Visualization in research and science teachers' professional development

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Abstract

Based on the importance and widely use of visualization in science, this article has a three-fold aim related to the terms of visualization, representation and model that in recent years have been introduced to the field of science education without clear differentiation. Firstly, the three terms are discussed with examples to provide a common ground for the following discussion. Secondly, the roles of visualization in science education are delineated to inform teachers how visualization can be used to enhance their teaching and students' learning in science. Thirdly, based on visualization research in science education, there are a number of aspects that we need to consider while embedding the proposed visualization into the development of teachers' professional knowledge. We hope to contribute to pre- and in-service science teachers' professional development linked to the use of visualization in science education.

Keywords: visualization, science education, teacher' professional knowledge, teachers' professional development

Introduction

In line with the research progress in science, science teaching and learning involve conceptual relationships on macroscopic, microscopic and symbolic levels, especially in chemistry (e.g. Gabel, Samuel, & Hunn, 1987; Johnstone, 1982) and molecular life sciences (e.g. Gilbert, 2008; Rundgren, Hirsch, Chang Rundgren, & Tibell, 2012). Visual communication, for example, showing graphs and simulation as well as using concept mapping in the classroom, is one of the important and effective strategies in promoting student learning and assessing student understanding in science education (Chang, 2007; Rundgren, Chang Rundgren, & Schönborn, 2010; Vavra et al., 2011). However, the limitations of different visual representations have also been revealed in science education research and these call for further attention (Cook, 2006; Glazer, 2011; Tibell & Rundgren, 2010). Hence, in this article, we present the roles that visualization plays in science education and propose a number of aspects that we need to consider in developing teachers' professional knowledge based on visualization research in science education. In addition, since the terms of visualization, representation and model have been used in science education during the past decades without clear differentiation, it is necessary to address the sameness and differences of these terms at the beginning of this article to provide a common ground for our discussion.

The definitions of visualization, representation and model

Visual communication is essential to unfolding ideas in science lessons, and visualization has been widely used in science education to represent scientific concepts for many years (Cook, 2006; Gilbert, 2008). To date, there are a number of educational studies dealing with visualization, representation and model. However, the sameness and differences of these three terms have not been discussed. In this article, we feel the need to define and discuss the three terms with examples to build our knowledge upon a common ground.

The definition of visualization, representation and model

Today, there are different definitions of visualization, but mainly of the external representation (ER), internal representation (IR) and visualizing process (VP) of cognitive and brain activities. Tufte (1983) views visualization as ER with a systematic demonstration of information via the form of pictures, diagrams, tables, and the like. By the same token, in the later years, colleagues in different research groups have defined visualization as any type of physical representation designed to make an abstract concept visible (Rapp & Kurby, 2008; Uttal & O' Doherty, 2008). Uttal and O'Doherty (2008) indicate that visualization should be thought of as one type of ER that includes photographs, 2-D graphs, diagrams, charts and 3-D models. However, the concept has been slightly shifted by Rapp and Kurby. They claim that, based on visualization, learners construct their mental models, which are related to IR. Gilbert (2008) concludes that visualization has to do with the formation of an IR from an ER, in which the temporal/spatial relationships of the entities from ER are retained in IR. In addition to the notion of ER and IR, Reiner provides different views on visualization and regards visualization as the cognitive and brain processes associated with the act of visualizing rather than as a pictorial representation, which is linked to VP (Reiner, 2008).

Regarding representation, we can say that people create representations through their intention to have one thing stand for something else (P. Bloom & Markson, 1998; Deacon, 1997; DeLoache, 2000; Tomasello, Striano, & Rochat, 1999), that is, a **representation** is seen as "a structure that stands for something else: a word for an object, a sentence for a state of affairs, a diagram for an arrangement of things, a picture for a scene" (McKendree, Small, Stenning, & Conlon, 2002, p. 59). Moreover, Gilbert (2008) argues that a representation is the depiction of anything and that it can be classified into two groups of ER and IR. Again, an ER is situated in the public sphere with an object of visual, verbal, or symbolic form and an IR is constructed mentally by an individual.

For a specific purpose, a model in science can be developed as a representation to represent a simplification of a phenomenon, and then to be used in the inquiry to develop explanations of the phenomenon (Gilbert, Boulter, & Elmer, 2000). In this sense, a model can be seen as an idea, for example, the scientific model of global warming phenomenon. A model can be also expressed as an ER (physically available to others) or an IR (mentally available by an individual and deemed as a mental model). The transforming process between ER and IR is called modeling process, which is happening in our brain, similar to VP. Only, the modeling process can be a developing process of an idea to explain a phenomenon, and does not necessarily involve a visual model. Similar to visualization and representation, a model of an object (ER) can be different sizes, either smaller than the real object it represents (e.g., of a train), or the same size as the real object is (e.g., of the human body), or bigger than the object in reality (e.g., of a virus).

The sameness and differences of visualization, representation and model

Through Figure 1 together with examples, the sameness and differences of visualization, representation and model are discussed in this section. From the above-mentioned definitions, it is not hard to perceive that the terms of visualization and model share the same arenas of ER, IR and VP, so they are included in the same domain of representation (see the (a) part in Figure 1). Besides the sameness of the cognitive and brain process to bridge ER and IR, visualization and model can also make abstract concepts/complex ideas simplified and explicit through IR and ER. However, there are parts not totally overlapping and that show the differences of visualization, representation and model (see as the (b), (c) and (d) parts in Figure 1). Science educators and/or science education researchers need to be aware of the differences while using the terms concerning visualization, representation and model.

1. Some representations cannot be regarded as models, but as visualization (the (b) part in Figure 1). For example, when something flashes in front of our eyes

quickly, we can visualize it and have an image of it, termed IR, but we cannot map this image in our brain with any model that we have memorized/saved in our schemas.

2. One important feature of a model is that it is recognized and agreed on within a community (i.e. science community) or a majority of people (i.e. in a specific culture). A model can be formed in visual, auditory or tactile modes. Therefore, the (c) part in Figure 1 could be regarded as auditory and tactile modes that are not visible. The various sounds of different species of birds, esp. the sounds made by birds while trying to give signals to other birds, could be the example of (c). However, if the model of birds' sound signals is transformed and expressed by a notation, it becomes a visual model and is seen as the (a) part in Figure 1.
3. A representation is not necessarily a model or a visualization, but just auditory sense or sense of touch to represent some kind of meaning for a person. For example, while hearing a bell ringing, for some persons, it could represent a school bell to remind teachers and students for the start or the end of a lesson. However, for people in another culture or having different experiences with the same bell sound, they have different representations linked to it. This kind of bell sound is not a model to be generalized, but individualized. Another kind of example for the (d) part in Figure 1 could be metaphor, which represents some kind of meaning, but we cannot say that it is a model and even visible. For example, a linguistic metaphor, help words, has been revealed in Swedish students' non-conventional expression ('Flopp') to represent the nitrogen-base of DNA by some Swedish students and that is not a model (Rundgren, Hirsch, Chang Rundgren, & Tibell, 2012). In addition, after the novel, Frankenstein, published 1818, people start using Franken as a prefix to describe ''strange'' object discovered in nature by scientists like Frankenseeds. In reality, there is no model or visualization to show a Franken object (retrieved on 2014-12-14 from http://scitechvista.most.gov.tw/zh-tw/Articles/C/0/8/10/1/1004.htm), but people could understand the implied meaning.

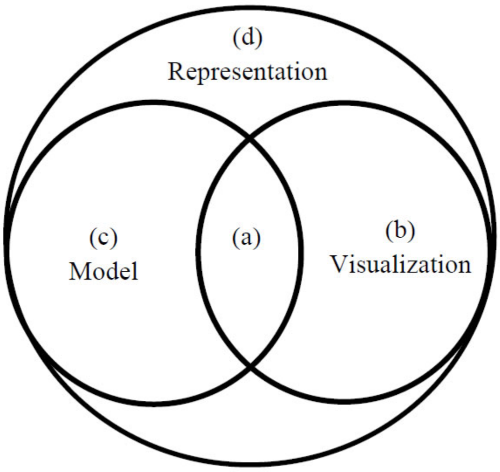

Figure 1. The relationship of visualization, model and representation.

In sum, ER, IR and cognitive process in the brain are the overlapping parts of (a) as visualization and model in science education. But in the basic science research, (b) and (c) parts are of importance to research progression. To make students learn better regarding a variety of profound scientific concepts, science education researchers, need to investigate more about whether the different forms of ER can be used by teachers to convey scientific models and whether different IR might be created by students considering the different scientific models. Of course, the (d) part of representation is also important to reveal in science education for better science teaching and learning. However, in this article, we emphasize visualization, and more specifically, ER.

The roles of visualization in science education linked to Bloom's Taxonomy

In order to promote higher-order thinking in education (i.e. analyzing and evaluating), Benjamin Bloom created Bloom's Taxonomy with the three identified domains (cognitive, affective and psychomotor domains) as educational activities (B. S. Bloom, 1956). In other words, these three domains can also be seen as knowledge, attitude and skills that learners ought to achieve through education. On the basis of the above-mentioned Bloom's Taxonomy of the cognitive, affective and psychomotor domains, the roles visualization can play to benefit science teaching and learning are addressed as follows.

The cognitive domain

The cognitive domain involves knowledge and intellectual skills (B. S. Bloom, 1956). For example, recall and/or recognition of facts, interpretation of instruction and problems, application of knowledge to a new situation as well as making judgments on ideas. Here, the use of visualizations in science education relating to the cognitive domain has the role of not only making invisible concepts/ideas visible but also illustrating abstract concepts and making it concrete.

- **Making abstract knowledge and ideas concrete**

  Basically, through visualization, complex or abstract knowledge and ideas can be expressed in effective and concrete ways that then can make learners encode and recall their knowledge easier. For example, the mechanisms of molecular transporting through the cell membrane are easily shown through visualization (Figure 2) instead of verbal representation. In this way, it might help to overcome the common problem concerning some students who have difficulties in reading (Mallinson, Sturm, & Mallinson, 1952).

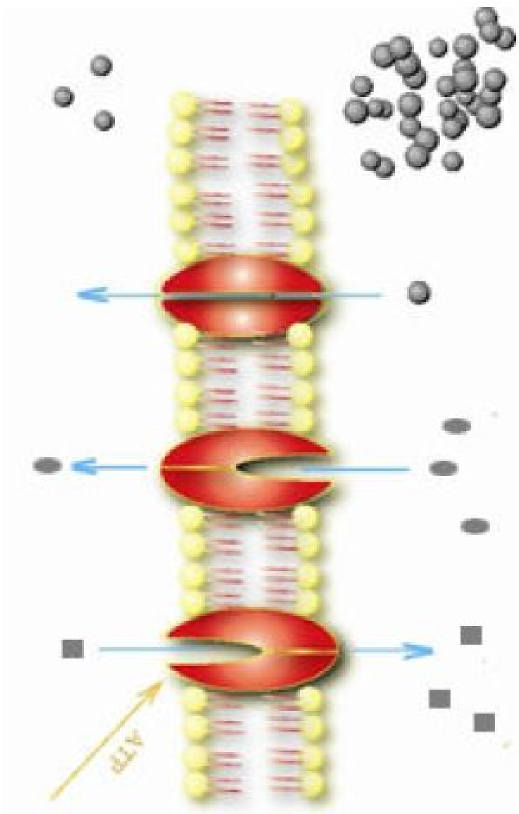

Figure 2. The mechanisms of molecular transporting through the cell membrane (Cited from Rundgren et al., 2012, p. 910).

- **Translating scientific ideas between macro, micro, and symbolic levels**

Visualization is used to convey information that is not easily seen or is impossible to see with the naked eyes (Tversky, Zacks, Lee, & Heiser, 2000). In other words, visualization is to make invisible objects visible. Johnstone (1993) has pointed out that the models produced in science are expressed in three distinct representational levels including (1) the macroscopic level: such as snow that we can see on the roof of a building; (2) the sub-microscopic level: like the snowflake under a microscope; (3) the symbolic level: for example, H2O or H-O-H can be used to present the composition of snow. All the above-mentioned levels can be represented by visualization to make students learn science better.

- **Showing the processes of scientific concepts**

Visualization has its benefits in representing the process of scientific concepts explicitly via still images and/or animations (e.g. Rundgren et al., 2012). For example, the process of protein synthesis can be clearly presented by a still image (Figure 3). However, dynamic visualization can improve student understanding of abstract concept of molecular processes more than static illustrations. Research has shown that animations did help students to understand biomolecular process and the random nature of biomolecular interaction better (Rundgren & Tibell, 2010). Ryoo and Linn (2012) also found that dynamic visualization had the potential to enhance 7th graders' understanding of the concept of photosynthesis compared to static illustrations. Similarly, animations have been found to have the same learning effect in chemistry education (e.g. Jones, Jordon, & Stillings, 2005; Sanger & Greenbowe, 1997; Williamson & Abraham, 1995)

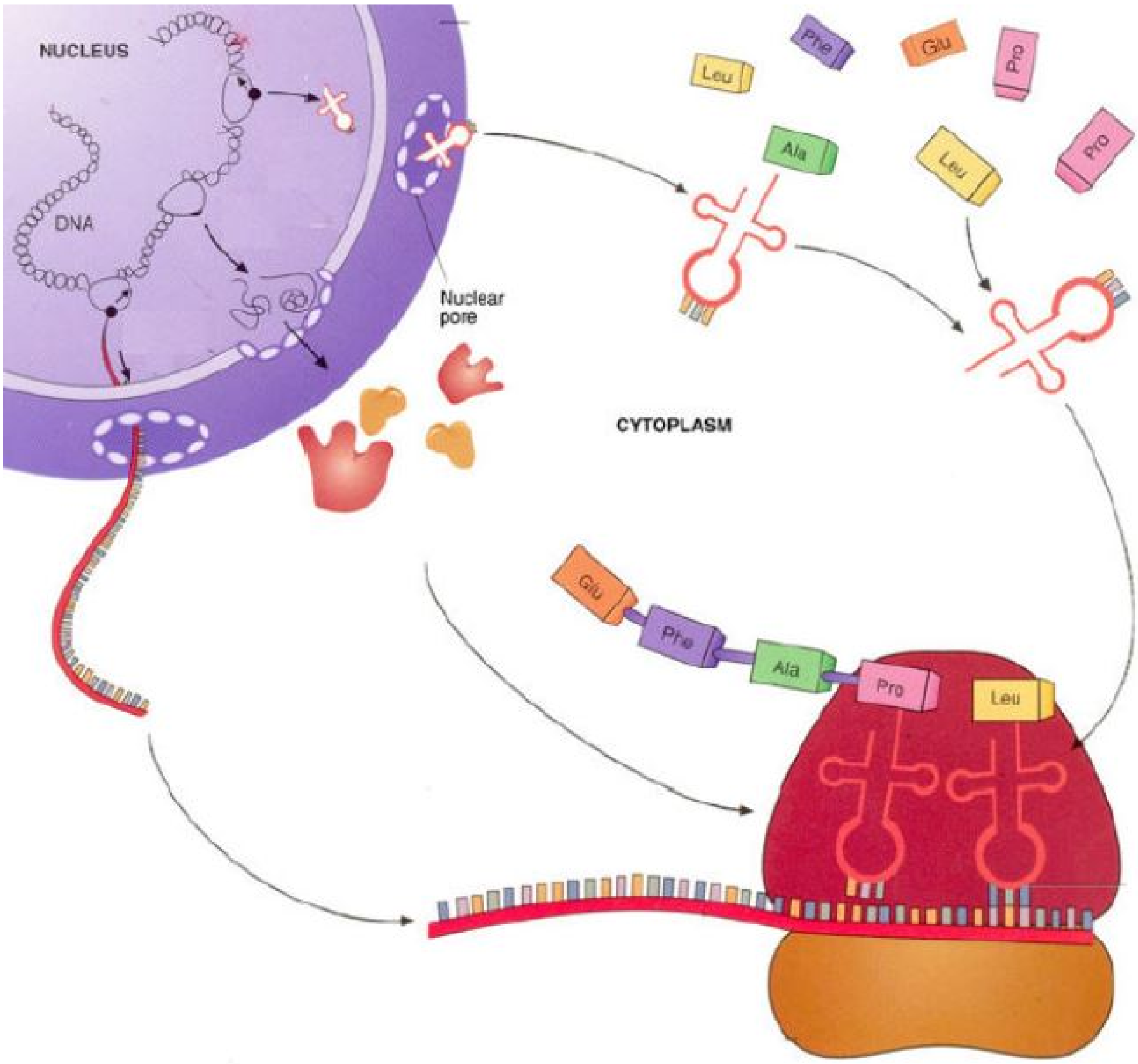

Figure 3. The visualization of protein synthesis by an original of Mix/Farber/King (Cited from Rundgren et al., 2012, p. 911).

- **Modeling process and visualization**

The modeling process and visualization have been the fruitful subject of scientific research. In science education, modeling and visualization are important mental skills for students to develop, esp. while learning science. Gilbert (2008) argues that students need to learn the skills of explaining and understanding historical models and contemporary models in science; learn to develop new qualitative models, which is a major task for scientist as an inquiry into a hitherto unexplored phenomena; learn to develop new quantitative models of qualitative models to produce a comprehensive representation. By using visualization in science teaching, we hope to help students to develop intellectual skills, such as modeling, in learning and developing science.

The affective domain

According to Krathwohl and colleagues (1964), the affective domain includes emotion, attitude and value. In other words, receiving, responding and showing feelings, values, appreciation, enthusiasm, motivation, and attitudes are all embraced in the affective domain. Based on the perceptual theory applied in the field of visualization, the role of visualization can (1) attract student attention and induce emotion via the colorful visual representations combined with audio/verbal representations, and (2) make students enthusiastic by engaging them in an interactive visual environment, i.e., a game-based learning environment.

To gain student's attention, the first stage is perception. The perceptual theories have indicated that perception and action are central to the cognitive processes involved in the brain system (Barsalou, 1999; Glenberg, 1997; Zwaan & Yaxley, 2004). Here, representations can be seen as modality specific: tactile experiences lead to representations that encode touch (Rapp & Kurby, 2008). Mental representations (or IR as we mentioned earlier in this article) are directly linked to the real world concepts and sensory perceptions to what we have experienced (Barsalou, 1999; Glenberg, 1997; Hesslow, 2002; Lakoff & Johnson, 1980; Svensson & Ziemke, 2004; Zwaan & Yaxley, 2004). When representations embrace different perceptual sources, they become multimodal, which can be linked to the Dual-Coding theory (Paivio, 1971, 1986). However, cognitive load theory has also proven useful in the visualization of instructional design (Cook, 2006)

The psychomotor domain

Physical movement and coordination are embedded in the psychomotor domain (Simpson, 1966). The embraced skills demand practice and are judged in terms of speed, precision, procedures, or techniques in the execution. The roles of visualization linked to the psychomotor domain are:

- **Enhance students' spatial skills**

  Visualization research in science education has shown that learners' spatial skills and prior knowledge are related to the use of ER in science learning (e.g.

Wu, Lin, & Hsu, 2013). Even though visualization demands spatial skills, it might be a useful way to improve learners' spatial skills via visualization.

- **Externalizing students' ideas and enhance communication skill**

  Drawing has been used to investigate students' understanding of science for a long time. Drawing is seen as a meaning-making medium (Brooks, 2009) as well as a 'shared reference point' (Tytler, Prain, & Peterson, 2007). In science education, 'concept map' and 'V-diagram' are used to teach and construct ideas (Novak & Gowin, 1984). For example, a concept map is a useful tool to externalize students' conceptions regarding homeostasis of blood sugar (Chang, 2007) as well as discussing students' own ideas on the water transport concept through drawing (Rundgren et al., 2010). Through externalizing ideas via visual representations, a 'shared reference point' to enhance communication skills is established.

- **Promoting students' sensory perception**

  By combining the five senses of smell, sight, taste, touch and hearing, we can learn better. Visualization is traditionally associated with what we see, yet research reveals that we can generate an image without seeing visuals (Reiner, 1999) mainly through touch. This suggests that visualization processes can be enhanced by adding or replacing visual information with other sensory modalities. A combination of touch and visual cues is beneficial to learning. Haptic learning is one example of learning enhancement (e.g. Schönborn, Bivall, & Tibell, 2011). Also, through color perception, students can represent each element involved in the concepts and encode easily (i.e. Figure 3). However, color perception might cause misconception for younger kids, which will be discussed in the following section concerning teachers' professional knowledge to show what aspects teachers ought to be aware of while using visualization.

In sum, before adopting a visualization in science teaching, it is important for teachers to reflect upon Bloom's Taxonomy and concern about how students' cognitive, affective and psychomotor domains are going to be developed and related through the chosen visualization.

Teachers' professional knowledge and the use of visualization in science teaching

Teachers play important roles in influencing students' learning and achievements (e.g. Darling-Hammond, 2000; Nye, Konstantopoulos, & Hedges, 2004). Therefore, we see the importance of contributing our knowledge concerning visualization in science education to teacher's professional development. In this section, teachers' professional knowledge is presented together with the aspects that teachers need to be aware of while using visualization in their teaching.

Lee Shulman introduced the notion of teachers' professional knowledge, which it includes 'mainly' content knowledge (CK), pedagogical knowledge (PK) and pedagogical content knowledge (PCK) (Shulman, 1986/1987). PCK (Figure 4) can be seen as the knowledge used by teachers in the process of teaching (Kind, 2009) or as the knowledge of the teaching and learning of a particular CK (Bucat, 2004). PCK has become a way of understanding the complex relationship between teaching and learning with a target CK via the use of specific teaching strategies (van Driel, de Vos, Verloop, & Dekkers, 1998). During the past decades, PCK and its critical reflection have been suggested to be a requirement in teaching practice (de Jong, van Driel, & Verloop, 2005; Nilsson, 2008; van Driel, Verloop, & de Vos, 1998). Here, linking to the roles of visualization in science teaching and learning, we can say that the use of visualization is part of teachers' professional knowledge, PCK, which teachers ought to acquire during their professional development. Surely, visualizations are ubiquitous in the teachers' learning of CK in science, but it is not our focus in this article.

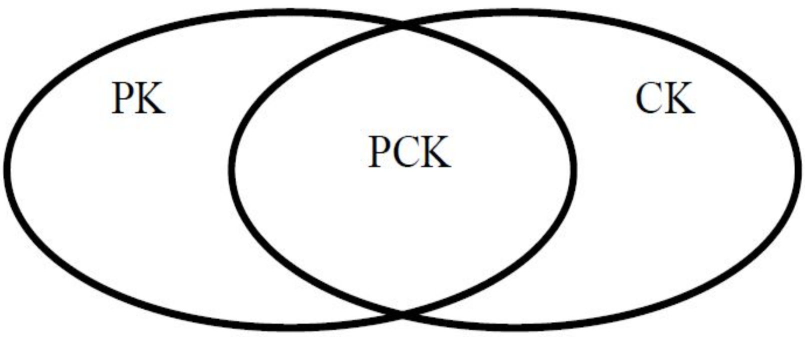

Figure 4. Pedagogical content knowledge (PCK) inspried by Lee Shulman (1986/1987).

The use of visualization in science teaching

Although visualization has proven to be effective in learning (e.g. Phillips, Macnab, & Norris, 2010), it is necessary to point to the limitations of using visualization for teachers. The following aspects are seen as important to be aware of when using visualization in science teaching and learning.

- **Students' representational competence**

  The interpretation of visualizations is highly related to prior knowledge in the domain as well as familiarity with, complexity of, and symbolism used in the visualization (Tibell & Rundgren, 2010). To make students move freely between Johnstone's three representation levels (macroscopic, sub-microscopic and symbolic) is a challenge, particularly for the novices. Kozma (2003) revealed that experienced chemists could move freely between different representations of a phenomenon, but among students, the interpretations were constrained by superficial features shown in the representations. Therefore, developing students' representational competence is needed, esp. in science education. Through the visualization environment, the representational competence could be developed (e.g. Stieff, 2011). Kozma and Russell (1997) have identified the following skills in the experts' performance as constituting representational competence in chemistry.

  "(1)The ability to identify and analyze features of a particular representation (such as a peak on a coordinate graph) and patterns of features (such as the shape of a line in a graph) and use them as evidence to support claims or to explain, draw inferences, and make predictions about relationships among chemical phenomena or concepts. (2) The ability to transform one representation into another, to map features of one onto those of another, and to explain the relationship (such as mapping a peak on a graph with the end point of a reaction in a video and a maximum concentration in a molecular-level animation). (3) The ability to generate or select an appropriate representation or set of representations to explain or warrant claims about relationships among chemical phenomena or concepts. (4) The ability to explain why a particular representation or set of representations is more appropriate for a particular purpose than alternative representations. (5) The ability to describe how different representations might say the same thing in different ways and how one representation might say something that cannot be said with another (Kozma and Russell, 1997, p.964).''

- **The choice of visualization**

Research has shown that different types of visualization in science can be used for difference purposes (Vavra et al., 2011), the way schematic diagram (i.e. electrical circuit diagram) can illustrate relationships, assist in calculations or provide description of a phenomenon or process. Moreover, animations are able to provide more detailed and accurate representations by showing the movements (e.g. Jones et al., 2005; Rundgren et al., 2012; Sanger & Greenbowe, 1997; Williamson & Abraham, 1995). Teachers must be aware of the effects of using different visualization on students learning and how to use visualization. Burke, Greenbowe and Windschitl (1998) give advice that animation sequences should be short (20 - 60 seconds) and allow students to interact with appropriate feedback. The authors concluded that when care is taken in the design and use of animation appropriately, student understanding should improve as a result (Burke et al., 1998). In another study, Velazquez-Marcano and colleagues (2004) revealed that molecular-level animations combined with video clips of macroscopic phenomena were found more effective in enabling students to predict the outcome of effusion and diffusion problems than animation or video alone. They concluded that the combination of animation and video allowed students to interpret a concrete phenomenon in terms of an abstract concept.

Even though research has shown that animation can improve student understanding of abstract and dynamic process, the potential of animation to cause new and resistant misconceptions is also discussed (Tasker & Dalton, 2008). For example, the visualizations of the human body in the textbooks are presented in red and blue colors to represent arteries and veins. This might cause the misconception among young children that human blood has different colors. Rundgren and Tibell (2010) examined how secondary and tertiary students interpret the visualization of transport through the cell membrane in the form of a still image and an animation. These results also suggest that animations are more useful in helping students to understand the dynamic processes of the transport through the cell membrane. However, they found that the amount of information presented simultaneously in the animation gave rise to some difficulties for students.

- **The use of multiple representations**

Multi-representation has been suggested for use in science teaching to compensate for the limitation of using any single representation (Larkin & Simon, 1987). Ainsworth (2006) conducted a research on the advantage of multiple representations in science education. Based on her research, she proposed that the functions of multiple representations can be classified into three categories of (1) multiple representations can support learning by allowing for complementary information or complementary roles; (2) multiple representations can be used so that one representation constrains interpretations of another one; (3) constructing deeper understanding.

- **Representation sequences**

As a result of the benefit of using multiple representations in science teaching, it is important to consider the representation sequences and/or the combination of representations used in teaching (e.g. Ainsworth, 2006). Wu, Lin and Hsu (2013) conducted a study to compare the learning effect between two groups of different representation sequences (SD group: static –dynamic representations versus DS group: dynamic –static representations), and they revealed that the SD group of eight students gained significantly more factual knowledge. The representation sequences had no effect on students who had low spatial abilities. Wu and Puntambekar (2012) reviewed the effectiveness of different conditions, i.e. (1) one type of presentation versus another, (2) multiple representations versus a single one, and (3) teacher-provided versus student-generated representations as well as the findings of pairing multiple representations. Each teaching mode and pairing type has its own pros and cons, so it is advisable to make teachers try out in their own teaching practices and collect evidence to support teaching later.

- **Scaffolding**

Scaffolding is the idea that existing knowledge can be used as a supporting guide in understanding new information and it was introduced in educational psychology by Wood, Bruner and Ross (1976). Since visualization is highly related to students' prior knowledge (e.g. Cook, 2006; Wu et al., 2013), scaffolding is one of the important teaching strategies to consider in science education, also when using visualization. Wu and Puntambekar (2012) suggest six types of scaffolding using multiple representations in science teaching: (1)

dynamic linking (enabling translation between representations, i.e. showing concrete, diagrammatic, numerical in a single entity), (2) model progression (engaging students in constructing deviational links among different types of multiple representations, i.e. concreteness fading), (3) sequence (making students learn better by different representation sequences), (4) support in instructional materials (providing students with explicit instructional strategies, i.e. self-explanation), (5) teacher support (i.e. teachers' verbal guide or questioning while students' interact with visualizations) and (6) active engagement (making students active learners in exploiting the affordances of representations, i.e. letting students generate their own representations).

Conclusion

Visualization is not panaceas, but based on what we know of visualization research, we hope to contribute to teachers' professional development and help to promote students' science learning. According to Variation Theory, every object, in our case, visualization, can be interpreted differently through different perspectives and by different persons (Rundgren & Tibell, 2010). For teachers it is therefore important to know how the visualization was developed and what concepts were embraced in the different features of the visualization. What features of visualization together with teaching strategies that can be applied to teaching and what concepts that have been learned by students are also important for teachers to be equipped with. Accordingly, there are three aspects we want to make teachers consider before using visualization. Firstly, teachers need to know the key features linked to the concepts embedded in the specific visualization and how to direct students' attention towards that. In so doing, the overload of working memory and the causes of misconceptions could be avoided. Secondly, they need to know how to promote meaningful integration between students' prior knowledge and their efforts to provide proper scaffolding strategies. Thirdly, it is necessary for teachers to know how to assess students' understanding of the target concepts and how to know what prior knowledge is lacking and what knowledge can be learned by students.

From the design perspective, the effective design of visualization needs to focus on how to facilitate the deep understanding of science concept for students. Because of the complexity of visualization, the design of visualization is hard to balance against often-competing demands of scientific accuracy, technical constraints, and clarity of communication (Tasker & Dalton, 2008). Therefore, multi-disciplinary teams as well as the involvement of different stakeholders (scientists, teachers, students and visual designers) are needed to improve the design of visualization in science education in order to benefit science teaching and learning.

References

Ainsworth, S. (2006). DeFT: A conceptual framework for considering learning with multiple representations. *Learning and Instruction, 16*(3), 183-198.

Barsalou, L. W. (1999). Perceptual symbol systems. *Behavioral and Brain Sciences, 22*(4), 577-660.

Bloom, B. S. (1956). *Taxonomy of educational objectives. Handbook I: Cognitive Domain.* New York: David McKay Company. Inc.

Bloom, P., & Markson, L. (1998). Intention and analogy in children's naming of pictorial representations. *Psychological Science, 9*(3), 200-204.

Brooks, M. (2009). Drawing, visualisation and young children's exploration of "big ideas". *International Journal of Science Education, 31*(3), 319-341.

Bucat, R. (2004). Pedagogical content knowledge as a way forward: Applied research in chemistry education. *Chemistry Education Research and Practice, 5*(3), 215-228.

Burke, K. A., Greenbowe, T. J., & Windschitl, M. A. (1998). Developing and using conceptual computer animations for chemistry instruction. *Journal of Chemical Education, 75*(12), 1658.

Chang, S. N. (2007). Externalizing students' mental models through concept maps. *Journal of Biological Education, 41*(3), 107-112.

Cook, M. (2006). Visual representations in science education: The influence of prior knowledge and cognitive load theory on instructional design principles. *Science Education, 90*(6), 1073-1091.

Darling-Hammond, L. (2000). Teacher quality and student achievement: a review of state policy evidence. *Educational Policy Analysis Archives, 8*(1), 1-44.

De Jong, O., van Driel, J. H., & Verloop, N. (2005). Preservice teachers' pedagogical content knowledge of using particle models in teaching chemistry. *Journal of Research in Science Teaching, 42*(8), 947-964.

Deacon, T. (1997). *The symbolic species: The co-evolution of language and the brain.* New York: Norton & Co.

DeLoache, J. S. (2000). Dual representation and young children's use of scale models. *Child Development, 71*(2), 329-338.

Gabel, D. L., Samuel, K. V., & Hunn, D. (1987). Understanding the particulate nature of matter. *Journal of Chemical Education, 64*(8), 695.

Gilbert, J. (2008). Visualization: An emergent field of practice and enquiry in science education. In J. Gilbert, & M. Nakhelh (Ed.), *Visualization: Theory and Practice in Science Education* (pp. 3-24). The Netherlands: Springer.

Gilbert, J., Boulter, C. J., & Elmer, R. (2000). Positioning models in science education and in design and technology education. In J. Gilbert & C. J. Boulter (Eds.), *Developing models in science education* (pp. 3-17). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Glazer, N. (2011). Challenges with graph interpretation: a review of the literature. *Studies in Science Education, 47*(2), 183-210.

Glenberg, A. M. (1997). What memory is for. *Behavioral and Brain Sciences, 20*(01), 1-19.

Hesslow, G. (2002). Conscious thought as simulation of behaviour and perception. *Trends in Cognitive Sciences, 6*(6), 242-247.

Johnstone, A. H. (1982). Macro- and micro-chemistry. *School Science Review, 64*, 377–379.

Johnstone, A. H. (1993). The development of chemistry teaching: A changing response to changing demand. *Journal of Chemical Education*, *70*(9), 701.

Jones, L., Jordon, K., & Stillings, N. (2005). Molecular visualization in chemistry education: the role of multidisciplinary collaboration. *Chemistry Education Research and Practice*, *6*(3), 136-149.

Kind, V. (2009). Pedagogical content knowledge in science education: perspectives and potential for progress. *Studies in Science Education*, *45*(2), 169-204.

Kozma, R. (2003). The material features of multiple representations and their cognitive and social affordances for science understanding. *Learning and Instruction*, *13*(2), 205-226.

Kozma, R., & Russell, J. (1997). Multimedia and Understanding: Expert and Novice Responses to Different Representations of Chemical Phenomena. *Journal of Research in Science Teaching*, *34*(9), 949-968.

Krathwohl, D. R., Bloom, B. S., & Masia, B. B. (1964). *Taxonomy of educational objectives: The classification of educational goals. Handbook II: Affective domain*. New York: David McKay.

Lakoff, G., & Johnson, M. (1980). *Metaphors we live by*. University of Chicago Press.

Larkin, J. H., & Simon, H. A. (1987). Why a diagram is (sometimes) worth ten thousand words. *Cognitive Science, 11*(1), 65-100.

Mallinson, G. G., Sturm, H. E., & Mallinson, L. M. (1952). The reading difficulty of textbooks for high-school chemistry. *Journal of Chemical Education, 29*(12), 629.

McKendree, J., Small, C., Stenning, K., & Conlon, T. (2002). The role of representation in teaching and learning critical thinking. *Educational Review, 54*(1), 57-67.

Nilsson, P. (2008). Teaching for Understanding: The complex nature of pedagogical content knowledge in pre-service education.*International Journal of Science Education, 30*(10), 1281-1299.

Novak, J. D., & Gowin, D. B. (1984). *Learning how to learn*. Cambridge: Cambridge Univerity Press.

Nye, B., Konstantopoulos, S., & Hedges, L. V. (2004). How large are teacher effects? *Educational Evaluation and Policy Analysis, 26*(3), 237-257.

Paivio, A. (1971). *Imagery and verbal processes*. Holt, Rinehart & Winston.

Paivio, A. (1986). *Mental representations: A dual-coding approach*. New York: Oxford University Press.

Phillips, L. M., Macnab, J. S., & Norris, S. P. (2010). *Models and modeling in science education: Visualization in mathematics, reading and science education* (vol. 5). Dordrecht, The Netherlands: Springer.

Rapp, D. N., & Kurby, C. A. (2008). The 'ins' and 'outs' of learning: Internal representations and external visualizations. In J. Gilbert, M. Reiner & M. Nakhleh (Eds.), *Visualization: Theory and Practice in Science Education* (3 ed., pp. 29-52): Springer Netherlands.

Reiner, M. (1999). Conceptual construction of fields through tactile interface. *Interactive Learning Environments, 7*(1), 31-55.

Reiner, M. (2008). Seeing through touch: The role of haptic information in visualization. In J. Gilbert, M. Reiner & M. Nakhleh (Eds.), *Visualization: Theory and Practice in Science Education* (3 ed., pp. 73-84): Springer Netherlands.

Rundgren, C.-J., Chang Rundgren, S. N., & Schönborn, K. J. (2010). Students' conceptions of water transport. *Journal of Biological Education, 44*(3), 129-135.

Rundgren, C.-J., Hirsch, R., Chang Rundgren, S. N., & Tibell, L. E. (2012). Students' communicative resources in relation to their conceptual understanding - The role of non-conventionalized expressions in making sense of visualizations of protein function. *Research in Science Education, 42*(5), 891-913.

Rundgren, C.-J., & Tibell, L. E. (2010). Critical features of visualizations of transport through the cell membrane: An empirical study of upper secondary and tertiary students meaning-making of a still image and an animation. *International Journal of Science and Mathematics Education, 8*(2), 223-246.

Ryoo, K., & Linn, M. C. (2012). Can dynamic visualizations improve middle school students' understanding of energy in photosynthesis? *Journal of Research in Science Teaching, 49*(2), 218-243.

Sanger, M., Greenbowe, T. (1997). Common student misconceptions in electrochemistry: Galvanic, electrolytic and concentration cells. *Journal of Research in Science teaching, 34*(4), 377-398.

Schönborn, K. J., Bivall, P., & Tibell, L. A. E. (2011). Exploring relationships between students' interaction and learning with a haptic virtual biomolecular model. *Computers & Education, 57*(3), 2095-2105.

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher, 15*(2), 4-14.

Shulman, L. S. (1987). Knowledge and teaching: Foundations of the new reform. *Harvard Educational Review*, *57*(1), 1-22.

Simpson, B. J. (1966). The classification of educational objectives: Psychomotor domain. *Illinois Journal of Home Economics*, *10*(4), 110-144.

Stieff, M. (2011). Improving representational competence using molecular simulations embedded in inquiry activities. *Journal of Research in Science teaching*, *48*(10), 1137-1158.

Svensson, H., & Ziemke, T. (2004). *Making sense of embodiment: Simulation theories and the sharing of neural circuitry between sensorimotor and cognitive processes.* Paper presented at the 26th Annual Meeting of the Cognitive Science Society, Chicago.

Tasker, R. F., & Dalton, R. M. (2008). Visualizing the molecular world - Design, evaluation, and use of animations. In J. Gilbert, M. Reiner & M. Nakhleh (Eds.), *Visualization: Theory and Practice in Science Education* (pp. 103-131). Dordrecht: Springer.

Tibell, L. A. E., & Rundgren, C.-J. (2010). Educational challenges of molecular life science: Characteristics and implications for education and research. *CBE-Life Sciences Education*, *9*(1), 25-33.

Tomasello, M., Striano, T., & Rochat, P. (1999). Do young children use objects as symbols? *British Journal of Developmental Psychology*, *17*(4), 563-584.

Tufte, E. R. (1983). *The visual display of quantitative information* (Vol. 2). Cheshire, CT: Graphics press.

Tversky, B., Zacks, J. M., Lee, P. U., & Heiser, J. (2000). Lines, blobs, crosses, and arrows. In M. Anderson, P. Cheng & V. Haarslev (Eds.), *Theory and application of diagrams* (pp. 221-230). Edinburgh: Springer.

Tytler, R., Prain, V., & Peterson, S. (2007). Representational issues in students learning about evaporation. *Research in Science Education*, *37*(3), 313-331.

Uttal, D., & O' Doherty, K. (2008). Comprehending and learning from 'visualizations': A developmental perspective. In J. Gilbert, M. Reiner & M. Nakhleh (Eds.), v*isualization: Theory and Practice in Science Education* (3 ed., pp. 53-72): Springer Netherlands.

van Driel, J. H., de Vos, W., Verloop, N., & Dekkers, H. (1998). Developing secondary students' conceptions of chemical reactions: The introduction of chemical equilibrium. *International Journal of Science Education*, *20*(4), 379-392.

van Driel, J. H., Verloop, N., & de Vos, W. (1998). Developing science teachers' pedagogical content knowledge. *Journal of Research in Science Teaching*, *35*(6), 673-695.

Vavra, K. L., Janjic-Watrich, V., Loerke, K., Phillips, L. M., Norris, S. P., & Macnab, J. (2011). Visualization in science education. *Alberta Science Education Journal*, *41*(1), 22-30.

Velazquez-Marcano, A., Williamson, V., Ashkenazi, G., Tasker, R., & Williamson, K. (2004). The use of video demonstrations and particulate animation in general chemistry. *Journal of Science Education and Technology*, *13*(3), 315-323.

Williamson, V. M., & Abraham, M. R. (1995). The effects of computer animation on the particulate mental models of college chemistry students. *Journal of Research in Science Teaching*, *32*(5), 521-534.

Wood, D., Bruner, J. S., & Ross, G. (1976). The role of tutoring in problem solving. *Journal of Child Psychology and Psychiatry*, *17*(2), 89-100.

Wu, H.-K., Lin, Y.-F., & Hsu, Y.-S. (2013). Effects of representation sequences and spatial ability on students' scientific understandings about the mechanism of breathing. *Instructional Science, 41*(3), 555-573.

Wu, H.-K., & Puntambekar, S. (2012). Pedagogical affordances of multiple external representations in scientific processes. *Journal of Science Education and Technology, 21*(6), 754-767.

Zwaan, R. A., & Yaxley, R. H. (2004). Spatial iconicity affects semantic-relatedness judgments. *Psychonomic Bulletin & Review, 10*, 954-958.