Visual and verbal explanations were coded for depicting or describing structural and functional components. The structural components included information on the correct number of valence electrons, the correct charges of atoms, the bonds between non-metals for covalent molecules and between a metal and non-metal for ionic molecules, the crystalline structure of ionic molecules, and that covalent bonds were individual molecules. The functional components included transfer of electrons in ionic bonds, sharing of electrons in covalent bonds, attraction between ions of opposite charge, bonding resulting in atoms with neutral charge and stable electron shell configurations.

Arrows. The presence and uses of arrows was coded.

Specific Examples. Explanations were coded for the use of specific examples, such as NaCl, to illustrate ionic bonding.

Results

Spatial ability. The mean score on the MRT was 10.39, with a median of 11. Males (M = 12.5, SD = 4.8) scored significantly higher than females (M = 8.0, SD = 4.0), F(1, 125) = 24.49, p<.01. Participants were split into low and high spatial ability based on the median.

Structure and Function. The maximum score for structural and functional information was five points. Visual explanations contained a significantly greater number of structural components (M = 2.81, SD = 1.56) than verbal explanations (M = 1.30, SD = 1.54), F(1, 125) = 13.69, p<.05. There were no differences between verbal and visual explanations in the number of functional components. In the visual explanations, structural information was more likely to be depicted (M = 3.38, SD = 1.49) than described (M = .429, SD = 1.03), F(1, 62) = 21.49, p<.05, but functional information was equally likely to be depicted (M = 1.86, SD = 1.10) or described (M = 1.71, SD = 1.87). Functional information expressed verbally in the visual explanations significantly predicted scores on the post-test, F(1, 62) = 21.603, p<.01, while functional information in verbal explanations did not. Explanations created by high spatial participants contained significantly more functional components, F(1, 125) = 7.13, p<.05, but there were no ability differences in the amount of structural information created by high spatial participants in either visual or verbal explanations.

Arrows. 83% of visual explanations contained arrows. The use of arrows was positively correlated with scores on the post-test, r = .293, p<.05.

Specific examples. High spatial participants (M = 1.6, SD = .69) used specific examples in their verbal and visual explanations more often than low spatial participants (M = 1.07, SD = .79), a marginally significant effect F(1, 125) = 3.65, p=.06. Visual and verbal explanations did not differ in the presence of specific examples. The inclusion of a specific example was positively correlated with scores on the delayed post-test, r =.56, p<.05.

Learning outcomes. The maximum score (reported as proportion correct) for the immediate post-test was ten points. The mean score was .46, SD= .469. Scores for the subsequent visual (M= .486, SD = .308) and verbal groups (M = .443, SD = .260), F(1, 125) = .740, p>.05 did not differ, nor did scores of high (M= .532, SD - .421) and low spatial students (M= .402, SD = .390) F(1, 125) = 2.72, p>.05. As presented in Figure 4, the mean score on the delayed post-test, after participants generated explanations, was .704, SD = .299. Both groups improved significantly; those who created visual explanations (M = .822, SD = .208), F(1, 125) = 51.24, p<.01, Cohen's *d* = 1.27 as well as those who created verbal explanations (M = .631, SD = .273), F(1,125) = 15.796, p<.05, Cohen's *d* =.71. Importantly, as evident in Figure 4, participants who generated visual explanations (M = .822, SD = .208) scored considerably higher on the delayed post-test than participants who generated verbal explanations (M = .631, SD = .273), F(1, 125) = 19.707, p<.01, Cohen's *d*=.88. In addition, as shown in Figure 5, high spatial participants (M = .824, SD = .273) scored significantly higher than low spatial participants (M= .636, SD = .207), F(1, 125) = 19.94, p<.01, Cohen's *d*=.87. The interaction between explanation type and spatial ability was not significant.

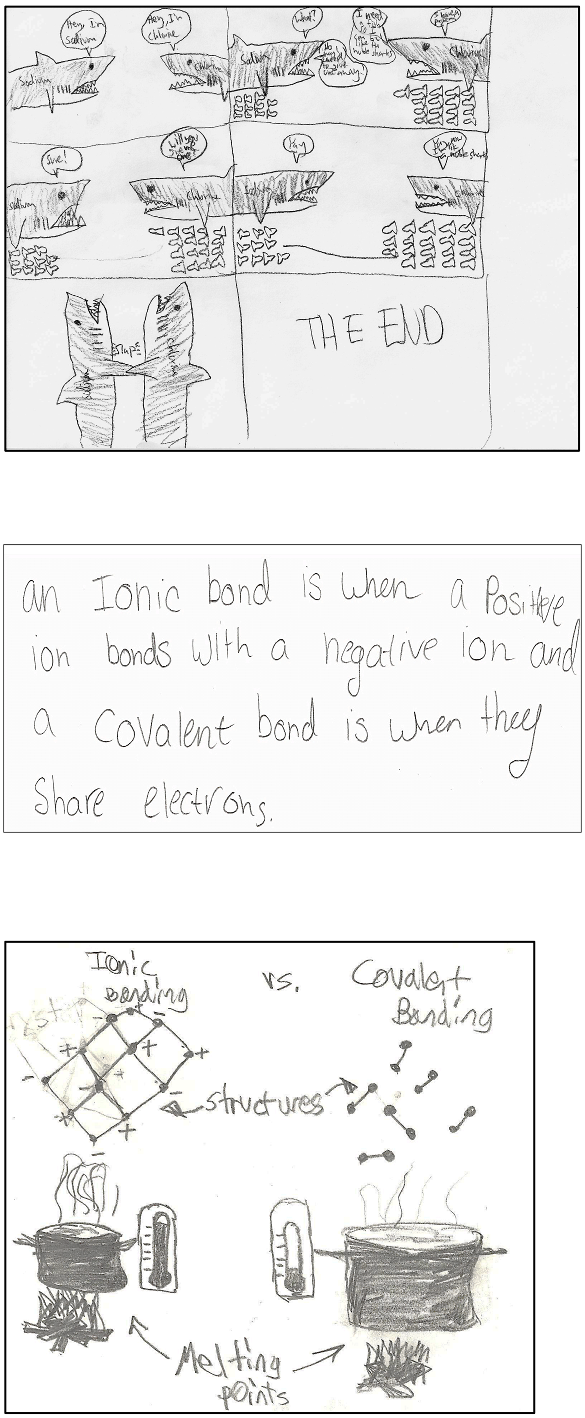

Figure 3: Examples of visual and verbal explanations.

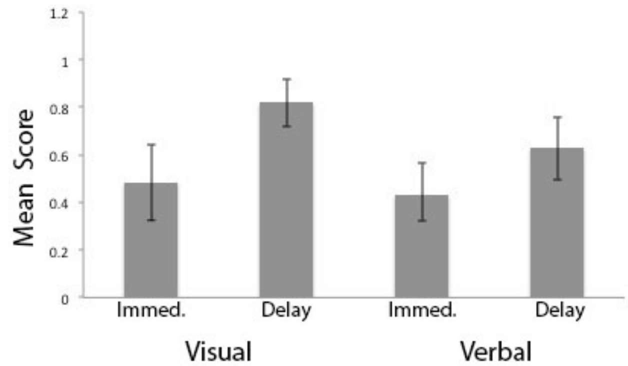

Figure 4: Immediate and delayed post-test scores by explanation type.

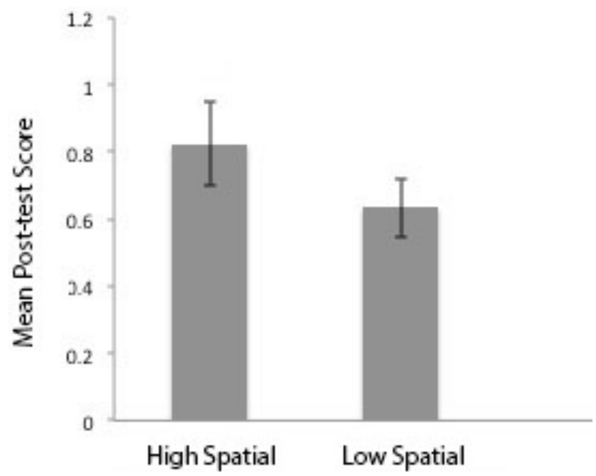

Figure 5: Delayed post-test scores by spatial ability.

Discussion

In the second experiment, students were taught chemical bonding, a more difficult, abstract, and complex phenomenon than the bicycle pump used in the first experiment. Students were tested immediately after learning. The following day, half the students created visual explanations and half created verbal explanations. Students were tested again, with different questions. Performance was considerably higher as a consequence of creating either explanation despite the absence of new teaching. Generating an explanation can be regarded as a test of learning. Seen this way, the results echo and amplify previous research showing the advantages of testing over study (Roediger et al., 2011). Importantly, creating a visual explanation gave an extra boost to learning outcomes over and above the boost provided by a verbal explanation. For this more abstract and complex material, generating a visual explanation benefited both low spatial and high spatial participants.

High spatials not only scored better, they also generated better explanations, including more of the information that predicted learning. Their explanations contained more functional information and more specific examples. Their visual explanations also contained more functional information.

As before, qualities of the explanations predicted learning outcomes, specifically including arrows in visual explanations and more specific examples in both types of explanation.

Conclusion

Two experiments have shown that creating an explanation of a STEM phenomenon benefits learning, even when the explanations are created considerably after learning. Explaining a complex system requires selecting the critical information and integrating it, a set of processes that apparently serves to consolidate memory and learning. Notably, creating a visual explanation conferred much larger benefits to learning than creating a verbal explanation.

As in previous research, students with high spatial ability both produced better explanations and performed better on tests of learning (e. g., Uttal, Meadow, Tipton, Hand, Alden, Warren, and Newcombe, 2013). The visual explanations of high spatial students contained more information and more of the information that predicts learning outcomes.

Surely some of the effectiveness of visual explanations is because they represent and communicate more directly than language. They also allow, indeed, encourage, the use of well-honed spatial inferences to substitute for and support abstract inferences (e. g., Tversky, 2011). Visual explanations use space and elements in space to represent the parts and configurations of complex systems. As noted, visual explanations provide checks for completeness and coherence, checks that the necessary elements of the system are represented and work together properly to produce the outcomes of the processes. Visual explanations also provide a concrete reference for making and checking inferences about the behavior, causality, and function of the system. Thus, creating a visual explanation facilitates the selection and integration of information underlying learning.

Drawing visual explanations appears to be an underused method of monitoring and supporting students' understanding of scientific concepts. One obstacle is an objective scoring system for evaluating visual explanations. We have shown that scoring systems can be devised, and have shown benefits to students of creating visual explanations. There are also benefits to teachers, specifically, revealing gaps in knowledge and misunderstandings. The bottom line is quite clear. Creating a visual explanation is a good way to learn and master complex systems. What's more, as evident from the examples here, it's creative and fun.

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