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Drawing to Learn: How Producing Graphical Representations Enhances Scientific Thinking

Judith E. Fan
Princeton University

When we understand something, we say that we "see" it. We arrive at the solution to a problem through "insight." Such metaphors likening cognitive processes to visual experience suggest a close correspondence between how we think about and how we see the world. Accordingly, major theoretical advances in the sciences have been frequently accompanied by the development of novel visualization tools and graphical conventions (e.g., the periodic table). Today, knowing how to make a graph is a critical component of any practicing scientist's repertoire, allowing her to gain insight when exploring a complex data set, and to communicate empirical findings to other scientists and the public. This paper reviews evidence from the cognitive science and educational research literatures that bears on the question of how drawing, the most basic visualization technique, interacts with cognitive functions that are core to scientific thinking, including: observation, problem-solving, explanation, and communication. Expanding the role of graphical literacy in science education may carry the potential to better reveal to students the dynamic and inquiry-based nature of scientific thinking, especially in contexts where visual representations have traditionally been subordinate to linguistic and numerical representations.

Keywords: visualization, problem-solving, communication, explanation, active learning

When we understand something, we say that we "see" it. We arrive at the solution to a problem through "insight." To better communicate our ideas, we aim to make them "clear." That such metaphors likening cognitive processes to visual experience are so pervasive suggests a close correspondence between how we think about and how we see the world. One of the most compelling demonstrations of this lies in the wide range of technologies humans have devised for creating graphical representations to convey knowledge. Some of these technologies are ancient (e.g., using a stylus to draw or write), whereas others are quite modern (e.g., computer graphics). The refinement of such representations over many generations has resulted in useful abstractions (e.g., written language or the Cartesian coordinate system) that have enabled sophisticated intellectual activities of broad cultural significance, including history and law, art and literature, and formal mathematics and science (Norman, 1990).

In particular, it may be no accident that major theoretical advances in the sciences have frequently been accompanied by the development of novel visualization tools and graphical conventions. For example, when the matrix-style representation of chemical elements in the periodic table was introduced by Mendeleev in 1869, its intuitive layout not only exposed orderly relations among the 66 elements then known, but also suggested predictions about the properties of "missing" elements in the table yet to be discovered (Scerri, 2006). Today, knowing how to make a graph is a critical component of any practicing scientist's repertoire, allowing her to gain insight when exploring a complex data set, and to communicate empirical findings to other scientists and the public (Johnson et al., 2006). Scientists use graphs in various ways: to extract numerical information (e.g., by reading

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Correspondence concerning this article should be addressed to Judith E. Fan, Department of Psychology, Peretsman–Scully Hall, Princeton University, Princeton, NJ 08544. E-mail: jefan@princeton.edu

numbers off the axis), to compare elements (e.g., the height of two bars), to categorize patterns (e.g., based on qualitative shape information), and to identify outliers or other anomalous observations (Springmeyer, Blattner, & Max, 1992). In many cases, multiple formats may be available for representing the same information (e.g., list of numbers, bar graph, scatterplot). Whereas some make interpretation difficult (as lists of numbers often do), others (e.g., bar graphs for categorical data, scatterplots for bivariate continuous data) can plainly reveal important patterns (Card, Mackinlay, & Shneiderman, 1999). Indeed, figuring out which representations are best suited for expressing the underlying structure in data itself constitutes a central aspect of scientific discovery.

Considering the great value that graphical representations confer to the scientist in the laboratory (Fisher, Green, & Arias-Hernández, 2011; Gooding, 2010), developing visualization skills may enhance learning and engagement of students in the classroom. Especially in contexts in which visual modes of understanding have historically been subordinate to linguistic and numerical ones (Balchin & Coleman, 1966; Fry, 1981; Postigo & Pozo, 2004), conferring greater priority to graphical literacy in science education may carry the potential to better reveal to students the dynamic and inquiry-based nature of scientific thinking (Ainsworth, Prain, & Tytler, 2011; Donovan, Bransford, & Pellegrino, 1999).

This paper considers how drawing, the most basic visualization technique, interacts with cognitive functions that are core to scientific thinking to support observation, problem-solving, explanation, and communication. Here, "drawing" refers to manual mark-making techniques which yield images that serve some purpose. Depending on the context, these images may carry different names, such as: "map," "graph," "sketch," "diagram," "chart," and so forth. Drawings may be neat or they may be untidy, but this paper is primarily concerned with drawings that "assist in the development of . . . ideas" (Fish & Scrivener, 1990), rather than those that merely possess aesthetic value. Moreover, although this paper does not explicitly address modern visualization techniques such as computer-assisted plotting, a thorough understanding of how manual drawing influences cognition should yield principles that also apply to our use of these other tools.

Drawing as a Mode of Observing the World

How does drawing support close observation in science? One domain in which image-making (and drawing, in particular) has long played an essential role in organizing scientific knowledge is the life sciences (Daston & Galison, 2010). Many biological processes unfold on a spatial and temporal scale that is impossible to visualize without the aid of sophisticated tools and techniques. For example, although cell division is ubiquitous among living organisms, being able to observe the subcellular mechanisms that perform this process requires the use of microscopes and appropriately stained tissue samples.

Thus, developing student's abilities to make sense of their own observations is a crucial objective of biology, and indeed, all science instruction. Drawing is one means by which students have an opportunity to move beyond initial assumptions about how a plant or animal looks, to concentrate on the physical properties of the actual specimen in front of them (Dirnberger, McCullagh, & Howick, 2005; Leslie, 1980). Attending to the unique aspects of their specimen helps to make clear to students how biological diversity manifests in multiple ways—both across taxonomic categories and between individual members of a species. To help students tackle the inherent complexity of organic forms, teachers may find inspiration from the elements of art (i.e., line, shape, form, texture, value, and color), which can direct students' gaze to different aspects of their specimen (Leslie, 1980). For example, as part of a unit on botany, it may be valuable to include plant drawing exercises exploring a few of these visual elements, e.g., tracing lines to record leaf venation patterns, outlining shape contours that identify plant species, rubbings to capture texture information (Dempsey & Betz, 2001).

The empirical literature on observational drawing in classroom settings suggests that such potential benefits are far from automatic. Rather, the success of drawing exercises crucially depends on whether drawing provide opportunities to reflect upon recently acquired information (Hall, Bailey, & Tillman, 1997), compare against reference knowledge (Van Meter, 2001), and receive targeted feedback from instructors (Landin, 2011). In other words, simply instructing students to draw is not enough to induce more attentive observation. For example, in one study that examined how high-school and teacher-training students drew landscapes based upon photographs and field-site observations, Martínez-Peña and Gil-Quílez (2014) found that many students either ignored the instructions to draw the landscape or produced "schematic" and/or "artistic" drawings that were missing crucial and relevant geological features (e.g., rocks). Consistent with the idea that these simplistic drawings reflected an impoverished conceptual understanding about the meaning of their observations, these students later performed poorly on test questions that tapped understanding of the causal relationships between geological features of the landscape.

In a longitudinal study of undergraduate majors in an introductory biology laboratory course, students were encouraged to attend closely to the structure and characteristics of the specimens examined in each laboratory session (Figure 1b). Some students were prompted to provide verbal descriptions of their observations (Description Only); other students were instructed to draw their specimens (Draw Only); and the remaining students drew their specimens and received feedback about their drawing technique throughout the semester (Draw with Instruction). Landin (2011) found that although all groups displayed greater biology content knowledge at the end of the semester, the Draw with Instruction group improved the most and significantly more than the Description-Only group, and the Draw-Only group exhibited an intermediate degree of improvement.

Taken together, these findings suggest that students may not spontaneously abstract the relevant features from their observations when asked to draw; nevertheless, these are skills that can be developed over time with adequate guidance and targeted feedback. Foundational questions remain concerning the relationship between drawing and observing. A potential route by which drawing from observation may facilitate learning is through common mechanisms that support visual learning induced by observation alone, such as by changing how students pay attention to different visual features of an object (Goldstone, 1998). For instance, students initially learning to distinguish leaves from different trees may be neither able to perceptually discriminate nor produce a drawing that differentiates them. However, practice making drawings that highlight fine contour information and textural details may improve students' ability to be more sensitive to that information when they later encounter other plants. Future research should aim to more directly evaluate causal links between drawing and observation skills in real-world learning environments (Coates, 1984), as well as elucidate the basic cognitive mechanisms by

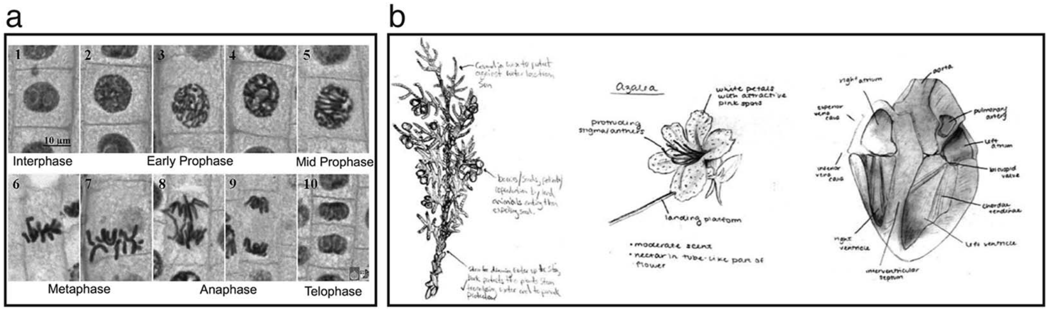


Figure 1. (a) Onion root tip cells labeled by phase of cell cycle. From "Lab: Mitosis in Onion Root Tip Cells" [Lab worksheet], n.d., Marietta College. Adapted with permission of the Department of Biology and Environmental Science, Marietta College. (b) Drawings of plant and animal specimens from students who received ~10 min of drawing instruction and feedback each week to supplement their observational drawing workbook exercises. Adapted from *Perceptual Drawing as a Learning Tool in a College Biology Laboratory* (p. 61), by J. Landin, 2011, doctoral dissertation, North Carolina State University.

which honing observational skills through drawing promotes conceptual learning (Kindfield, 1994; Nelson, Martin, & Baldwin, 1998).

Drawing as Window Into Ongoing Learning

Drawings are necessarily selective representations that include some details and omit others; thus, every mark a student makes in a drawing may be diagnostic of what students are and are not learning (Dove, Everett, & Preece, 1999; Ehrlén, 2009). Indeed, drawings have been used to identify misconceptions about biological processes held by beginning biology students as well as by student teachers who are poised to begin teaching biology classes (Dikmenli, 2015; Köse, 2008). Furthermore, multiple studies using different paradigms have shown that the quality and accuracy of drawings correlate with subsequent performance on tests of reasoning about just-learned material (Greene, 1989; Hall et al., 1997). Thus, a core goal of drawing interventions may be to develop self-directed activities that help students learn to detect their own errors and identify gaps in their own understanding (Van Meter, Aleksic, Schwartz, & Garner, 2006).

What is the best way to cultivate this kind of awareness about one's own learning? Many classic studies using drawing manipulations have focused on assessing how to strengthen reading comprehension, usually by soliciting either verbal paraphrases or drawings (Alesandrini, 1981; Lesgold, Levin, Shimron, & Guttmann, 1975). Unfortunately, the methods used to evaluate potential differences (e.g., free-recall vs. recognition tests) and the results of these studies have been mixed (Hall et al., 1997; Van Meter & Garner, 2005), precluding clear conclusions about the conditions under which drawing can effectively guide learning.

Van Meter (2001) sought to address these inconsistencies by testing the hypothesis that drawing exercises must be "supported" to be effective and that they may benefit "higher-order" (i.e., construction of a mental model, assessed through free recall) but not "lower-order" learning (i.e., mere recognition memory). In this study, all students (fifth graders) were given a text passage describing basic features of the human nervous system. Students in the most supported condition read the passage and then inspected two provided illustrations before producing their own drawings; they then answered questions that entailed comparing features of their drawing to the provided illustrations. Students in the second condition also produced drawings and were told that they could modify their drawings based upon the provided illustrations, but they were not guided to make detailed comparisons. In one of two control conditions, students read the text and produced drawings based on its content, but they were not provided with illustrations. The remaining students read the text and inspected the provided illustrations, but did not draw. The students who were prompted with questions to explicitly relate their drawings to the provided illustrations constructed the most accurate drawings and scored significantly higher on the free-recall posttest. No differences were found on recognition posttest items, which the author interprets as revealing a dissociation between higher-order and lower-order benefits of drawing. Interestingly, these participants also engaged in more self-monitoring than did reading-only control participants. This is consistent with the possibility that prompting students to compare their drawings against reference illustrations resulted in better encoding of the material, and it highlighted errors and inconsistencies in the students' initial drawings that might have gone undetected without the feedback provided by the reference illustrations. Taken together, this prior work suggests that drawings are a rich source of diagnostic information about how and what students perceive, and that producing drawings can benefit ongoing learning so long as these exercises are accompanied by sufficient instruction and explicit guidance as to how to make them and use them in conjunction with other sources of information to deepen their understanding of a new concept.

Nevertheless, there remain fundamental questions about how drawing supports learning that future investigations would do well to address. Much of the extant empirical literature that has examined the educational consequences of drawing practice has been motivated as a way to test for overall differences between verbal and pictorial modes of representation (Alesandrini, 1981; Bobek & Tversky, 2014; Landin, 2011; Mayer, Bove, Bryman, Mars, & Tapangco, 1996) rather than as a means of elucidating the underlying learning mechanisms engaged when students process what they see and/or are reading about by producing drawings.

However, drawing is a complex behavior that has both active (i.e., involving coordinated motor movements) and constructive (i.e., synthesizing forms from simpler elements) aspects (Chi, 2009). Yet most experimental designs that have contrasted drawing activities with visual inspection of provided images have confounded these two factors (Van Meter, 2001); thus, it is not clear which of these explains the effects of drawing practice. The active component of drawing may be isolated in future experiments by including a "guided-tracing" condition in which the student directly traces over an existing drawing, but does not generate drawings based on their own thoughts or experiences. The constructive component of drawing could be isolated by including an "observed-drawing" condition (Mattar & Gribble, 2005) in which a student watches someone else (e.g., a laboratory partner) make drawings but does not draw.

If the learning benefits of drawing may be reaped merely by watching marks accrue on the page over time, then one would predict that observed-drawing students would learn just as much as if they had been drawing for themselves. On the other hand, if the learning benefits of drawing derive from the student actively making the marks for themselves, then we would predict much less learning in the observed-drawing condition. Indeed, this latter possibility points to an important question that future research should address: How does visual and haptic feedback generated while producing a drawing, an important driver of motor learning and skill acquisition more generally, guide learning (Kording & Wolpert, 2004; Synofzik, Thier, & Lindner, 2006)?

Insofar as drawing constitutes a form of "self-directed learning" (Gureckis & Markant, 2012), general principles may be derived that govern this and other examples of self-directed learning, such as the physical manipulation of to-be-learned objects (Harman, Humphrey, & Goodale, 1999), self-paced study in which learners choose the order and timing in which items are presented (Kornell & Metcalfe, 2006; Voss, Gonsalves, Federmeier, Tranel, & Cohen, 2011), self-directed information sampling (Huttenlocher, 1962; Markant & Gureckis, 2014), and the generation effect, in which subsequent memory is enhanced for information that is self-generated versus externally delivered (Crutcher & Healy, 1989; Karpicke & Roediger, 2008; Roediger & Karpicke, 2006; Slamecka & Graf, 1978). In each of these cases, it has been generally observed that self-directed learners enjoy a learning advantage relative to matched "passive" learners who experience the same sequence of events, but who do not exert volitional control over the flow of information.

In actuality, both the "active" and "constructive" aspects of drawing may play important and independent roles. Future studies should use finer-grained drawing manipulations in their experimental designs, which may provide greater clarity into the nature of the underlying processes engaged during drawing versus other modes of perceptual, motor, and cognitive engagement. To the extent that these studies could be systematically conducted in laboratory settings and in classroom environments, we can be more confident in our conclusions about the relationship between drawing and learning. In the long run, the results of such investigations may provide a sounder basis for the integration of observational drawing into educational practice.

Drawing to Solve Problems

> The foot of a ladder rests against a vertical wall and on a horizontal floor. The top of the ladder is supported from the wall by a horizontal rope 30 ft long. The ladder is 50 ft long, weighs 100 lb with its center of gravity 20 ft from the foot, and a 150-lb man is 10 ft from the top. Determine the tension in the rope. (Novak & Bulko, 1992, p. 139)

When confronted with a scenario such as the one above, how does one begin to make sense of how these details are related to one another and to the unknown variable? A physicist would likely recommend starting by drawing a diagram (see Figure 2). Diagrams are schematic drawings that convey structured relationships between parts of a system. Such simplified representations may be especially useful when making inferences based on a series of logical propositions (as in the ladder problem above) or when trying to distill a set of complex observations into a unified representation (e.g., how a bike pump works; Bobek & Tversky, 2014).

One basic way in which diagrams facilitate cognition is by relieving the working memory load imposed by having to keep track of the various elements of a problem. This benefit is

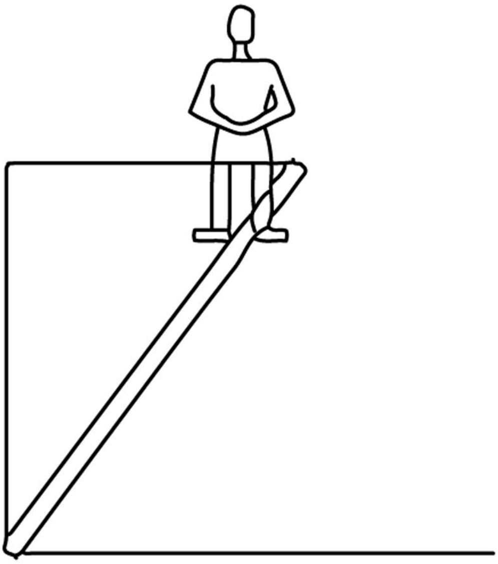


Figure 2. Diagram illustrating ladder problem stated in epigraph to this section. Adapted from "Uses of Diagrams in Solving Physics Problems," by G. Novak and W. Bulko, in *Reasoning With Diagrammatic Representations* (p. 139), edited by N. Hari Narayanan, 1992, Palo Alto, CA: Association for the Advancement of Artificial Intelligence. Copyright 1992 by the Association for the Advancement of Artificial Intelligence.

shared by other types of external representations (e.g., a shopping list, a phone directory) that can also serve as memory aids. Although this basic memory-storage function is obviously important, the focus of this section is on how drawing supports logical reasoning.

Diagrams can facilitate reasoning by converting effortful computational operations into easier perceptual tasks. In a pioneering laboratory study, Larkin and Simon (1987) directly compared the benefits of consulting a diagram versus verbal description in solving geometry and physics problems. Specifically, the authors examined how diagrams influenced three processes engaged during problem-solving: search, recognition, and inference. They found that searching for relevant information can be more efficient when consulting a well-structured diagram, and that diagrams can also make it easier to recognize familiar concepts than an equivalent verbal description. Moreover, to the extent that this information cued the next logical step in solving the problem, such diagrams also facilitated inference.

Another way in which graphical representations can support logical thinking is by actually restricting the set of (erroneous) possibilities that are likely to be considered when reasoning from a premise. According to theories of graphical reasoning, a well-constructed diagram aids the "processability" of the logical relations by constraining the space of plausible implications to ones that are visually consistent with the diagram (e.g., perceiving "overlapping" vs. "exclusion" cases in Venn diagrams; Stenning & Oberlander, 1995).

How are diagrams used by experts to solve problems? Seminal work by Chi, Feltovich, and Glaser (1981) highlighted several differences between expert (i.e., advanced PhD candidates in physics) and novice (i.e., beginning undergraduate physics students) approaches to physics problems. The authors found that although both experts and novices perform similar operations while working on a problem, novices tended to focus on surface features of the problem (e.g., 'involves a block on an inclined plane') whereas experts tended to extract their deep structure (e.g., 'invoke Newton's Second Law'). Moreover, experts tended to have multiple routes to a solution, often producing a drawing to solve the problem and to finally double-check their work (Rosengrant, Van Heuvelen, & Etkina, 2009). On the other hand, novices tended to rely on the drawing only during problem-solving.

Related findings come from a study conducted by Egan and Schwartz (1979), who found that skilled electrical technicians reproduced symbolic representations of circuit diagrams according to the functional role of each circuit element (e.g., amplifier, rectifier, filter), whereas novice technicians tended to draw elements according to their spatial proximity in the diagram. This shows that the use of diagrams per se is not what distinguishes the problem-solving strategies of experts and novices. Rather, it is how diagrams are used that matters—as one of several tools to parse a problem and organize its parts, and to provide "sanity checks" that constrain problem interpretation and mitigate the risk of error.

Cox and Brna (1995) analyzed the "workscratchings" students produced while solving problems similar to those tested in the Graduate Record Examinations (GRE). They found that a large proportion of students drew diagrams during the test, sometimes multiple diagrams at different stages in solving the same problem. However, whereas high-performing students switched between different diagrams in a directed manner, low-performing students tended to switch only when they were "stuck." High-performing students also tended to switch more often for more difficult problems, especially while initially trying to make sense of a problem. The authors speculated that this initial proliferation of sketched diagrams may constitute a search through the student's representational repertoire for the most appropriate type of diagram for the current problem. In general, students who fully understood how to use a particular graphical convention (e.g., Euler diagram, matrix) tended to perform better, whereas students relying on idiosyncratic representations tended to do worse.

These findings support the idea that what distinguishes skilled problem-solving is the ability to tap a larger set of representational techniques and select among them according to the demands of the problem. That is, improving one's ability to solve problems may not depend on accumulating more facts or rote procedures, but on practicing representational skills. In the long run, greater integration of symbolic, verbal, and graphical representations in science curricula may help students grasp the deep commonalities that underlie these different ways of expressing a given concept, and leverage this understanding to solve new problems (diSessa, 2004).

Drawing to Communicate

Unlike our private mental images, our drawings are visible to everyone. Because of their shareability, drawing can be used in the service of facilitating scientific thinking in social contexts. Schwartz (1995) found that high-school students working in pairs to solve a problem were more likely to come up with abstract principles than students working alone. For example, in attempting to model the behavior of interlocking gears, pairs were more likely to derive a numerical parity rule than individuals, who tended to focus on the physical features of the system. Moreover, when facing a biological transmission problem, pairs tended to generate more abstract visualizations (e.g., directed graphs) than individuals, who tended to make more pictorial drawings. Schwartz (1995) speculated that these differences in the level of abstraction used by pairs versus individuals may be attributable to the need for members of the pair to negotiate a common representation that bridges their distinct perspectives, resulting in greater abstraction.

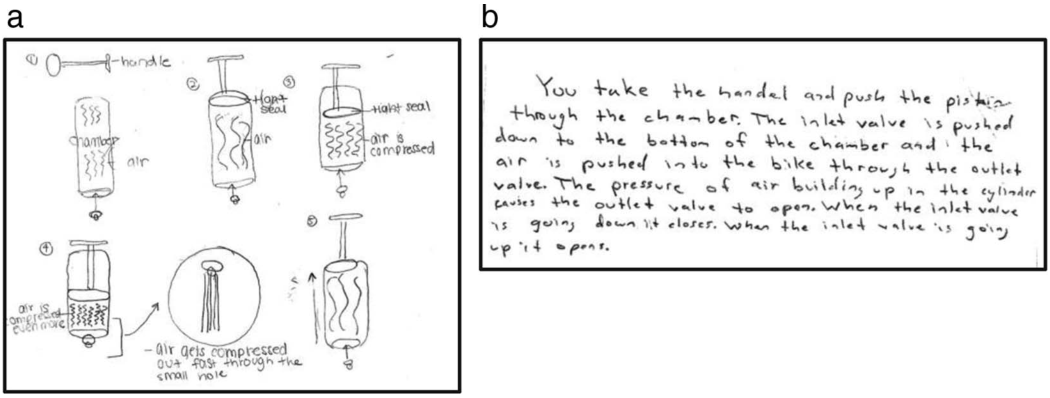
Such findings resonate with a much broader program of basic research examining how people spontaneously establish graphical conventions in the course of communicating with one another (Brennan & Clark, 1996; Fay, Garrod, Roberts, & Swoboda, 2010; Galantucci, 2005). One basic finding from a "music-drawing" paradigm used by Healey, Swoboda, Umata, and Katagiri (2001) is that enabling real-time interaction between participants (e.g., by allowing each pair member to erase or modify marks made by the other individual) promoted more abstract and generalizable graphical representations than in less-interactive conditions (e.g., pure turn-taking; Healey et al., 2001), in which partners tend to produce more figurative drawings. Using a similar paradigm with word cues, Fay et al. (2010) tracked pairs as they played several rounds of "Pictionary" with the same set of target items reappearing from round to round (e.g., "soap opera," "parliament"). People initially produced detailed drawings that directly resembled their referents; however, over successive rounds, fewer strokes were necessary to convey the same meaning, and the drawings became progressively more iconic/symbolic (Garrod, Fay, Lee, Oberlander, & MacLeod, 2007). Drawings produced by members of the same pair to refer to a given target became more similar to one another, whereas drawings of a given target were highly variable across pairs, suggesting that the resulting conventions depend on the specific history of interactions between communication partners (Fay et al., 2010).

Taken together, these studies provide converging evidence that rich social feedback plays a crucial role in refining graphical representations over repeated interactions; in the absence of this feedback, drawings can actually become more complex over time (Garrod et al., 2007; Hupet & Chantraine, 1992). One as yet untested implication of these findings for classroom practice is that relative to traditional lecture formats, more bidirectional communication between students and teachers may better promote student engagement and learning. One way this communication could be mediated is through a shared (virtual or physical) "whiteboard" upon which teachers and students could collaboratively provide information, ask questions, and resolve ambiguities in real time. Although this specific application of technology to mediate collaborative learning in physical classrooms has yet to be evaluated, exploring ways to apply basic research on graphical communication to real-world learning is in general a fruitful direction for future translational research.

Drawing to Explain

Drawing can function as a communication tool even in noninteractive social contexts. For example, generating an explanation of a concept can have the effect of inducing deeper conceptual understanding in the explainer as well as the (implied) explainee. In a pioneering experiment by Chi, Bassok, Lewis, Reimann, and Glaser (1989), students first studied worked-out examples of physics problems. Students who tended to generate many explanations to themselves (i.e., elaborate upon the components of the solution and relate them to the principles described in the textbook) tended to perform better on a separate set of new problems than students who did not self-explain. In follow-up experiments, students read a passage about the human circulatory system (Chi, De Leeuw, Chiu, & LaVancher, 1994). Some students were prompted to generate an explanation to themselves after reading each line, whereas other students read the text twice but did not self-explain. The authors found that students who were prompted to self-explain showed greater mastery of the material in the posttest than those who were not, suggesting that actively explaining one's emerging understanding of the material under study can enhance learning outcomes. Bobek and Tversky (2014) built on these findings by directly comparing the effectiveness of generating a visual explanation (i.e., by drawing a diagram, Figure 3a) versus generating a verbal one (i.e., writing a paragraph, Figure 3b) when learning about a natural phenomenon (i.e., how a bike pump works, and the difference between ionic and covalent bonds). Although both groups benefited from generating explanations, the visual-explanation group performed better than the verbal-explanation group in the delayed posttest. This shows that explanatory drawing can confer a learning benefit above and beyond that of verbal explanation at least under some circumstances. The authors speculated that one possible reason for this difference is that visual explanations may more readily provide explicit checks for completeness and coherence, as well as a platform for simulating how function is derived from structure (Bobek & Tversky, 2014).

Although the benefits of self-explaining are intuitive (Fonseca & Chi, 2011; Siegler, 2002),



You take the handel and push the pistin through the chamber. The inlet valve is pushed down to the bottom of the chamber and the air is pushed into the bike through the outlet valve. The pressure of air building up in the cylinder causes the outlet valve to open. When the inlet valve is going down it closes. when the inlet valve is going up it opens.

Figure 3. Example of (a) visual and (b) verbal explanations generated by students to communicate understanding of how a bike pump works. From "Creating Visual Explanations Improves Learning," by E. Bobek and B. Tversky, in *Proceedings of the 36th Annual Conference of the Cognitive Science Society* (p. 207), edited by P. Bello, M. Guarini, M. McShane, & B. Scassellati, 2014, Austin, TX: Cognitive Science Society. Copyright 2014 by the Cognitive Science Society.

recent work suggests that generating explanations can also lead a learner astray. In one study examining the effects of generating explanations in the context of category learning, participants (college-aged) were prompted to explain why each exemplar they saw was a member of one category or another. Williams, Lombrozo, and Rehder (2013) found that explaining led participants to overgeneralize based on their own explanations, allowing them to notice broad patterns, but preventing them from noticing patterns that involved exceptions. In a separate study, participants (5 year olds) were prompted to explain what kinds of objects they thought would set off a fictional "blicket detector." Consistent with previous work (Williams & Lombrozo, 2013), children were more likely to appeal to the patterns that explained more of their observations. However, when this pattern was at odds with children's prior knowledge (or assumptions) about which objects would trigger the detector, self-explaining made them less likely to generalize the pattern that explained more observations, suggesting that the act of generating an explanation increased the relative weight of prior knowledge in this inductive reasoning task (Walker, Williams, Lombrozo, & Gopnik, 2012).

In light of these findings, a logical direction for future studies would be to examine the cognitive benefits and potential pitfalls of drawing to explain, providing a fuller picture of the functional role of explanation in cognition. For instance, what are the costs associated with generating incorrect diagrams based on a biased or incomplete construal of the problem (Beth, de Jongh, & de Jongh-Kearl, 1970)? Another direction would be to manipulate whether explanatory drawings are elicited earlier or later in the course of a science lesson that introduces a complex new concept. To the extent that early drawings will express prior knowledge to a greater degree, how does this "graphical scaffolding" enable or constrain subsequent learning?

Prospects for Graphical Literacy in Science Education

When Balchin and Coleman (1966) made their case for the addition of "graphicacy" to the list of core intellectual skills championed within the U.S. education system, they may not have realized just how prescient their recommendation was. Today, we contend with vast quantities of information that stream over variegated channels, the flow of which we can control with a mere mouse click. Graphical representations, including pictures, tables, maps, graphs, and diagrams, help us to cope with this deluge of bits and symbols. When properly constructed, such visualizations are potent cognitive tools (Card et al., 1999; Milojevic et al., 2012; Munzner, 2015; Tversky et al., 2003) that help to organize this information and make it easier to see, at a glance, patterns that might have otherwise been hidden in the knots and folds of "raw" data. Given their versatility and pervasiveness, it may be more important than ever for educated citizens to develop the competencies to navigate such a visually dense world.

However, knowing how to read and interpret visualizations is only half of the story; graphical literacy also entails knowing how to make and adapt visualizations to address our questions and goals. This paper has focused on the cognitive affordances of one of the most basic of graphical techniques—drawing—as a window into how producing visualizations interacts with cognition more generally. Just as scientists generate graphs to think—to learn from observation, to reason about problems, to communicate and explain their findings to others—students learning how to think scientifically may stand to benefit by drawing as they observe, think, and communicate with one another in the classroom.

Can learning how to draw from observation enhance observational skills, perhaps through mechanisms similar to those that underlie visual learning from extensive observation alone? This is a fundamental question that should be addressed in future research because it is important for a deeper scientific understanding of the relationship between visual production and comprehension (Fan, Yamins, & Turk-Browne, in press) and of how graphical literacy can affect learning outcomes in real-world educational contexts. Effective interventions should be able to help students use their own drawings to identify gaps in their own knowledge, to reason logically about new problems, and to support collaborative scientific thinking. Ultimately, equipping students to think by creating visualizations may lead them to discover by their own hand not only truths about the present world they inhabit but also visions for a better world they could yet build.

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