Drawing to Learn in Science

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Should science learners be challenged to draw more? Certainly making visualizations is integral to scientific thinking. Scientists don't just use words but rely on diagrams, graphs, videos, photographs and other images to make discoveries, explain findings, and excite public interest. From the notebooks of Faraday and Maxwell (1) to current professional practices of chemists (2), scientists imagine new relationships, test ideas, and elaborate knowledge through visual representations (3-5).

However in the science classroom, learners mainly focus on interpreting others' visualizations; when drawing does occur, it is rare that learners are systematically encouraged to create their own visual forms to develop and show understanding (6). Drawing includes constructing a line graph from a table of values, sketching cells observed through a microscope, or inventing a way to show a scientific phenomenon (e.g., evaporation). Becoming proficient in science requires learners to develop many representational skills. We suggest five reasons why student drawing should be explicitly recognized alongside writing, reading and talking as a key element in science education. We offer distinct rationales, although in practice any single drawing activity will likely rest upon multiple justifications. We conclude by highlighting important questions yet to be answered and key future research to extend teachers' and learners' use of drawing.

Drawing to enhance engagement

Many students disengage from school science because rote learning and traditional topics reduce them to passive roles (7, 8). Reformers advocate more interactive, inquiry based, learning (9). Surveys of teachers and students indicate that when students drew to explore, coordinate, and justify understandings in science, they were more motivated to learn compared to conventional teaching (10). Individual learner differences are catered for if drawing is shaped by the learner's current or emerging ideas and knowledge of visual conventions.

Drawing to learn to represent in science

Students need to learn how scientists use multiple literacies of this subject to construct and record knowledge, where reading, writing, and talk are integrated with visual modes (11-13). Generating their own representations can deepen students' understanding of the specific conventions of representations (e.g., "This is how a line graph works.") and their purposes (e.g., "Line graphs are effective for showing continuous quantitative information."), as well as how representations work more generally (e.g., "The representation was better in this case as it was coherent, compact and parsimonious") (3, 14, 15). Teachers can guide students to acquire the visual literacies of science at the point when they will see their relevance and appreciate their explanatory power (16).

Drawing to reason in science

To show conceptual understanding, students must learn how to reason with multiple, often visual modes (9). Understanding 'sound waves', for instance, can involve being able to coordinate a range of wave diagrams, time sequenced representations of air particle movement and pressure variation. Different representations have distinctive attributes that both guide and constrain what learners do and come to understand (17-19). As they select specific features to focus on in their drawing, learners reason in various ways, aligning their drawing with observation, measurement, and/or emerging ideas (6, 20). Practice in flexible manipulation of representations has been argued to be central for developing expertise (21). Classroom research shows how students reason as they generate and refine models supported by expert teacher guidance (22, 23). This creative reasoning is distinct from, but complementary to, reasoning through argumentation (24).

Drawing as a learning strategy

Effective learning strategies help learners overcome limitations in presented material, organize their knowledge more effectively, integrate new and existing understanding, and ultimately can be transformative by generating new inferences (25, 26). Drawing can be one such effective strategy (6, 27). For example, asking learners to read a text and draw what they have understood requires them to make explicit this understanding in an inspectable form [(28) see Fig. S1 in supporting online material (SOM)]. Unlike other constructive strategies such as writing summaries or providing oral self explanations, visual representations have distinct attributes that match the visual-spatial demands of much science learning. Moreover, visual representation has been shown to encourage further constructive strategies (29). Inventing representations (including drawings) acts as preparation for future learning because it can help students discern key features and challenges of new tasks (30).

Drawing to communicate

Scientists draw to clarify ideas for colleagues, students, and the public (2, 5). In externalizing private knowledge more permanently, visual representation is one way to enable broader dissemination (4). Through drawing, students make their thinking explicit and specific, leading to opportunities to exchange and clarify meanings between peers (31). Where learners generate and publicly share their representations, they learn by critiquing the clarity and coherence of what they and their peers have drawn (32). These windows into student thinking can serve teachers in diagnostic, formative and summative assessment (33, 34) (Fig. S2).

Current Programs and New Directions

Various programs featuring drawing are now in progress (22, 23, 35). The Role of Representation in Learning Science (RiLS) project (36) is an exemplar showing how through hands-on activities and a variety of multimodal representations, in which drawing was central, learners aged 10 to 13 were guided to generate, justify and refine representations in science (Fig. S3)(authors are affiliated with RiLS). In a unit on 'water', students produced representations of particle ideas beyond the teachers' experience of previous performance.

In one task, students placed their wet hands on paper and then were challenged to represent what happens as the handprint diminishes. The drawings reflect learners expanding on previous work to reason about particle distribution and movement, energy exchange, and time-sequencing (Fig. 1). Students' visual choices indicate thoughtful engagement with the task of creating a coherent account. Through appraisal and refinement of drawings, teachers and students established some representational conventions, such as the circles reflecting particles. Teachers used these diagrams to assess and then further refine students' understandings

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of particle behavior.

The RiLS approach supported students to deepen their understanding of the selective purpose of representational choices. For example, a student justified the selective nature of his animation of particles in evaporation thus: “I was just focusing on what they do, not representing other things like shape and size, they are very, very tiny”. RiLS teachers have noted that their students engaged more in class, discussed at a higher level, and performed better in their workbooks (36). Analysis of test results showed stronger outcomes than in previous studies using comparable methods (37). Further research is now needed to establish explicit connections between drawing used in this way and learning.

Although there is growing evidence of the benefits of drawing to learn science, many unanswered questions remain. One active arena is exploration of how learning with new technologies can benefit from drawing. Learners can draw to help them understand what they are seeing in complex visualization environments (38). Drawing can be the way learners create models and interact with a system (39, 40) or their free-hand sketches can be automatically marked to provide timely feedback (41). Technology is also broadening our concept of drawing as learners create animations (42) or use cameras and clay models on drawn backdrops to generate one-second stop-frame movies of science processes (43).

We also need to research the fundamental mechanisms of drawing to learn. What skills do you first need to develop in order to best take advantage of learning by drawing? Perhaps some topics are sufficiently difficult to draw that attempting to do so is counterproductive. A further important research area concerns how teachers can best support their students to use drawing alongside writing and talking in the classroom. However, what is clear is the growing interest in drawing as it reflects new understandings of science as a multimodal discursive practice as well as mounting evidence for its value in supporting quality learning.

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Figures

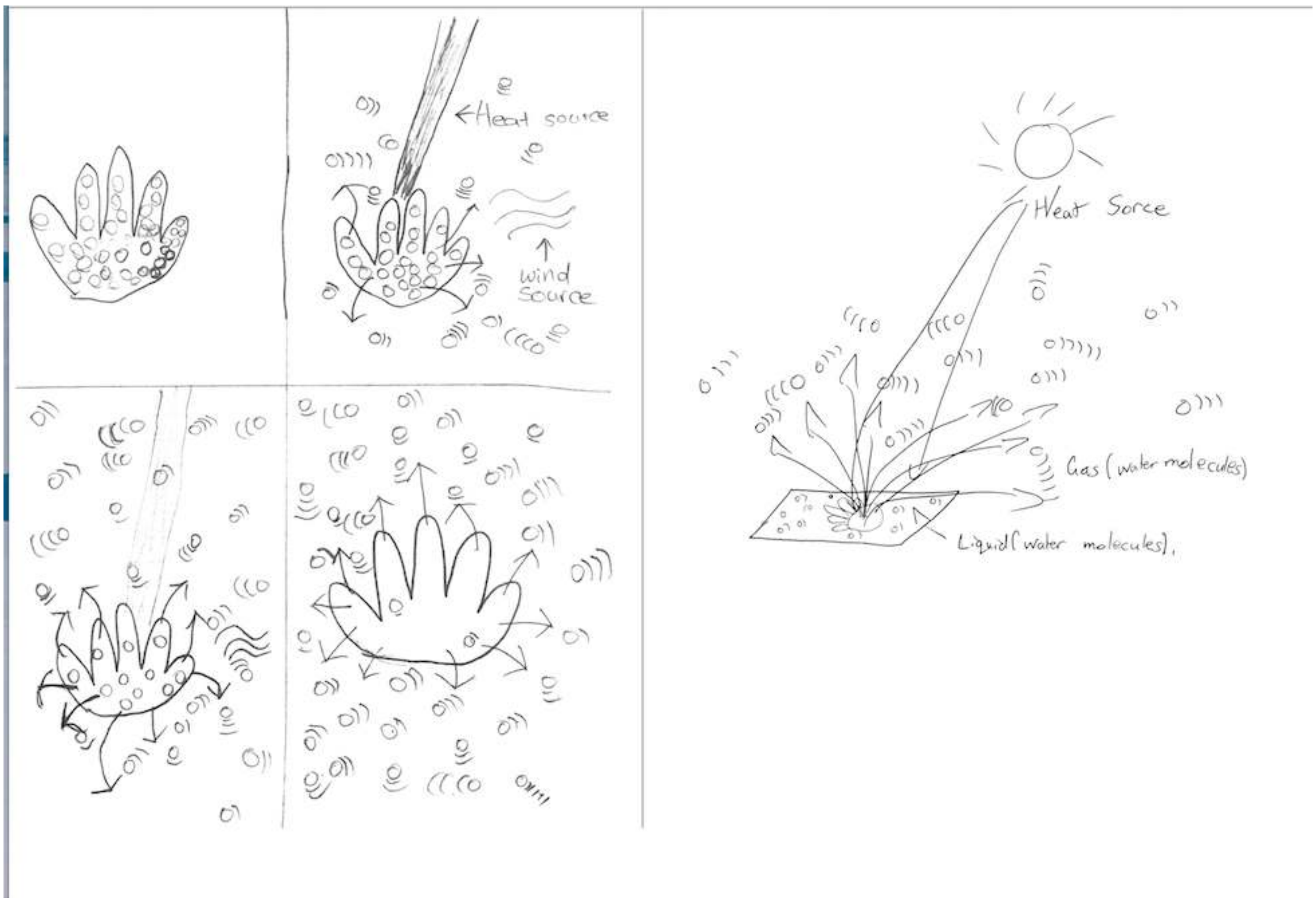

Fig.1 Drawings by two 11 year olds (A and B) of an evaporating handprint show representational choices that guide and communicate individu-al understandings. Image courtesy of RiLS (ARC DP070999)

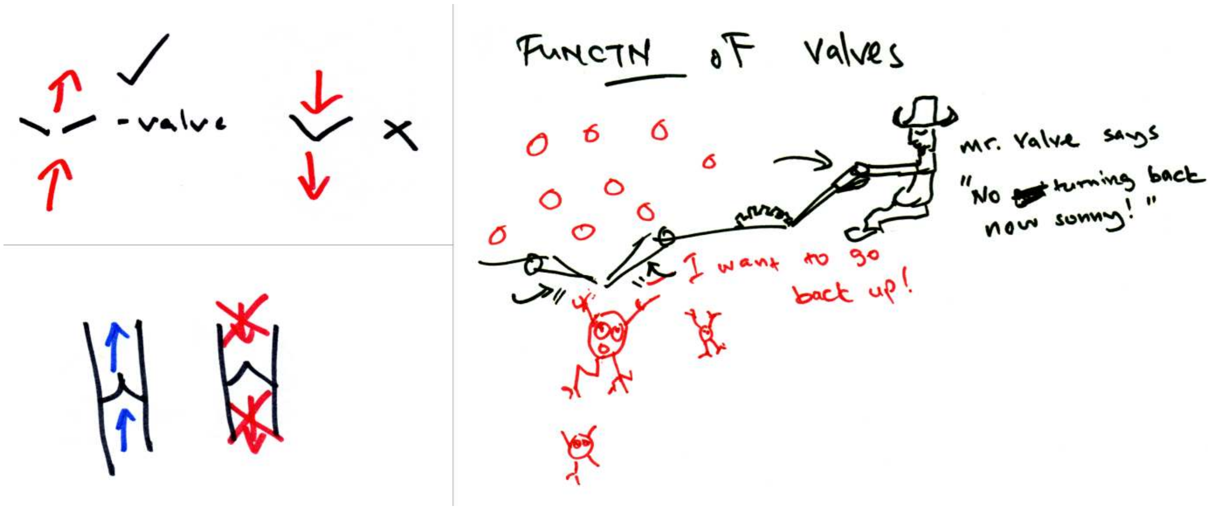

Fig. 1S Two typical (left hand side, top and bottom) and one less typical (right hand side) drawings created by university students given instructions to draw for their own understanding after reading the text *“Valves prevent the blood from moving backward or downward. These valves allow blood to flow in only one direction through the veins.” (Image courtesy of S Ainsworth)*

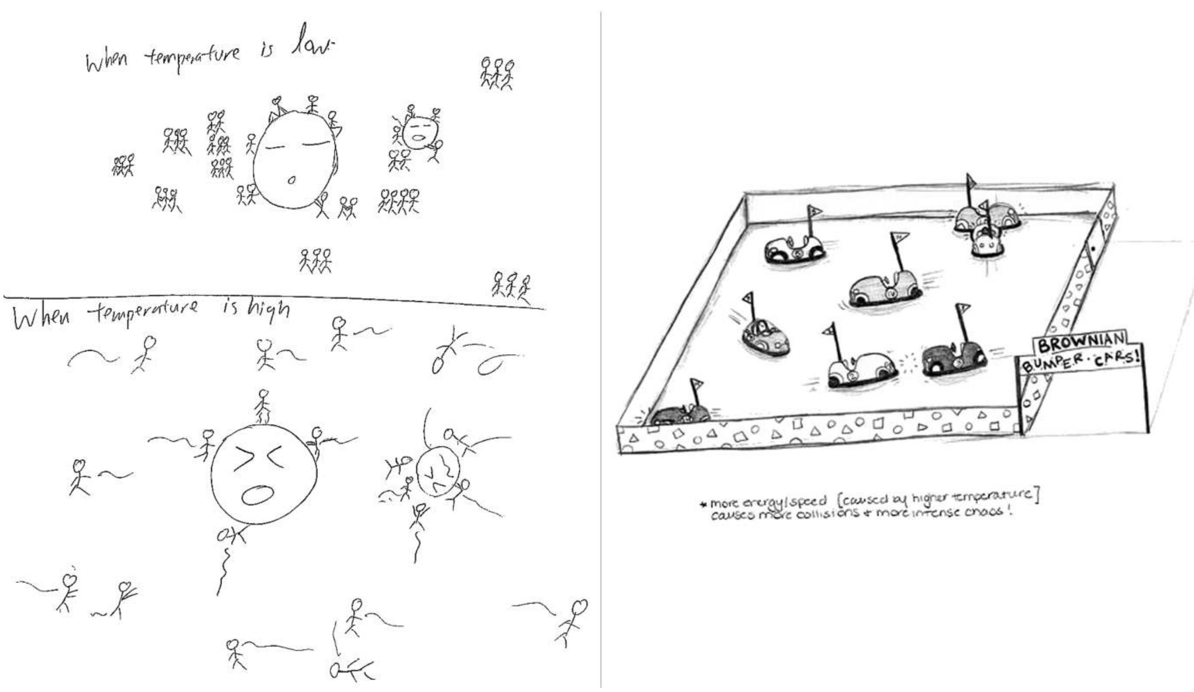

Fig. 2S Drawings created by university students after the instructions *“Draw, as if explaining to a high school student, how the motions of large and small particles suspended in a fluid are affected by an increase in temperature of the fluid”.* The two related drawings on the left hand side demonstrate a greater understanding of concepts such as particle size and motion compared to the picture on the right hand side. (Image courtesy of Picturing to Learn, funded by NSF DUE-0925110)

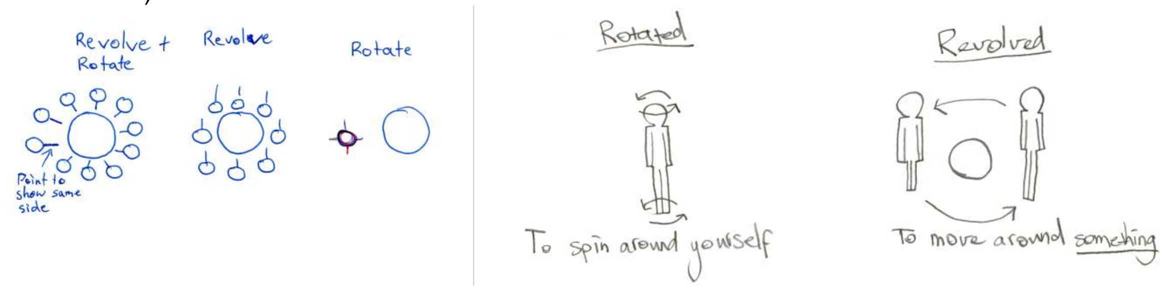

Fig. 3S Two examples of drawings by 12 year old students who were challenged to explain the meaning of the terms 're-volve' and 'rotate' in planetary motion. (Image courtesy of Representation in Learning Science, funded by ARC DP070999.)