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The role of visual representations in scientific practices: from conceptual understanding and knowledge generation to ‘seeing’ how science works

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Abstract

Background: The use of visual representations (i.e., photographs, diagrams, models) has been part of science, and their use makes it possible for scientists to interact with and represent complex phenomena, not observable in other ways. Despite a wealth of research in science education on visual representations, the emphasis of such research has mainly been on the conceptual understanding when using visual representations and less on visual representations as epistemic objects. In this paper, we argue that by positioning visual representations as epistemic objects of scientific practices, science education can bring a renewed focus on how visualization contributes to knowledge formation in science from the learners’ perspective.

Results: This is a theoretical paper, and in order to argue about the role of visualization, we first present a case study, that of the discovery of the structure of DNA that highlights the epistemic components of visual information in science. The second case study focuses on Faraday’s use of the lines of magnetic force. Faraday is known of his exploratory, creative, and yet systemic way of experimenting, and the visual reasoning leading to theoretical development was an inherent part of the experimentation. Third, we trace a contemporary account from science focusing on the experimental practices and how reproducibility of experimental procedures can be reinforced through video data.

Conclusions: Our conclusions suggest that in teaching science, the emphasis in visualization should shift from cognitive understanding—using the products of science to understand the content—to engaging in the processes of visualization. Furthermore, we suggest that it is essential to design curriculum materials and learning environments that create a social and epistemic context and invite students to engage in the practice of visualization as evidence, reasoning, experimental procedure, or a means of communication and reflect on these practices. Implications for teacher education include the need for teacher professional development programs to problematize the use of visual representations as epistemic objects that are part of scientific practices.

Keywords: Visual representations; Epistemic practices; Science learning

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Background

During the last decades, research and reform documents in science education across the world have been calling for an emphasis not only on the content but also on the processes of science (Bybee 2014; Eurydice 2012; Duschl and Bybee 2014; Osborne 2014; Schwartz et al. 2012), in order to make science accessible to the students and enable them to understand the epistemic foundation of science. Scientific practices, part of the process of science, are the cognitive and discursive activities that are targeted in science education to develop epistemic understanding and appreciation of the nature of science (Duschl et al. 2008) and have been the emphasis of recent reform documents in science education across the world (Achieve 2013; Eurydice 2012). With the term scientific practices, we refer to the processes that take place during scientific discoveries and include among others: asking questions, developing and using models, engaging in arguments, and constructing and communicating explanations (National Research Council 2012). The emphasis on scientific practices aims to move the teaching of science from knowledge to the understanding of the processes and the epistemic aspects of science. Additionally, by placing an emphasis on engaging students in scientific practices, we aim to help students acquire scientific knowledge in meaningful contexts that resemble the reality of scientific discoveries.

Despite a wealth of research in science education on visual representations, the emphasis of such research has mainly been on the conceptual understanding when using visual representations and less on visual representations as epistemic objects. In this paper, we argue that by positioning visual representations as epistemic objects, science education can bring a renewed focus on how visualization contributes to knowledge formation in science from the learners' perspective. Specifically, the use of visual representations (i.e., photographs, diagrams, tables, charts) has been part of science and over the years has evolved with the new technologies (i.e., from drawings to advanced digital images and three dimensional models). Visualization makes it possible for scientists to interact with complex phenomena (Richards 2003), and they might convey important evidence not observable in other ways. Visual representations as a tool to support cognitive understanding in science have been studied extensively (i.e., Gilbert 2010; Wu and Shah 2004). Studies in science education have explored the use of images in science textbooks (i.e., Dimopoulos et al. 2003; Bungum 2008), students' representations or models when doing science (i.e., Gilbert et al. 2008; Dori et al. 2003; Lehrer and Schauble 2012; Schwarz et al. 2009), and students' images of science and scientists (i.e., Chambers 1983). Therefore, studies in the field of science education have been using the term visualization as "the formation of an internal

representation from an external representation" (Gilbert et al. 2008, p. 4) or as a tool for conceptual understanding for students.

In this paper, we do not refer to visualization as mental image, model, or presentation only (Gilbert et al. 2008; Philips et al. 2010) but instead focus on visual representations or visualization as epistemic objects. Specifically, we refer to visualization as a process for knowledge production and growth in science. In this respect, modeling is an aspect of visualization, but what we are focusing on with visualization is not on the use of model as a tool for cognitive understanding (Gilbert 2010; Wu and Shah 2004) but the on the process of modeling as a scientific practice which includes the construction and use of models, the use of other representations, the communication in the groups with the use of the visual representation, and the appreciation of the difficulties that the science phase in this process. Therefore, the purpose of this paper is to present through the history of science how visualization can be considered not only as a cognitive tool in science education but also as an epistemic object that can potentially support students to understand aspects of the nature of science.

Scientific practices and science education

According to the New Generation Science Standards (Achieve 2013), scientific practices refer to: asking questions and defining problems; developing and using models; planning and carrying out investigations; analyzing and interpreting data; using mathematical and computational thinking; constructing explanations and designing solutions; engaging in argument from evidence; and obtaining, evaluating, and communicating information. A significant aspect of scientific practices is that science learning is more than just about learning facts, concepts, theories, and laws. A fuller appreciation of science necessitates the understanding of the science relative to its epistemological grounding and the process that are involved in the production of knowledge (Hogan and Maglienti 2001; Wickman 2004).

The New Generation Science Standards is, among other changes, shifting away from science inquiry and towards the inclusion of scientific practices (Duschl and Bybee 2014; Osborne 2014). By comparing the abilities to do scientific inquiry (National Research Council 2000) with the set of scientific practices, it is evident that the latter is about engaging in the processes of doing science and experiencing in that way science in a more authentic way. Engaging in scientific practices according to Osborne (2014) "presents a more authentic picture of the endeavor that is science" (p.183) and also helps the students to develop a deeper understanding of the epistemic aspects of science. Furthermore, as Bybee (2014) argues, by engaging students in scientific practices, we

involve them in an understanding of the nature of science and an understanding on the nature of scientific knowledge.

Science as a practice and scientific practices as a term emerged by the philosopher of science, Kuhn (Osborne 2014), refers to the processes in which the scientists engage during knowledge production and communication. The work that is followed by historians, philosophers, and sociologists of science (Latour 2011; Longino 2002; Nersessian 2008) revealed the scientific practices in which the scientists engage in and include among others theory development and specific ways of talking, modeling, and communicating the outcomes of science.

Visualization as an epistemic object

Schematic, pictorial symbols in the design of scientific instruments and analysis of the perceptual and functional information that is being stored in those images have been areas of investigation in philosophy of scientific experimentation (Gooding et al. 1993). The nature of visual perception, the relationship between thought and vision, and the role of reproducibility as a norm for experimental research form a central aspect of this domain of research in philosophy of science. For instance, Rothbart (1997) has argued that visualizations are commonplace in the theoretical sciences even if every scientific theory may not be defined by visualized models.

Visual representations (i.e., photographs, diagrams, tables, charts, models) have been used in science over the years to enable scientists to interact with complex phenomena (Richards 2003) and might convey important evidence not observable in other ways (Barber et al. 2006). Some authors (e.g., Ruivenkamp and Rip 2010) have argued that visualization is as a core activity of some scientific communities of practice (e.g., nanotechnology) while others (e.g., Lynch and Edgerton 1988) have differentiated the role of particular visualization techniques (e.g., of digital image processing in astronomy). Visualization in science includes the complex process through which scientists develop or produce imagery, schemes, and graphical representation, and therefore, what is of importance in this process is not only the result but also the methodology employed by the scientists, namely, how this result was produced. Visual representations in science may refer to objects that are believed to have some kind of material or physical existence but equally might refer to purely mental, conceptual, and abstract constructs (Pauwels 2006). More specifically, visual representations can be found for: (a) phenomena that are not observable with the eye (i.e., microscopic or macroscopic); (b) phenomena that do not exist as visual representations but can be translated as such (i.e., sound); and (c) in experimental settings to provide visual data representations (i.e., graphs

presenting velocity of moving objects). Additionally, since science is not only about replicating reality but also about making it more understandable to people (either to the public or other scientists), visual representations are not only about reproducing the nature but also about: (a) functioning in helping solving a problem, (b) filling gaps in our knowledge, and (c) facilitating knowledge building or transfer (Lynch 2006).

Using or developing visual representations in the scientific practice can range from a straightforward to a complicated situation. More specifically, scientists can observe a phenomenon (i.e., mitosis) and represent it visually using a picture or diagram, which is quite straightforward. But they can also use a variety of complicated techniques (i.e., crystallography in the case of DNA studies) that are either available or need to be developed or refined in order to acquire the visual information that can be used in the process of theory development (i.e., Latour and Woolgar 1979). Furthermore, some visual representations need decoding, and the scientists need to learn how to read these images (i.e., radiologists); therefore, using visual representations in the process of science requires learning a new language that is specific to the medium/methods that is used (i.e., understanding an X-ray picture is different from understanding an MRI scan) and then communicating that language to other scientists and the public.

There are much intent and purposes of visual representations in scientific practices, as for example to make a diagnosis, compare, describe, and preserve for future study, verify and explore new territory, generate new data (Pauwels 2006), or present new methodologies. According to Latour and Woolgar (1979) and Knorr Cetina (1999), visual representations can be used either as primary data (i.e., image from a microscope), or can be used to help in concept development (i.e., models of DNA used by Watson and Crick), to uncover relationships and to make the abstract more concrete (graphs of sound waves). Therefore, visual representations and visual practices, in all forms, are an important aspect of the scientific practices in developing, clarifying, and transmitting scientific knowledge (Pauwels 2006).

Methods and Results: Merging Visualization and scientific practices in science

In this paper, we present three case studies that embody the working practices of scientists in an effort to present visualization as a scientific practice and present our argument about how visualization is a complex process that could include among others modeling and use of representation but is not only limited to that. The first case study explores the role of visualization in the construction of knowledge about the structure of DNA, using visuals as evidence. The second case study focuses on Faraday's use of the lines of magnetic force and the

visual reasoning leading to the theoretical development that was an inherent part of the experimentation. The third case study focuses on the current practices of scientists in the context of a peer-reviewed journal called the *Journal of Visualized Experiments* where the methodology is communicated through videotaped procedures. The three case studies represent the research interests of the three authors of this paper and were chosen to present how visualization as a practice can be involved in all stages of doing science, from hypothesizing and evaluating evidence (case study 1) to experimenting and reasoning (case study 2) to communicating the findings and methodology with the research community (case study 3), and represent in this way the three functions of visualization as presented by Lynch (2006). Furthermore, the last case study showcases how the development of visualization technologies has contributed to the communication of findings and methodologies in science and present in that way an aspect of current scientific practices. In all three cases, our approach is guided by the observation that the visual information is an integral part of scientific practices at the least and furthermore that they are particularly central in the scientific practices of science.

Case study 1: use visual representations as evidence in the discovery of DNA

The focus of the first case study is the discovery of the structure of DNA. The DNA was first isolated in 1869 by Friedrich Miescher, and by the late 1940s, it was known that it contained phosphate, sugar, and four nitrogen-containing chemical bases. However, no one had figured the structure of the DNA until Watson and Crick presented their model of DNA in 1953. Other than the social aspects of the discovery of the DNA, another important aspect was the role of visual evidence that led to knowledge development in the area. More specifically, by studying the personal accounts of Watson (1968) and Crick (1988) about the discovery of the structure of the DNA, the following main ideas regarding the role of visual representations in the production of knowledge can be identified: (a) The use of visual representations was an important part of knowledge growth and was often dependent upon the discovery of new technologies (i.e., better microscopes or better techniques in crystallography that would provide better visual representations as evidence of the helical structure of the DNA); and (b) Models (three-dimensional) were used as a way to represent the visual images (X-ray images) and connect them to the evidence provided by other sources to see whether the theory can be supported. Therefore, the model of DNA was built based on the combination of visual evidence and experimental data.

An example showcasing the importance of visual representations in the process of knowledge production in this case is provided by Watson, in his book *The Double Helix* (1968):

...since the middle of the summer Rosy [Rosalind Franklin] had had evidence for a new three-dimensional form of DNA. It occurred when the DNA 2molecules were surrounded by a large amount of water. When I asked what the pattern was like, Maurice went into the adjacent room to pick up a print of the new form they called the "B" structure. The instant I saw the picture, my mouth fell open and my pulse began to race. The pattern was unbelievably simpler than those previously obtained (A form). Moreover, the black cross of reflections which dominated the picture could arise only from a helical structure. With the A form the argument for the helix was never straightforward, and considerable ambiguity existed as to exactly which type of helical symmetry was present. With the B form however, mere inspection of its X-ray picture gave several of the vital helical parameters. (p. 167-169)

As suggested by Watson's personal account of the discovery of the DNA, the photo taken by Rosalind Franklin (Fig. 1) convinced him that the DNA molecule must consist of two chains arranged in a paired helix, which resembles a spiral staircase or ladder, and on March 7, 1953, Watson and Crick finished and presented their model of the structure of DNA (Watson and Berry 2004; Watson 1968) which was

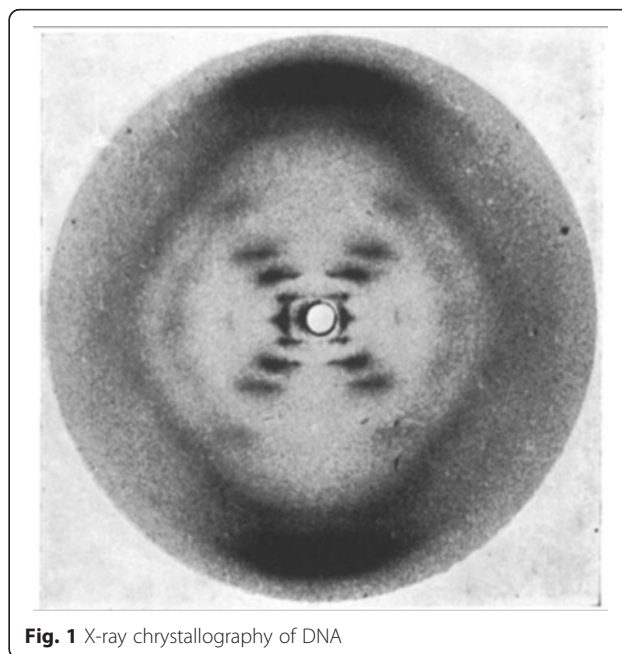


Fig. 1 X-ray crystallography of DNA

based on the visual information provided by the X-ray image and their knowledge of chemistry.

In analyzing the visualization practice in this case study, we observe the following instances that highlight how the visual information played a role:

- (a) Asking questions and defining problems: The real world in the model of science can at some points only be observed through visual representations or representations, i.e., if we are using DNA as an example, the structure of DNA was only observable through the crystallography images produced by Rosalind Franklin in the laboratory. There was no other way to observe the structure of DNA, therefore the real world.
- (b) Analyzing and interpreting data: The images that resulted from crystallography as well as their interpretations served as the data for the scientists studying the structure of DNA.
- (c) Experimenting: The data in the form of visual information were used to predict the possible structure of the DNA.
- (d) Modeling: Based on the prediction, an actual three-dimensional model was prepared by Watson and Crick. The first model did not fit with the real world (refuted by Rosalind Franklin and her research group from King's College) and Watson and Crick had to go through the same process again to find better visual evidence (better crystallography images) and create an improved visual model.

Example excerpts from Watson's biography provide further evidence for how visualization practices were applied in the context of the discovery of DNA (Table 1).

In summary, by examining the history of the discovery of DNA, we showcased how visual data is used as *scientific evidence* in science, identifying in that way an aspect of the nature of science that is still unexplored in the history of science and an aspect that has been ignored in the teaching of science. Visual representations are used in many ways: as images, as models, as evidence to support or rebut a model, and as interpretations of reality.

Case study 2: applying visual reasoning in knowledge production, the example of the lines of magnetic force

The focus of this case study is on Faraday's use of the lines of magnetic force. Faraday is known of his exploratory, creative, and yet systemic way of experimenting, and the visual reasoning leading to theoretical development was an inherent part of this experimentation (Gooding 2006). Faraday's articles or notebooks do not include mathematical formulations; instead, they include images and illustrations from experimental devices and setups to the recapping of his theoretical ideas (Nersessian 2008). According to Gooding (2006), "Faraday's visual method was designed not to copy apparent features of the world, but to analyse and replicate them" (2006, p. 46).

The lines of force played a central role in Faraday's research on electricity and magnetism and in the development of his "field theory" (Faraday 1852a; Nersessian

Table 1 Scientific practices and exemplar quotes on visualization from Watson's autobiography (emphasis added)

Scientific practice	Representative quote
Observation	"It was downright obvious to her [Ros] that the only way to establish the DNA structure was by pure crystallographic approaches." (p.49)
Analyzing and interpreting data	"Maurice's X-ray diffraction picture of DNA was to the point. It was flicked on the screen near the end of his talk. Maurice's dry English form did not permit enthusiasm as he stated that the picture showed <i>much more detail than previous pictures</i> , and could in fact, be considered as <i>arising from a crystalline substance</i> . And when the structure of DNA was known, we might be in a better position to understand how genes work." (p. 23)
Prediction as Visual	"Six weeks of listening to Francis had made me realize that the crux of matter was <i>whether Rosy's new X-ray pictures would lend any support for a helical DNA structure</i> . The really relevant experimental details were those which might provide clues in constructing molecular models." (p. 49) "Francis would survey the progress of the past few hours, bringing our listener up-to-date on how we decided upon models in which the sugar-phosphate backbone was in the center of the molecule. <i>Only in that way would it be possible to obtain a structure regular enough to give the crystalline diffraction patterns observed by Maurice and Rosy</i> " (p.57)
Model as visual	"The a-helix had not been found by only staring at X-ray pictures; the essential trick, instead, was to ask which atoms like to sit next to each other. In place of pencil and paper, <i>the main working tools were a set of molecular models superficially resembling the toys of pre-school children</i> . We could thus see no reason why we should not solve DNA in the same way. <i>All we had to do was to construct a set of molecular models and begin to play – with luck; the structure would be a helix. Any other type of configuration would be much more complicated.</i> " (p. 35–36)
Other aspects of scientific practice	"Virtually all biochemist, including Herman, <i>were unable to understand the arguments of the X-ray people</i> " (p. 23) As model building did not appeal to her [Rosalind], <i>at no time did she mention Pauling's triumph over the A-helix. The idea of using tinker-like models to solve biological structures was clearly a last resort.</i> " (p.49)

1984). Before Faraday, the experiments with iron filings around magnets were known and the term “magnetic curves” was used for the iron filing patterns and also for the geometrical constructs derived from the mathematical theory of magnetism (Gooding et al. 1993). However, Faraday used the lines of force for explaining his experimental observations and in constructing the theory of forces in magnetism and electricity. Examples of Faraday’s different illustrations of lines of magnetic force are given in Fig. 2. Faraday gave the following experiment-based definition for the lines of magnetic forces:

A line of magnetic force may be defined as that line which is described by a very small magnetic needle, when it is so moved in either direction correspondent to its length, that the needle is constantly a tangent to the line of motion; or it is that line along which, if a transverse wire be moved in either direction, there is no tendency to the formation of any current in the wire, whilst if moved in any other direction there is such a tendency; or it is that line which coincides with the direction of the magnecrystallic axis of a crystal of bismuth, which is carried in either direction along it. The direction of these lines about and amongst magnets and electric currents, is easily represented and understood, in a general manner, by the ordinary use of iron filings. (Faraday 1852a, p. 25 (3071))

The definition describes the connection between the experiments and the visual representation of the results. Initially, the lines of force were just geometric representations, but later, Faraday treated them as physical objects (Nersessian 1984; Pocovi and Finlay 2002):

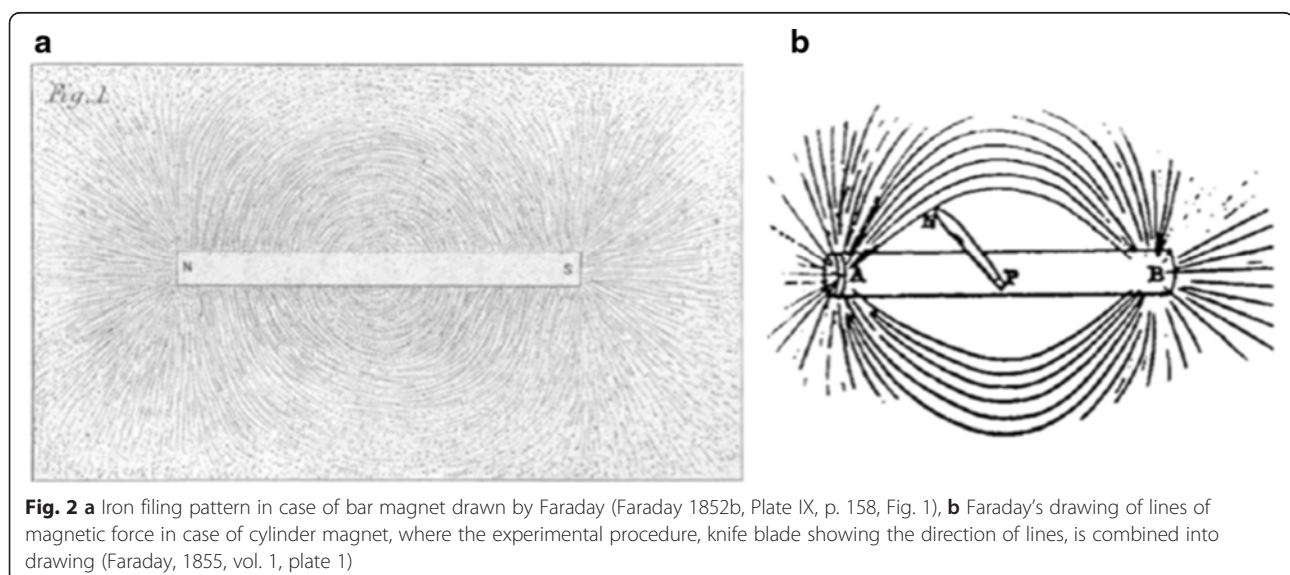
I have sometimes used the term lines of force so vaguely, as to leave the reader doubtful whether I intended it as a merely representative idea of the forces, or as the description of the path along which the power was continuously exerted. ... wherever the expression line of force is taken simply to represent the disposition of forces, it shall have the fullness of that meaning; but that wherever it may seem to represent the idea of the physical mode of transmission of the force, it expresses in that respect the opinion to which I incline at present. The opinion may be erroneous, and yet all that relates or refers to the disposition of the force will remain the same. (Faraday, 1852a, p. 55-56 (3075))

He also felt that the lines of force had greater explanatory power than the dominant theory of action-at-a-distance:

Now it appears to me that these lines may be employed with great advantage to represent nature, condition, direction and comparative amount of the magnetic forces; and that in many cases they have, to the physical reasoned at least, a superiority over that method which represents the forces as concentrated in centres of action... (Faraday, 1852a, p. 26 (3074))

For giving some insight to Faraday’s visual reasoning as an epistemic practice, the following examples of Faraday’s studies of the lines of magnetic force (Faraday 1852a, 1852b) are presented:

(a) Asking questions and defining problems: The iron filing patterns formed the empirical basis for the visual



model: 2D visualization of lines of magnetic force as presented in Fig. 2. According to Faraday, these iron filing patterns were suitable for illustrating the direction and form of the magnetic lines of force (emphasis added):

It must be well understood that these forms give no indication by their appearance of the relative strength of the magnetic force at different places, inasmuch as the appearance of the lines depends greatly upon the quantity of filings and the amount of tapping; *but the direction and forms of these lines are well given, and these indicate, in a considerable degree, the direction in which the forces increase and diminish.* (Faraday 1852b, p.158 (3237))

Despite being static and two dimensional on paper, the lines of magnetic force were dynamical (Nersessian 1992, 2008) and three dimensional for Faraday (see Fig. 2b). For instance, Faraday described the lines of force “expanding,” “bending,” and “being cut” (Nersessian 1992). In Fig. 2b, Faraday has summarized his experiment (bar magnet and knife blade) and its results (lines of force) in one picture.

(b) Analyzing and interpreting data: The model was so powerful for Faraday that he ended up thinking them as physical objects (e.g., Nersessian 1984), i.e., making interpretations of the way forces act. Of course, he made a lot of experiments for showing the physical existence of the lines of force, but he did not succeed in it (Nersessian 1984). The following quote illuminates Faraday’s use of the lines of force in different situations:

The study of these lines has, at different times, been greatly influential in leading me to various results, which I think prove their utility as well as fertility. Thus, the law of magneto-electric induction; the earth’s inductive action; the relation of magnetism and light; diamagnetic action and its law, and magnetocrystallic action, are the cases of this kind... (Faraday 1852a, p. 55 (3174))

(c) Experimenting: In Faraday’s case, he used a lot of exploratory experiments; in case of lines of magnetic force, he used, e.g., iron filings, magnetic needles, or current carrying wires (see the quote above). The magnetic field is not directly observable and the representation of lines of force was a visual model, which includes the direction, form, and magnitude of field.

(d) Modeling: There is no denying that the lines of magnetic force are visual by nature. Faraday’s views of lines of force developed gradually during the years, and he applied and developed them in different contexts such as electromagnetic, electrostatic, and magnetic induction (Nersessian 1984). An example of Faraday’s

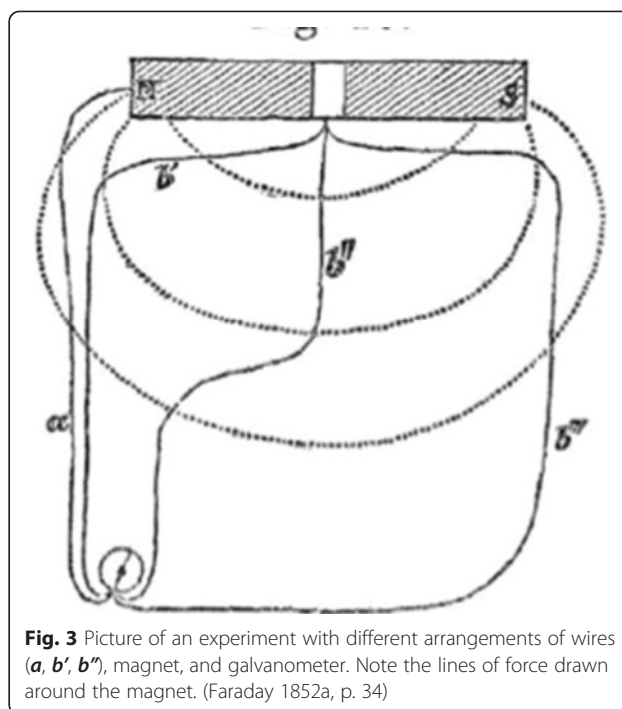


Fig. 3 Picture of an experiment with different arrangements of wires (*a, b', b''*), magnet, and galvanometer. Note the lines of force drawn around the magnet. (Faraday 1852a, p. 34)

explanation of the effect of the wire *b*'s position to experiment is given in Fig. 3. In Fig. 3, few magnetic lines of force are drawn, and in the quote below, Faraday is explaining the effect using these magnetic lines of force (emphasis added):

*It will be evident by inspection of Fig. 3, that, however the wires are carried away, the general result will, according to the assumed principles of action, be the same; for if *a* be the axial wire, and *b', b'', b'''* the equatorial wire, represented in three different positions, whatever magnetic lines of force pass across the latter wire in one position, will also pass it in the other, or in any other position which can be given to it. The distance of the wire at the place of intersection with the lines of force, has been shown, by the experiments (3093.), to be unimportant.* (Faraday 1852a, p. 34 (3099))

In summary, by examining the history of Faraday’s use of lines of force, we showed how visual imagery and reasoning played an important part in Faraday’s construction and representation of his “field theory”. As Gooding has stated, “many of Faraday’s sketches are far more that depictions of observation, they are tools for reasoning with and about phenomena” (2006, p. 59).

Case study 3: visualizing scientific methods, the case of a journal

The focus of the third case study is the *Journal of Visualized Experiments (JoVE)*, a peer-reviewed publication indexed in PubMed. The journal devoted to the publication

of biological, medical, chemical, and physical research in a video format. The journal describes its history as follows:

JoVE was established as a new tool in life science publication and communication, with participation of scientists from leading research institutions. JoVE takes advantage of video technology to capture and transmit the multiple facets and intricacies of life science research. Visualization greatly facilitates the understanding and efficient reproduction of both basic and complex experimental techniques, thereby addressing two of the biggest challenges faced by today's life science research community: i) low transparency and poor reproducibility of biological experiments and ii) time and labor-intensive nature of learning new experimental techniques. (<http://www.jove.com/>)

By examining the journal content, we generate a set of categories that can be considered as indicators of relevance and significance in terms of epistemic practices of science that have relevance for science education. For example, the quote above illustrates how scientists view some norms of scientific practice including the norms of “transparency” and “reproducibility” of experimental methods and results, and how the visual format of the journal facilitates the implementation of these norms. “Reproducibility” can be considered as an epistemic criterion that sits at the heart of what counts as an experimental procedure in science:

Investigating what should be reproducible and by whom leads to different types of experimental reproducibility, which can be observed to play different roles in experimental practice. A successful application of the strategy of reproducing an experiment is an achievement that may depend on certain isiosyncratic aspects of a local situation. Yet a purely local experiment that cannot be carried out by other experimenters and in other experimental contexts will, in the end be unproductive in science. (Sarkar and Pfeifer 2006, p.270)

We now turn to an article on “Elevated Plus Maze for Mice” that is available for free on the journal website (<http://www.jove.com/video/1088/elevated-plus-maze-for-mice>). The purpose of this experiment was to investigate anxiety levels in mice through behavioral analysis. The journal article consists of a 9-min video accompanied by text. The video illustrates the handling of the mice in soundproof location with less light, worksheets with characteristics of mice, computer software, apparatus, resources, setting up the computer software, and the video recording of mouse behavior on the computer. The authors

describe the apparatus that is used in the experiment and state how procedural differences exist between research groups that lead to difficulties in the interpretation of results:


The apparatus consists of open arms and closed arms, crossed in the middle perpendicularly to each other, and a center area. Mice are given access to all of the arms and are allowed to move freely between them. The number of entries into the open arms and the time spent in the open arms are used as indices of open space-induced anxiety in mice. Unfortunately, the procedural differences that exist between laboratories make it difficult to duplicate and compare results among laboratories.

The authors' emphasis on the particularity of procedural context echoes in the observations of some philosophers of science:

It is not just the knowledge of experimental objects and phenomena but also their actual existence and occurrence that prove to be dependent on specific, productive interventions by the experimenters” (Sarkar and Pfeifer 2006, pp. 270-271)

The inclusion of a video of the experimental procedure specifies what the apparatus looks like (Fig. 4) and how the behavior of the mice is captured through video recording that feeds into a computer (Fig. 5). Subsequently, a computer software which captures different variables such as the distance traveled, the number of entries, and the time spent on each arm of the apparatus. Here, there is visual information at different levels of representation ranging from reconfiguration of raw video data to representations that analyze the data around the variables in question (Fig. 6). The practice of levels of visual representations is not particular to the biological sciences. For instance, they are commonplace in nanotechnological practices:

In the visualization processes, instruments are needed that can register the nanoscale and provide raw data, which needs to be transformed into images. Some Imaging Techniques have software incorporated already where this transformation automatically takes place, providing raw images. Raw data must be translated through the use of Graphic Software and software is also used for the further manipulation of images to highlight what is of interest to capture the (inferred) phenomena – and to capture the reader. There are two levels of choice: Scientists have to choose which imaging technique and embedded software to use for the job at hand, and they will then have to

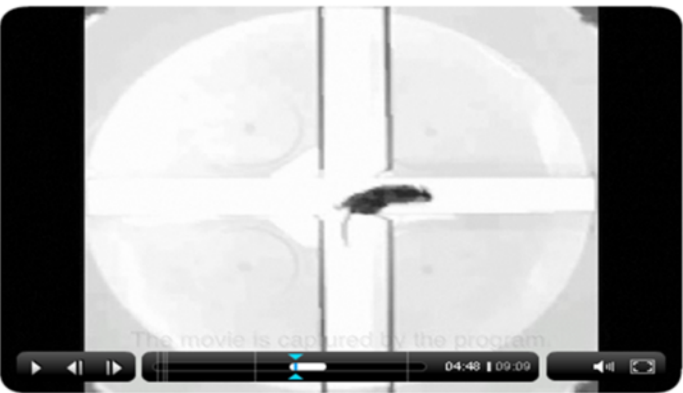


The screenshot shows a video player interface. At the top, there is a search bar with the text "What are you looking for?" and a "Search" button. Below the search bar is a navigation menu with links for "Home", "About", "For Authors", "Subscribe", "Editorial Boards", and "Testimoni". The main content area features the title "Elevated Plus Maze for Mice" and the authors "Munekazu Komada¹, Keizo Takao², Tsuyoshi Miyakawa²". Below the authors are their affiliations: "¹Genetic Engineering and Functional Genomics Unit, Kyoto Prefectural University for Medicine" and "²Institute for Comprehensive Medical Science Division of Systems Medicine, Fujita Health University". The video player shows a person in a white lab coat and mask placing a mouse into a maze. A subtitle at the bottom of the video reads: "A mouse placed in the center are with its head directed toward a closed arm." To the right of the video player is a table of contents:

0:00	Title
0:12	Setup
3:25	Experiment
8:41	Conclusion

Below the video player is a blue bar with the word "Abstract" and a minus sign icon.

Fig. 4 Visual illustration of apparatus



The screenshot shows a video player interface, similar to the one in Fig. 4. It features the same search bar, navigation menu, title "Elevated Plus Maze for Mice", and authors. The video player shows a top-down view of a mouse in a plus-maze apparatus. A subtitle at the bottom of the video reads: "The movie is captured by the program." To the right of the video player is a table of contents:

0:00	Title
0:12	Setup
3:25	Experiment
8:41	Conclusion

Below the video player is a blue bar with the word "Abstract" and a minus sign icon.

Fig. 5 Video processing of experimental set-up

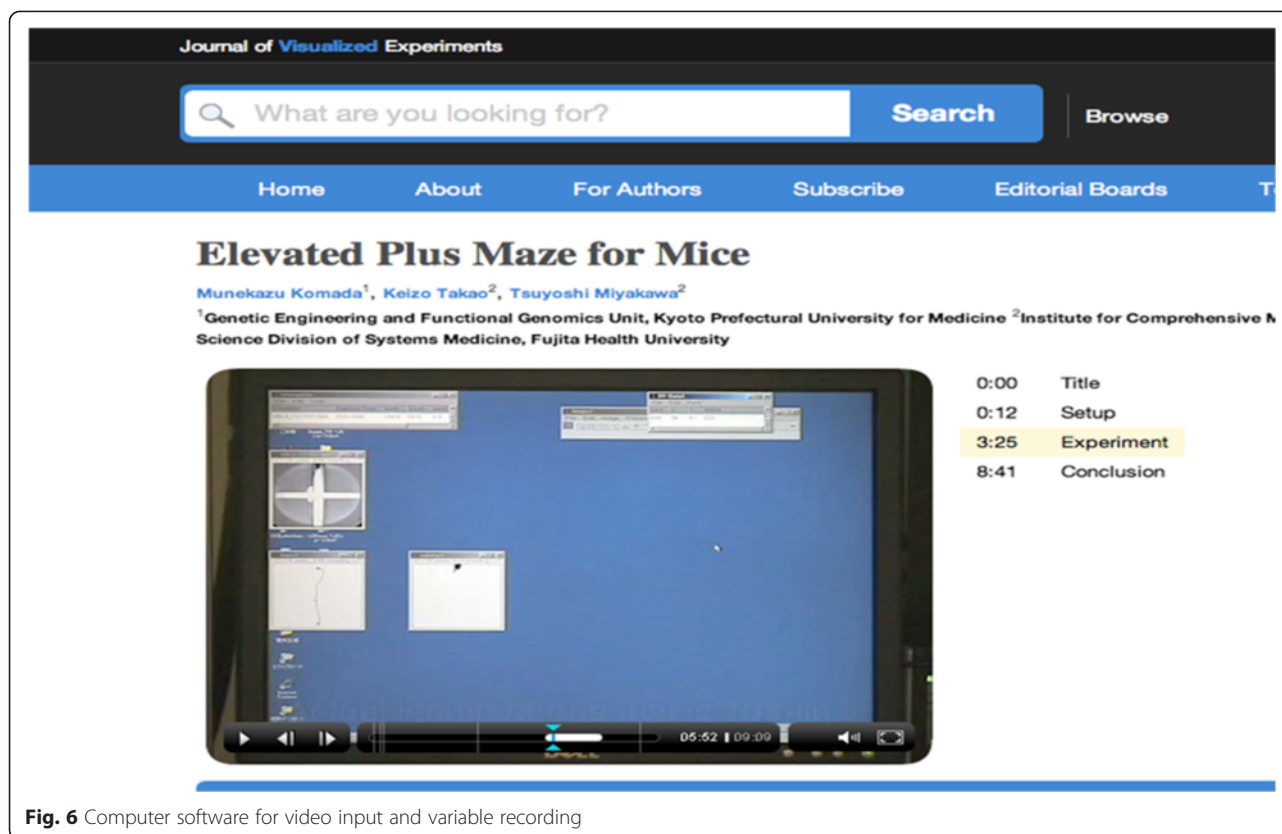


Fig. 6 Computer software for video input and variable recording

follow the structure of the software. Within such software, there are explicit choices for the scientists, e.g. about colour coding, and ways of sharpening images. (Ruivenkamp and Rip 2010, pp.14–15)

On the text that accompanies the video, the authors highlight the role of visualization in their experiment:

Visualization of the protocol will promote better understanding of the details of the entire experimental procedure, allowing for standardization of the protocols used in different laboratories and comparisons of the behavioral phenotypes of various strains of mutant mice assessed using this test.

The software that takes the video data and transforms it into various representations allows the researchers to collect data on mouse behavior more reliably. For instance, the distance traveled across the arms of the apparatus or the time spent on each arm would have been difficult to observe and record precisely. A further aspect to note is how the visualization of the experiment facilitates control of bias. The authors illustrate how the olfactory bias between experimental procedures carried on mice in sequence is avoided by cleaning the equipment.

Discussion

Our discussion highlights the role of visualization in science, particularly with respect to presenting visualization as part of the scientific practices. We have used case studies from the history of science highlighting a scientist's account of how visualization played a role in the discovery of DNA and the magnetic field and from a contemporary illustration of a science journal's practices in incorporating visualization as a way to communicate new findings and methodologies. Our implicit aim in drawing from these case studies was the need to align science education with scientific practices, particularly in terms of how visual representations, stable or dynamic, can engage students in the processes of science and not only to be used as tools for cognitive development in science. Our approach was guided by the notion of "knowledge-as-practice" as advanced by Knorr Cetina (1999) who studied scientists and characterized their knowledge as practice, a characterization which shifts focus away from ideas inside scientists' minds to practices that are cultural and deeply contextualized within fields of science. She suggests that people working together can be examined as epistemic cultures whose collective knowledge exists as practice.

It is important to stress, however, that visual representations are not used in isolation, but are supported by

other types of evidence as well, or other theories (i.e., in order to understand the helical form of DNA, or the structure, chemistry knowledge was needed). More importantly, this finding can also have implications when teaching science as argument (e.g., Erduran and Jimenez-Alexandre 2008), since the verbal evidence used in the science classroom to maintain an argument could be supported by visual evidence (either a model, representation, image, graph, etc.). For example, in a group of students discussing the outcomes of an introduced species in an ecosystem, pictures of the species and the ecosystem over time, and videos showing the changes in the ecosystem, and the special characteristics of the different species could serve as visual evidence to help the students support their arguments (Evagorou et al. 2012). Therefore, an important implication for the teaching of science is the use of visual representations as evidence in the science curriculum as part of knowledge production. Even though studies in the area of science education have focused on the use of models and modeling as a way to support students in the learning of science (Dori et al. 2003; Lehrer and Schauble 2012; Mendonça and Justi 2013; Papaevripidou et al. 2007) or on the use of images (i.e., Korfiatis et al. 2003), with the term using visuals as evidence, we refer to the collection of all forms of visuals and the processes involved.

Another aspect that was identified through the case studies is that of the visual reasoning (an integral part of Faraday's investigations). Both the verbalization and visualization were part of the process of generating new knowledge (Gooding 2006). Even today, most of the textbooks use the lines of force (or just field lines) as a geometrical representation of field, and the number of field lines is connected to the quantity of flux. Often, the textbooks use the same kind of visual imagery than in what is used by scientists. However, when using images, only certain aspects or features of the phenomena or data are captured or highlighted, and often in tacit ways. Especially in textbooks, the process of producing the image is not presented and instead only the product—image—is left. This could easily lead to an idea of images (i.e., photos, graphs, visual model) being just representations of knowledge and, in the worse case, misinterpreted representations of knowledge as the results of Pocovi and Finlay (2002) in case of electric field lines show. In order to avoid this, the teachers should be able to explain how the images are produced (what features of phenomena or data the images captures, on what ground the features are chosen to that image, and what features are omitted); in this way, the role of visualization in knowledge production can be made “visible” to students by engaging them in the process of visualization.

The implication of these norms for science teaching and learning is numerous. The classroom contexts can model the generation, sharing and evaluation of evidence, and

experimental procedures carried out by students, thereby promoting not only some contemporary cultural norms in scientific practice but also enabling the learning of criteria, standards, and heuristics that scientists use in making decisions on scientific methods. As we have demonstrated with the three case studies, visual representations are part of the process of knowledge growth and communication in science, as demonstrated with two examples from the history of science and an example from current scientific practices. Additionally, visual information, especially with the use of technology is a part of students' everyday lives. Therefore, we suggest making use of students' knowledge and technological skills (i.e., how to produce their own videos showing their experimental method or how to identify or provide appropriate visual evidence for a given topic), in order to teach them the aspects of the nature of science that are often neglected both in the history of science and the design of curriculum. Specifically, what we suggest in this paper is that students should actively engage in visualization processes in order to appreciate the diverse nature of doing science and engage in authentic scientific practices.

However, as a word of caution, we need to distinguish the products and processes involved in visualization practices in science:

If one considers scientific representations and the ways in which they can foster or thwart our understanding, it is clear that a mere object approach, which would devote all attention to the representation as a free-standing product of scientific labor, is inadequate. What is needed is a process approach: each visual representation should be linked with its context of production (Pauwels 2006, p.21).

The aforementioned suggests that the emphasis in visualization should shift from cognitive understanding—using the products of science to understand the content—to engaging in the processes of visualization. Therefore, an implication for the teaching of science includes designing curriculum materials and learning environments that create a social and epistemic context and invite students to engage in the practice of visualization as evidence, reasoning, experimental procedure, or a means of communication (as presented in the three case studies) and reflect on these practices (Ryu et al. 2015).

Finally, a question that arises from including visualization in science education, as well as from including scientific practices in science education is whether teachers themselves are prepared to include them as part of their teaching (Bybee 2014). Teacher preparation programs and teacher education have been critiqued, studied, and rethought since the time they emerged (Cochran-Smith 2004). Despite the

years of history in teacher training and teacher education, the debate about initial teacher training and its content still pertains in our community and in policy circles (Cochran-Smith 2004; Conway et al. 2009). In the last decades, the debate has shifted from a behavioral view of learning and teaching to a learning problem—focusing on that way not only on teachers' knowledge, skills, and beliefs but also on making the connection of the aforementioned with how and if pupils learn (Cochran-Smith 2004). The *Science Education in Europe* report recommended that “Good quality teachers, with up-to-date knowledge and skills, are the foundation of any system of formal science education” (Osborne and Dillon 2008, p.9).

However, questions such as what should be the emphasis on pre-service and in-service science teacher training, especially with the new emphasis on scientific practices, still remain unanswered. As Bybee (2014) argues, starting from the new emphasis on scientific practices in the NGSS, we should consider teacher preparation programs “that would provide undergraduates opportunities to learn the science content and practices in contexts that would be aligned with their future work as teachers” (p.218). Therefore, engaging pre- and in-service teachers in visualization as a scientific practice should be one of the purposes of teacher preparation programs.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

ME carried out the introductory literature review, the analysis of the first case study, and drafted the manuscript. SE carried out the analysis of the third case study and contributed towards the “Conclusions” section of the manuscript. TM carried out the second case study. All authors read and approved the final manuscript.

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