POINTS OF VIEW

Pencil and paper

A unique set of tools facilitate thinking and hypothesis generation.

Creating pictures is integral to scientific thinking. In the visualization process, putting pencil to paper is an essential act of inward reflection and outward expression. It is a constructive activity that makes our thinking specific and explicit. Compared to other constructive approaches such as writing or verbal explanations, visual representation places distinct demands on our reasoning skills by forcing us to contextualize our understanding spatially.

Words afford us a level of ambiguity that is not extended to pictures. For example, although a protein can be described verbally in general terms as being intracellular, making a picture of an intracellular protein forces us to be specific about the cellular compartment in which the protein resides. Even if we use the most generalized depiction of a cell, indicating the position of the protein requires us to place it either in the cytoplasm, inside the nucleus or somewhere in between (**Fig. 1a**). Though all locations within the cell abide by the original parameter of 'intracellular', the interpretation of the illustration is more direct: the protein would be understood as being cytoplasmic, nuclear or associated with the nuclear membrane (**Fig. 1a**).

Visual depictions demand that we continually evaluate the premise of our understanding. Making quick sketches or doodles as a way to rationalize information can expose gaps in our thinking and lead to alternative conclusions and new ideas. It is useful to approach exploratory drawing with some abandonment of visual accuracy. We have a tendency to expect the objects we depict to look like the objects themselves. This expectation of technical mastery is likely the reason that so many adults give up drawing as an exercise. When drawing, it is productive to work quickly to refine sketches in order to explore many possibilities.

Pencil and paper provide an immediacy that is unmatched. The medium allows us to use whatever is within arm's reach: the back of a journal, a Post-it note or the napkin from lunch. There is no learning curve with pencil and paper as there often is with software designed for generating graphics. The typical input devices for computers (that is, keyboard and mouse) are woefully inadequate for supporting the kinds of expressiveness and fluidity that is required to engage the mind. The practical aspects of the digital medium often interfere with the cognitive process because we frequently need to stop and think about 'how' to do something.

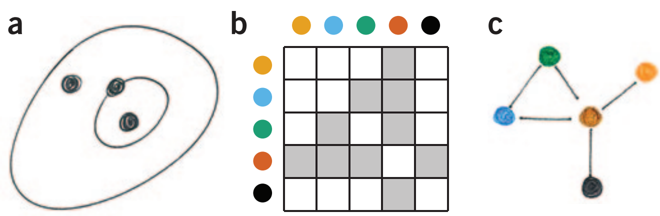

Figure 1 | The utility and constraints of drawing. (**a**) The nature of drawing requires spatial specificity. (**b**) Nodes are ordered as rows and columns, and connections between nodes are indicated as filled cells. (**c**) Drawing the data in **b** reveals the underlying data structure and extends the capacity of working memory.

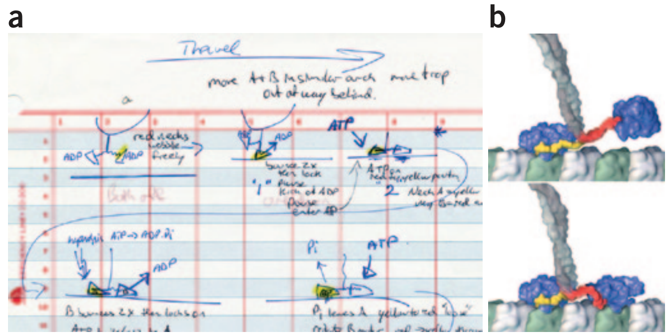

Figure 2 | Drawing of a scientific process. (**a**) Sketches and notes from R. Vale and R. Milligan. (**b**) An animated model of kinesin traveling along microtubules by Graham Johnson (http://www.youtube.com/watch?v=YAva4g3Pk6k). Images courtesy of R. Vale.

The process of drawing is linked to the process of thinking, and creating mental models can help us gain insights into scientific data. By externalizing our knowledge to a tangible form, for example, we create opportunities to exchange interpretations and to clarify meaning with our colleagues. In educational settings, drawing has been shown to improve comprehension of scientific concepts in schoolchildren. Students were found to perform markedly better after they had been prompted to generate, justify and refine visual representations of classroom material[1].

One function of drawing is to augment our short working memory. Visual working memory describes our ability to retain visual information in order to achieve a specific task (such as reading a map). It is difficult for us to remember the attributes of more than a few objects for longer than several seconds. The table shown in **Figure 1b** describes a simple network where connections between the nodes (arranged as rows and columns) are indicated by filled cells. Reading the connections successively and storing them in memory to create a mental picture of the underlying network is not trivial. By portraying the same information as a diagram, we can overcome the limitation of our working memory and easily see complex relationships such as the number of intervening nodes between any pair of nodes (**Fig. 1c**).

The history of science is full of examples documenting the importance of drawing and sketches in the creative scientific process. Ronald Vale and his colleagues used drawings such as the ones shown in **Figure 2a** to build the intricate molecular picture that illustrates how the kinesin motor protein achieves its forward motion. Visual depiction of their data makes clear that the interactions of a kinesin dimer's neck linkers limit the protein's physical movement to 'foot-over-foot' as it travels along the microtubules (**Fig. 2b**).

Visualization is vital to the scientific process. Relying on the powerful connection between thinking, seeing and understanding, exploratory drawing is critical for creating frameworks for knowledge.

COMPETING FINANCIAL INTERESTS
The authors declare no competing financial interests.

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1. Hubber, P., Tytler, R. & Haslam, F. *Res. Sci. Educ.* **40**, 5–28 (2010).

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