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When Graphs are More than 'Pictures': Visual Literacy as a Challenge for STEM education

Vasilia Christidou

Aristotle University of Thessaloniki, Thessaloniki, Greece
vchristidou@nured.auth.gr

ABSTRACT: Science Technology Engineering and Mathematics (STEM) education relies heavily on visual images. Images constitute a system of meaning making, parallel with language or symbolic representations. Understanding, creating and communicating with visual images in STEM requires competence in using the specialized visual codes pertinent to the STEM disciplines. Therefore, STEM Visual Literacy (STEM-VL) is considered as a fundamental aspect of STEM literacy, hence a crucial instructional objective for all education levels. The development of students' STEM-VL presupposes that they are continually, systematically, and purposefully engaged in active 'reading' and construction of visual representations during instruction. The paper reviews recent research in the field of STEM-VL and proposes a taxonomy of commonly used categories of STEM visual images. Research-based instructional practices to 'scaffold' the development of students' STEM-VL are discussed. Lastly, implications for teaching and research aimed at promoting students' STEM-VL are outlined.

Keywords: Images, Multimodality, Scientific Visual Literacy, STEM Education, Visual representations

1 Multimodality, multiliteracies and visual literacy

We live in a multimodal, image-saturated environment. In this environment, effective communication entails being able to comprehend and use different representational modes, such as language, image, sound, movement, etc. and their co-deployment. Thus, the notion of 'literacy', in the traditional sense of being able to read and write, has been replaced by 'multiliteracies', which call for preparing students to master a range of representational modes. In this multimodal communicative landscape, the visual mode, i.e. the use of images, is pervasive. Images of all kinds are used to effectively convey information and to support the construction of meaning (Cope & Kalantzis, 2009; Danos & Norman, 2009; Jarman et al., 2012; Jewitt, 2008; Lemke, 1998a, 1998b).

The dominance of images underscores the importance of preparing students as active readers, learners and producers of multimodal texts. The possibilities of combining image and verbal text are practically infinite. Thus, students need to be competent in selecting and evaluating information, in modifying and reinventing meaning in creative ways. Therefore, we should consider how images can be 'harnessed', to the benefit of education (Avgerinou & Pettersson, 2011; Jarman et al., 2012; Jewitt, 2008; Matusiak et al., 2019).

This discussion brings forward *visual literacy* as a major challenge for education worldwide (Jewitt, 2008). Several attempts to define visual literacy have been made since the '60s. Despite particular differences, relevant theories converge on some key assumptions regarding visual literacy (Avgerinou & Pettersson, 2011; Kedra, 2018; Trumbo, 1999):

- There is a visual language, parallel to verbal, with its distinct grammar, syntax and vocabulary;
- Visual literacy involves the abilities to (a) comprehend and interpret, (b) create and (c) think and learn by means of visual images;
- The competences related to visual literacy can be taught, developed and improved.

The delay of educational systems to set visual literacy as a priority (Trumbo, 1999) possibly originates from the illusion that its associated competences are intuitively acquired. However, visual language is complex (Avgerinou & Pettersson, 2011). The higher-order competences related to visual literacy are cognitively demanding and require deliberate instruction (Ainsworth, 2008; Matusiak et al., 2019; Rau, 2017).

2 Images in STEM education

Science, Technology, Engineering and Mathematics (STEM) involve intensely multimodal discourses. They rely on verbal, symbolic/mathematical and visual resources, interweaved in sophisticated explanations (Anagnostopoulou et al., 2012; Lemke, 1998b; Ramadas, 2009; Rau, 2017; Trumbo, 1999). The fundamental STEM concepts are themselves multimodal in nature. No verbal text can convey an identical meaning to that of an image; no graph can carry the exact same meaning with a mathematical equation (Lemke, 1998a; Cope & Kalantzis, 2009). For instance, a physics, or an electrical engineering expert conceptualize electromagnetic waves by means of (at least) three different semiotic modes: the verbal (Figure 1, left), the symbolic/mathematical (Figure 1, right) and the visual (Figure 2).

Maxwell's equations

1. The electric flux through a closed surface is proportional to the charge enclosed.
2. There are no magnetic monopoles; the total magnetic flux through a closed surface is zero.
3. Change of magnetic flux produces an electric field.
4. Electric currents and changes in electric flux produce a magnetic field.

$$\begin{aligned} \nabla \cdot \mathbf{D} &= \rho \\ \nabla \cdot \mathbf{B} &= 0 \\ \nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\ \nabla \times \mathbf{H} &= \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \end{aligned}$$

Figure 1. Maxwell's equations on electromagnetic waves expressed verbally (left) ["Maxwell's equations" by MITOPENCOURSEWARE (CC BY-NC-SA), and symbolically (right) ["Differential form of Maxwell's equations by Oliver Heaviside", by Yassine Mrabet (2008) (CC BY-SA 3.0)]

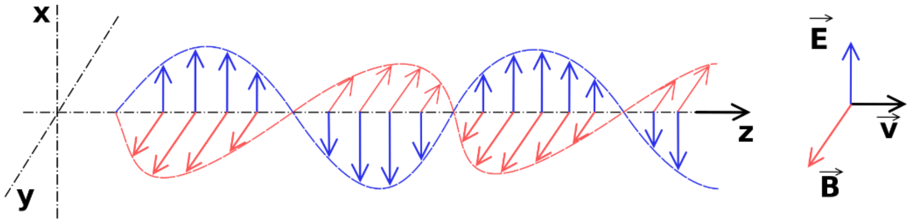

Figure 2. Visual representation of an electromagnetic wave ["Onde electromagnetique", by Emmanuel Boutet (2007) (CC BY-SA 3.0)]

Visual images are an intrinsic part of thinking and practice in any STEM-related field. They are used to represent phenomena and entities and describe data in concise and coherent ways. Visual images are then an essential aspect of STEM literacy (Ainsworth et al., 2011; Anagnostopoulou et al., 2012; Glazer, 2011; Rau, 2017; Roth & Bowen, 2003).

Similarly to STEM concepts, STEM education is also multimodal. Visual representations pervade classroom instruction, textbooks and digital teaching material. During STEM classes, teachers and students communicate using verbal, motor and visual resources. Images are increasingly used to introduce, define and analyze new concepts. They are extremely valuable in rendering abstract concepts visible and concrete, thus supporting the development of scientific competences along with conceptual understanding of the entities they represent. Besides, images and verbal language highlight different aspects of reality: images emphasize spatiality and synchronicity, while verbal language emphasizes temporality and sequentiality (Bowen, 2017; Carifio & Perla, 2009; Cope & Kalantzis, 2009; Jarman et al., 2012; Jewitt, 2008; Lemke, 1998a; Rau, 2017; Trumbo, 1999).

Likewise, learning in STEM is also multimodal. It involves constructing mental models that integrate information mediated by artefacts, verbal expressions, symbolic representations (e.g. mathematical or chemical formulae), visual images (e.g. diagrams, maps) and gestures. Visual images are key representational resources for students to develop their understanding of STEM concepts. Multimodal learning in STEM also assumes that the learner is competent in 'translating' between different representations of the same entity. Multiple representations are common practice in the STEM fields because they provide complementary information and allow deeper understanding, if embedded in cohesive mental models (see Figures 1 and 2). More specifically, multiple *visual* representations enhance understanding of abstract concepts (Figure 3). One image can support students in interpreting other, more complex and demanding images (Ainsworth, 2008; Britsch, 2013; Cheng et al., 2001; Cook et al., 2008; Matusiak et al., 2019; McTigue & Flowers, 2011; Rau, 2017).

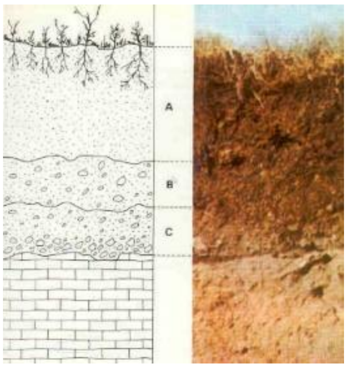

Figure 3. Multiple (dual) representation of the structure of a typical soil
["Estructura vertical de un suelo tipico. Suelo rojo mediterráneo" by Carlosblh (2006) (CC BY-SA 3.0)]

Despite widespread use of visual images, education has not been effective in meeting the communicative requirements for students and future scientists and engineers posed by multimodality and intense visuality. STEM teaching often emphasizes verbal and mathematical language, overlooking visual communication, especially in higher education (Kędra, 2018; Ramadas, 2009). Most often in secondary education images in a text are seen as decorative, thus not significant for learning. Accordingly, teachers do not pay much attention to students' understanding, production and use of visual images, while assessment (i.e. tests, examinations) is mostly logocentric (Bowen, 2017; Britsch, 2013; Cope & Kalantzis, 2009; Jewitt, 2008; Lemke, 1998b; Matusiak et al., 2019). This "verbal bias" (Coleman & Dantzler, 2016, p. 36) significantly restricts students' familiarization with visual representations and their ability to use them adequately. Additionally, students themselves often view textbook illustrations primarily as ornamental, paying minimal attention to the information they convey (Matusiak et al., 2019; McTigue & Flowers, 2011). However, images in STEM fields are -exactly like specialized verbal terminology- important meaning-making devices and deriving the relations between depicted variables requires significant effort from students (Åberg-Bengtsson, 2006).

3 STEM visual literacy

3.1 Defining visual literacy in STEM education

The previous discussion points to the necessity of explicitly teaching students how to interpret and use images in the context of STEM. This would enable them to develop reasoning skills and become more effective in communication and problem solving within STEM subjects (Jewitt, 2008; McTigue & Flowers, 2011; Moline, 2011; Rau, 2017; Trumbo, 1999). These competences are at the intersection of visual literacy and STEM literacy and describe *STEM visual literacy* (STEM-VL), which involves (Byrd, 2018; Danos & Norman, 2009):

- A complex form of communication using visual language to express spatial and/or temporal relations that could not be conveyed by verbal or mathematical signs alone;
- The ability to understand, interpret and create images with specialized STEM-related content.

Therefore, mastering the 'STEM visual language' in order to understand and create expert-like images, presupposes the acquisition of high-level visual abstraction, which requires specifically focused instruction (Coleman & Dantzler, 2016; Kędra, 2018; McTigue & Flowers, 2011).

3.2 Proposing a taxonomy of STEM visual images

STEM education relies on an enormous range of images requiring STEM-VL competences to be used appropriately and effectively. Several classification schemes of STEM visual images have previously been proposed (Danos & Norman, 2009; Koulaidis et al., 2002; Kress & van Leeuwen, 1996; Moline, 2011). Figure 4 suggests a taxonomy of visual images with which students are expected to become familiar as STEM apprentices (Christidou, 2018). The taxonomy involves three distinct dimensions, namely (a) the *specialization of the visual code*; (b) the *scientific thinking competences* required for their comprehension; and (c) the *types of representations* in which the two aforementioned dimensions apply.

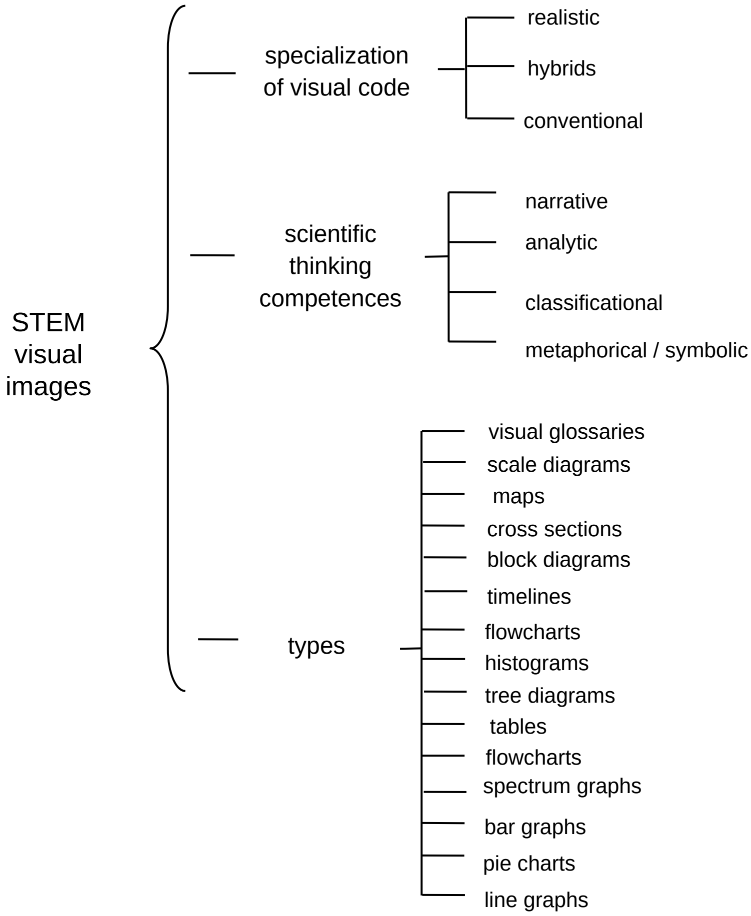

Figure 4. Taxonomy of STEM visual images

In regards to *specialization of the visual code* images can be *realistic*, i.e. depict entities as perceived by the human eye. These images involve photographs or sketches and even non-specialized readers readily understand most of them (e.g. the right-hand photograph in Figure 3). At the other end of the spectrum, *conventional* images are highly specialized images following discipline-specific visual conventions. Typical examples of conventional images are graphs (Figure 5), or depictions of dynamic fields (e.g. electric fields, flow fields). Conventional images are the most challenging to interpret and normally are addressed to expert readers who are both familiar with the conceptual content (e.g. magnetic fields) and the visual conventions used (e.g. field lines). *Hybrids* are visual images that include realistic and conventional elements. Cross-sections (Figure 6), block diagrams (Figure 7) and maps are usually hybrids (Koulaidis et al., 2002).

The second dimension of the taxonomy, i.e. the *scientific thinking competences* required to effectively interpret or construct an image, relates to the function of images in a text. *Narrative* images represent events that evolve in space and time, denoted by lines or vectors indicating direction. Timelines and graphs (Figure 5) are representative examples of narrative images. *Analytic* images represent the parts forming a whole, such as a map indicating a continent and its constituent countries, or a slope cross section (Figure 6). Classificational images present relations between depicted elements, for instance different categories of the same class (Figure 7), or relations of subordination between categories and subcategories. In *metaphorical* images, the *symbolic* denotation of depicted elements dominates (Koulaidis et al., 2002; Kress & Van Leeuwen, 1996).

The two aforementioned dimensions are realized in different *types* of visual images. Thus, the third dimension of the taxonomy involves diagrams, maps, cross sections, tables, histograms, timelines, graphs, etc. (Moline, 2011).

Figures 5, 6 and 7 present three different images belonging to different categories concerning the dimensions of specialization of visual code, scientific thinking competences and image types comprised in the taxonomy. It should be noted that in regards to the second dimension, a STEM visual image can often require different scientific thinking competences at the same time. For example, Figure 6 has both an *analytic* (the soil mass consists of two parts: the failing mass and the stable mass) and a *narrative* function (implies that the slope may fail), while Figure 7 is simultaneously *classificational* (indicates different landslide types), *analytic* (indicates the parts of each landslide) and *narrative* (depicts landslide processes).

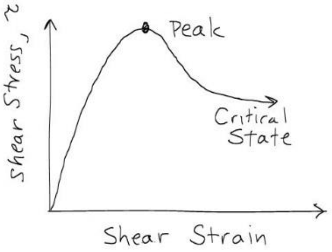

Figure 5. A conventional, narrative line graph [“Typical shear-stress shear-strain curve for a soil showing the peak and critical states”, by Bruce Kutter (2010) (CC0 1.0)]

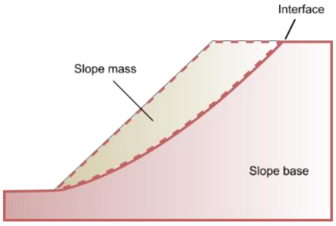

Figure 6. A hybrid, analytic-narrative, cross section (2D) [“Slope 2d plain”, by Biswajit Banerjee (2015) (CC BY-SA 3.0)]

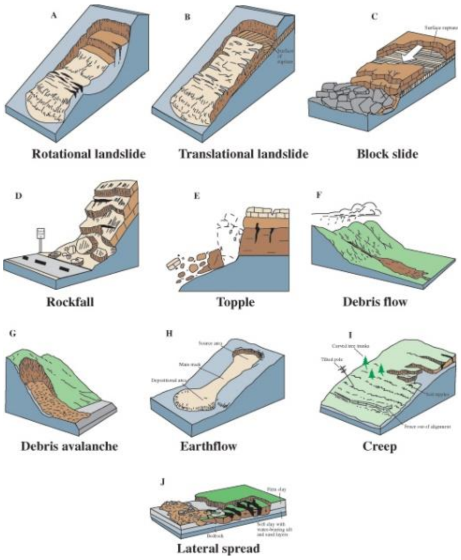

Figure 7. A hybrid, classificational-analytic-narrative set of block diagrams (3D) [“Landslide Types and Processes”, by USGS (2004) (CC0 1.0)]

4 STEM Visual literacy: Challenges for students

Interpreting STEM-related images is a complex and demanding process. For instance, understanding a graph involves three levels, namely extracting points, finding trends and relationships, and generalizing the depicted information (Glaser, 2011). It also involves recognizing the visual conventions, symbols, or equations visualized, along with understanding the conceptual content to which it refers. Therefore, in order to interpret the graph in Figure 5 students are expected to be acquainted with Cartesian coordinate systems and with what the lines in a graph indicate about the relationship between the variables. They are also required to comprehend the concepts involved, i.e. shear stress, shear strain, peak and critical state and the relations between them. Lastly, in this specific example, the students are expected to recognize that, in principle, a test producing the results depicted in Figure 5 can be conducted either by controlling stress (stress is the independent variable) and measuring strain, or by controlling strain (strain is the independent variable) and measuring stress (like the experiment shown in Figure 5); however, in both cases strain will be plotted in the x axis, i.e. the independent and dependent variables can swap between the x and y axes in this graph.

Students are frequently challenged when interpreting and constructing visual images in the STEM fields. Common difficulties students face involve (Åberg-Bengtsson, 2006; Coleman & Dantzler, 2016; Glazer, 2011; Kress & van Leuween, 1996; Lemke, 1998b; McTigue & Flowers, 2011; Rau, 2017; Roth & Bowen, 2003):

- The polysemy of some visual conventions used in the STEM visual language. For example, arrows can signify vectors, direction, change, or sequence;
- The slope-height confusion (i.e. being unable to visually distinguish between the rate of change and particular values of a variable, see Glazer, 2011, Figure 1);
- Reading a graph as a realistic image, or as a map instead of reading it as an abstract, symbolic representation, or uncritically reproducing shapes and forms (see Figure 8);
- Seeing a graph as an array of distinct points, instead of a continuous line (e.g. when students follow a ‘connect the dots’ strategy instead of finding the best-fit trend line);
- Uncritically memorizing and imitating graph shapes and forms without paying attention to selecting the appropriate variables, or correctly positioning the variables on the x-y axes (Figure 8).

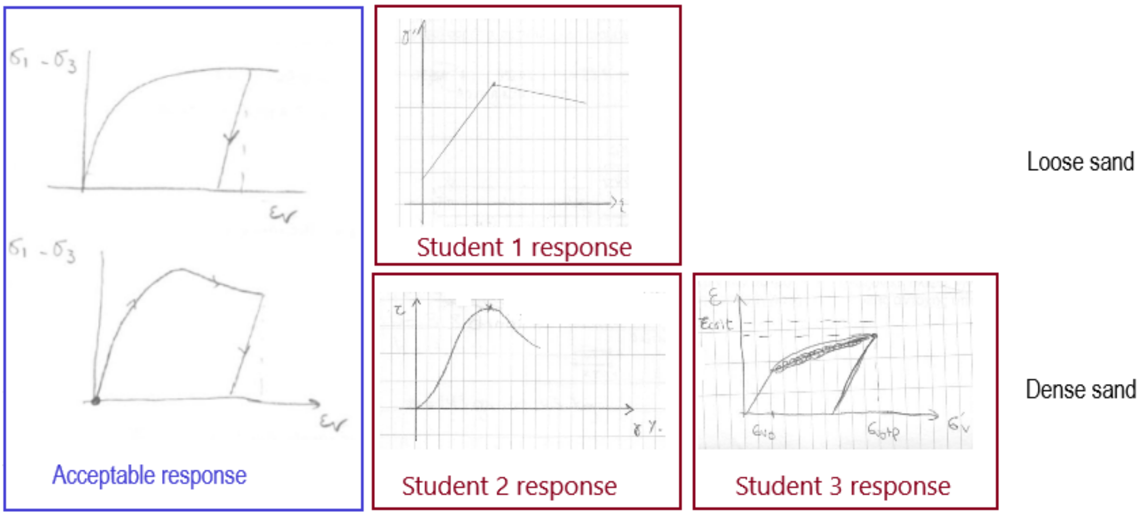

Figure 8. A problem asking civil engineering students in a Soil Mechanics class to draw a stress-axial strain diagram resulting from a triaxial test with a loose or dense sand upon loading and unloading. Students’ responses reveal superficial memorization and imitation of shapes and forms (Student 1), confusing conditions (loose vs. dense sand, Students 1 and 3), using inappropriate variables (all three students), and shifting variable positioning between the x-y axes (Student 3)

Another factor that could hamper students’ understanding of visual images is that they introduce an additional layer of complexity in multimodal texts. Reading and interpreting images requires processing each image individually and interrelating it with the verbal text and with other images on the page. These elements should be considered as parallel, interweaved meaning-making devices

(Coleman & Dantzler, 2016; Kress & van Leuween, 1996). Students may be selective as to which information is essential in visually complex layouts. For example, students tend to focus on particular elements on a page based on their salience, or familiarity (e.g. a realistic image), thereby disregarding other, and equally essential information (Avgerinou & Pettersson, 2011; Matusiak et al., 2019; McTigue & Flowers, 2011). Students' previous knowledge about the depicted concepts is a key factor for interpreting images. Students with sufficient knowledge of the domain can successfully locate conceptually relevant components in different representations. In contrast, students with inadequate previous knowledge tend to focus on superficial features of images, e.g. to see graphs as pictures (Figure 8), thus failing to locate their underlying similarities and to relate them appropriately (Cook et al., 2008).

In summary, not all visual images are appropriate for STEM education. Visual representations that have been found more effective in communicating STEM-related concepts, possess one or more of the following qualities (Avgerinou & Pettersson, 2011; Byrd, 2018; Carifio & Perla, 2009; McTigue & Flowers, 2011; Rau, 2017):

- They involve some level of realism in depicting STEM entities;
- They highlight the crucial components of phenomena, while concealing redundant information and preventing informational 'noise';
- They comprise labels for crucial entities, explanatory captions, or other reading aids that clarify the intended meaning and promote the appropriate -among several possible- interpretation;
- They add complementary information in a text, expanding and clarifying the meaning expressed verbally and enabling students to connect the verbal with the visual mode in a coherent whole.

Such criteria are essential for selecting and designing visual representations of STEM-related knowledge appropriate for each educational setting. Nevertheless, being more or less comprehensible is not entirely an inherent feature of an image. As already mentioned, this significantly depends on the reader's prior knowledge and experience with similar images. When students 'read' specialized STEM visual images intuitively, they often rely on specific expectations, which possibly leads to misinterpretations of the images and misconceptions about the knowledge at stake (Åberg-Bengtsson, 2006; Avgerinou & Pettersson, 2011; Cheng et al., 2001; Glazer, 2011; Lemke, 1998b; McTigue & Flowers, 2011; Roth & Bowen, 2003; Rau, 2017). Besides, constructing visual images in the context of STEM education is even more demanding than reading pre-constructed ones. Students may leave out important details in their visual constructions, or fail to use appropriate visual codes for representing STEM knowledge. This in turn could impede their cognitive progress. These findings indicate that the tenets of visual literacy should be explicitly taught in the context of STEM education (Britsch, 2013).

5 Scaffolding students' STEM visual literacy

The development of STEM-VL presupposes that students are systematically engaged in activities of reading and interpreting visual images in the context of investigations involving data selection, graph construction and argumentation based on visual information. Visual representation of experimental data in the form of tables, diagrams, etc., allows students to reflect on STEM-related concepts, exchange and clarify meanings, while it contributes to the acquisition of specialized conventions of scientific visual language (Britsch, 2013; Glazer, 2011). Such practices 'scaffold' students in using visual representations effectively. They entail social interaction, collective mental activity and guidance by experts. Through interaction with more visually literate individuals, students first observe how these individuals use visual representations to deduce the important visual elements, and finally acquire the STEM 'visual language' (Åberg-Bengtsson, 2006; Rau, 2017).

To promote these competences, teachers should explicitly aim at the development of their students' STEM-VL. Interpretation and construction of visual images, students' familiarization with different kinds of visual representations and with the visual conventions they integrate, are considered to be good teaching practices (Gonitsioti et al., 2013). For instance, supporting students in determining the similarities between a laboratory experiment (Figure 9) and a diagram (Figure 10) and subsequently asking them to construct similar diagrams themselves (Figure 11), would be a valuable learning experience for them and a documentation of their learning for the engineering teacher.

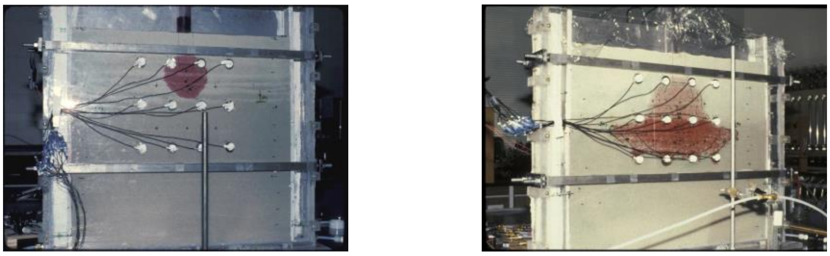

Figure 9. **Laboratory experiments simulating spills of a light nonaqueous phase liquid (LNAPL) (Pantazidou, 2020: used with permission)**

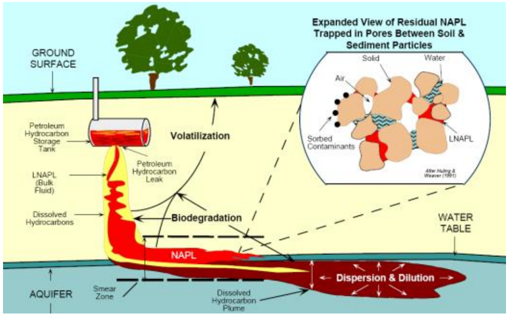

Figure 10. A schematic diagram (a hybrid) of a LNAPL spill (US Environmental Protection Agency, 1999)

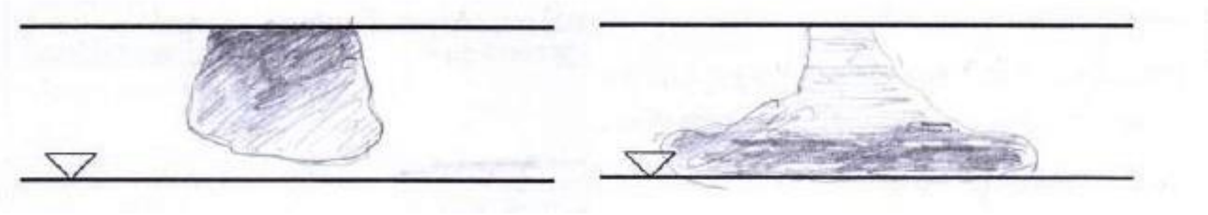

Figure 11. Civil engineering student's schematic diagrams of the area contaminated by the LNAPL shortly (left) and long (right) after the LNAPL spill

As already mentioned, understanding STEM concepts often requires that these be addressed by means of multiple (visual) representations. In this case, students' learning would need to be scaffolded in 'translating' one image to another (Ainsworth, 2008). A common practice in this case is providing students with different images and explaining their similarities and differences in terms of form and information involved. The indicated scaffolding strategy would be to emphasize how different visual representations highlight different aspects of the same entity, to discuss the relevant advantages and disadvantages of each representation in a specific context and to stress the importance of selecting the appropriate representations (Cook et al., 2008; Glazer, 2011; McTigue & Flowers, 2011). Other potentially helpful strategies could involve moving between different levels of difficulty in terms of the specialization of the visual code, or the scientific thinking competencies required to master each visual image. For example, introducing images with varying degrees of realism and abstraction (e.g. a photograph, a hybrid and a diagram of the same phenomenon, see Figures 9, 10 and 11) would be expected to support students in making apposite connections between reality as perceived and its increasingly elaborated representations. Similarly, the advancement from narrative images depicting events or processes to classificational or analytic images would expand students' visual resources related to a variety of thinking competences. Discussion about what lines, symbols, or different color codes signify in an image are extremely helpful in initiating students in the STEM visual language (Åberg-Bengtsson, 2006; Carifio & Perla, 2009; Gonitsioti et al., 2013; Koulaidis et al., 2002; Kress & Van Leeuwen, 1996).

Lastly, having students construct images is another effective learning and problem-solving strategy, enabling them to master scientific concepts and to develop higher order competences. Furthermore, when asked to introduce visual representations in their multimodal texts, students make complex semiotic selections, which document their learning process. Research suggests that students' visual constructions should be recognized explicitly and equally with verbal productions as indicators of their progression in STEM-related disciplines (Ainsworth et al., 2011; Britsch, 2013; Glazer, 2011; Jewitt, 2008; McTigue & Flowers, 2011).

6 Implications for teaching and research

Acknowledging the value of visual representations in STEM education brings about specific demands from teachers. These involve (i) selecting the appropriate multimodal texts and contexts that support learning; (ii) guiding students while navigating these texts with strategies and practices like the aforementioned; and (iii) explicitly asking students to construct and use visual images in the context of STEM education (Ainsworth et al., 2011; Jewitt, 2008; Lemke, 1998b). Furthermore, students' images are valuable tools for assessing their knowledge and their level of STEM-VL. Thus, teachers would be expected to introduce coherent, comprehensive assessment criteria to evaluate students' visual images and multimodal texts (Ainsworth et al., 2011; Britsch, 2013; Jewitt, 2008).

However, research (McTigue & Flowers, 2011) indicates that teachers are not very systematic in selecting and analyzing visual images. The opportunities they provide to their students to develop an understanding of STEM visual language are limited. This could be expected, since teachers are not trained on topics of visual literacy. Therefore, they are not aware of the conventions and particularities of the STEM visual language necessary to assess the visual meanings conveyed by teaching material and students' constructions. This lack of knowledge evidently prevents teachers from adopting practices that 'scaffold' their students' STEM-VL (Glazer, 2011). Teachers at all levels would therefore need to be appropriately trained to meet this challenge. First, teachers' training could aim at raising their awareness that images are an integral part of students' learning. Second, it could also provide teachers with criteria for selecting and evaluating appropriate visual images as conceptual and STEM-VL scaffolds. Third, teachers' training should provide them with assessment frameworks for estimating students' STEM-VL and taking the necessary steps to improve it (Bowen, 2017; Britsch, 2013; Kędra, 2018; Matusiak et al., 2019).

As already pointed out, the development of STEM-VL is a multidimensional research area. Despite the argumentation calling for more frequent and more systematic student engagement with visual images, several STEM-VL issues require more investigation. More specifically, more research is needed on how students integrate different semiotic modes (e.g. verbal language and images) to construct meaning; the transfer of representational competencies from one conceptual field (e.g. physics) to another (e.g. engineering); the optimal number of different (kinds of) images to be used when teaching with multiple representations, according to the conceptual domain and students' knowledge level; how STEM-VL could be included in STEM curricula and in guidelines for teachers (Ainsworth et al., 2011; Byrd, 2018; Glazer, 2011; Lemke, 1998b; Rau, 2017; Trumbo, 1999). This list is only indicative of the scope and interdisciplinarity of STEM-VL as a research field. The overarching goal of STEM-VL research is to empower all students as future engineers or scientists, but also as citizens, to participate successfully in an increasingly complex, visually saturated environment (Kędra, 2018).

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