The Importance of Multiple Representations for Teaching and Learning Science

David F. Treagust

Curtin University

Introduction

Science concepts are presented in multiple modes of representation such as text, diagrams, analogies, models, equations, mathematical relationships and computer simulations as well as different representations such as the macro, submicro and symbolic levels. A prime goal of teaching is to help learners develop an understanding of the science concepts under investigation by considering these different representational modes and levels. One way to understand how these different representational modes and levels help learners is to consider their functions as discussed in the theoretical framework of Ainsworth. In this chapter, I explain that without considering science concepts from the vantage point of several different representations, a full understanding of science may not be possible and learning opportunities are reduced. The chapter describes the findings in a case study of Year 11 students learning the human breathing mechanism with a range of different representations.

Modes of Representations

Students learning science are presented with a multitude of information in terms of text to read, words to listen to, experiments and activities, photographs, drawings, diagrams, models, charts, tables, equations, animations and simulations. These different modes of representation, used to depict scientific ideas, concepts or phenomena in a particular way, can be considered on a continuum from concreteness to abstraction – from doing experiments to using language to listen to ideas or to express them. Essentially, the purpose of these different modes of representing aspects of the same scientific ideas, concepts or phenomena is to help the learner develop his or her understanding of the scientific ideas, concepts or phenomena. However, there is significant research data to show that these expectations are not always met (van Someren, Reimann, Boshuizen, de Jong, 1998).

Levels of Representation

For the learner of science, there is an additional aspect to develop a complete understanding of a concept because each concept can be represented by different levels of abstraction. First used by Johnstone (1993) in chemistry education for explaining chemical events, these multilevel representations of concepts include the macro, the submicro and the symbolic. The macro level of chemistry such as the combustion of methane gas includes what one can see, smell or hear when doing the experiment.

How methane burns can be understood by knowing what happens at the submicro level, that is methane combines with oxygen to produce carbon dioxide and water. To have a deeper understanding one needs to know that a methane molecule is made of carbon and hydrogen and this can be represented at a symbolic level in a chemical equation: CH_4 + $2O_2$ -> CO_2 + $2H_2O$. At the symbolic level, this chemical equation can be used to represent either the change in substances at the macro level or the particle interactions at the submico level.

In physics, there are similar levels of representation. The macro level refers to observable events such as the movement of a large box dragged across the floor or light reflecting from mirrors. For physics concepts, as for chemistry concepts, the submicro level is needed to develop an understanding of phenomena involved in understanding the gas laws. A deeper understanding of these events can be made using the symbolic level that can include arrows to show the forces acting, equations and graphing relationships; sometimes these relationships are of idealised phenomena such as not considering friction in a study of gas laws.

Biology has four levels in which concepts are represented because the organisation of biology knowledge is different to chemistry and physics. The macro level involves biological structures visible to the naked eye such as the plants and animals we see in our daily lives – making these observations was how the science of biology began. An additional level of representation in biology is the cellular where plant and animal cell structures invisible to the naked human eye are visible under a light microscope and sub-cellular structures visible under electron microscope. The submicro or molecular level involves DNA or proteins identified using analytical tools such as electrophoresis, chromatography, or a centrifuge. As with chemistry concepts and to a lesser extent physics concepts, the symbolic level provides explanations of phenomena such as metabolic pathways with chemical equations and numerical calculations or in the case of genetics representing inheritance patterns through genotypes or inheritance patterns, and for evolution using phylogenetic trees.

A Theory to Explain the Functions of Multiple Representations

As described by Opfermann, Schmeck and Fischer (2017), there a number of theories to best explain learning with multiple representations. One theoretical framework, that of Ainsworth (2006), describes the pedagogical functions of external representations in learning, namely to complement information and cognitive processes, to constrain interpretation/misinterpretation of phenomena, and to construct deeper understanding in problem solving and reasoning.

Many of the chapters in Tsui and Treagust (2013) used Ainsworth's framework, especially how information and processes from graphs, tables, equations, and pictures of scientific phenomena provide complementary information. For example, graphs allow patterns to be seen and equations indicate precise quantitative relationships of these patterns. Representations that constrain interpretation or misinterpretation of phenomena by familiarity or inherent properties can aid understanding when, for example, a diagram accompanying a description, by way of its inherent properties, can visually support the learners' interpretation of text that is not well understood. Lastly, different representations can promote the construction of deeper understanding through abstraction, extension, and relations.

Multiple Representations in Chemistry, Biology and Physics

During the past decade there has been an increased interest in research on teaching and learning science with multiple representations. Much of this research is in journals or chapters in books and not always readily accessible or easy to locate. An idea suggested to Springer was to bring much of the research on multiple representations for each of the science disciplines, chemistry, biology and physics, under separate covers. Springer accepted this idea and beginning with chemistry education research, John Gilbert and I invited authors researching in chemistry education and we edited Multiple representations in chemistry education. Some years later, Chi-Yan Tsui and I invited authors researching in biology education and we edited Multiple representations in biological education. More recently, Reinders Duit, Hans Fischer and I invited authors researching in physics education and we edited Multiple representations in physics education. Each chapter reports research about how multiple representations have been used to support and/or investigate student learning. Selected chapters from the three books, shown in Figures 1, 2 and 3, illustrate this range of topics with the multiple representations being in bold type.

Challenges
- Teaching structural representations in organic chemistry
- Better utilization of diagrams in research of learning chemistry
- Teaching chemistry with the symbolic level of representation

Improving existing pedagogy
- The role of practical work to emphasize the macro level
- Teaching inorganic qualitative analysis
- Linking macro and submicro levels with diagrams

Classroom Solutions
- **Structure-property relationships** involving meso levels in authentic tasks
- **Historical materials** - looking for explanations of macro phenomena
- The **role of multimedia** - computer simulations/animations

Figure 1. Selected Chapters with Emphasis on Different Multiple Representations in Chemistry Education (Gilbert & Treagust 2009)

The role of multiple external representations in learning biology

- **Pictures** in biology education
- Possible **constraints of visualisation** in biology
- Learning **genetics reasoning** with multiple representations
- Learning and biotechnological methods with **animations**

Implications for biology teaching and teacher education

- Multiple representations in **human genetics** in textbooks
- Understanding **photosynthesis and cellular respiration**
- Representation and decoding of **complex process diagrams**
- Learning **tree diagram thinking** in evolutionary related taxa

Assessment of learning and teaching with multiple representations

- The development of **systems thinking** in biology education
- Secondary students' understanding of **genetics using BioLogica**
- **Analogy and gesture** for mental visualisation of DNA structure

Figure 2. Selected Chapters with Emphasis on Different Multiple Representations in Biology Education (Treagust & Tsui, 2013)

Focus on models and analogies

- Teaching and learning representations in upper secondary physics
- Integrating **computational artifacts** into multi-representational toolkit
- Evaluating multiple **analogical representations**

Focus on multiple modes

- **Social semiotics** in university physics education
- Learning optics with multiple representations
- Enacting a representation construction for **astronomy**
- Learning about **forces** using representations
- Textbooks' representations of **electric current**

Focus on reasoning and representational competence

- Representational competence in **geometrical optics**
- Effective **use of representations** in physics learning
- Role of representations in **dynamics, thermal physics**
- **Global heat transfer** in an online learning environment

Figure 3. Selected Chapters with Emphasis on Different Multiple Representations in Physics Education (Treagust, Duit & Fischer, 2017)

Learning Science with multiple representations

Research from these three volumes and other publications (for example, Eilam & Poyas, 2010) has shown that effective use of different modes and multiple representations can

- improve students' understanding of science conceptual knowledge
- enhance students' problem-solving skills
- reduce difficulties in understanding the links between different representations
- lead to less fragmented knowledge and more coherent understanding and
- increase students' enjoyment of learning science.

When students do not master the ideas within the different representational modes and levels, their learning opportunities are reduced. For example, when students do not recognise the reasons for using a ball and stick or space filling models to explain particular molecular phenomena, they misunderstand the reason for using these different models in learning. Similarly, they do not connect the macro level laboratory work to explanations of observed chemical phenomena at the submicro level and represent chemical reactions with symbols. Indeed, the goal of teaching should be to move mentally between the three levels of representations with a high level of understanding why this is taking palace. It is also likely that not fully understanding the different representational modes and levels can lead to the development of alternative conceptions (Adadan, 2013; Kohl & Finkelstein, 2017).

Science teachers frequently make well-meaning assumptions about students' ability to use and understand the different modes and representations and how they function. However, when students have difficulties understanding and integrating different modes and levels of representation, this can give rise to ineffective learning. One way to address this situation is to overtly emphasize the functions of these different representations. Faced with several representation of the same concept, students with a limited understanding tend to focus on surface features of a representation to prevent being overloaded with information (Sweller, 2005). Often students prefer to use only one or two representations. This situation was demonstrated in the work by Kuo et al. (2017) when first year university non-major physics students were taught optics phenomena with representations of descriptions of the phenomena using words, drawings, equations and graphs; they tended to refer to only two representations in tasks despite being asked to use words, drawings, equations and graphs.

Learning the human respiratory system with multiple representations

As noted above, multiple presentations are ubiquitous in science and how the teacher and his or her students attend to the different representations in their learning can have vastly different outcomes. I illustrate these different outcomes by referring to a study conducted by Won, Yoon and Treagust (2014) that examined the roles of representations contributing to students' conceptual understanding of the human respiratory system.

The research took place in a Year 11 Human Biology class taught by an experienced biology teacher at a private girl's school in Australia. Students in Year 11, the penultimate year of secondary school, are 16-17 years old. The lessons on the topic of the human respiratory system took place over four class hours, during which time the teacher taught the subtopic of the human breathing mechanism using the different representations of a bell-jar model-which is a simple analogical model for the lungs and human thorax, textbook diagrams, written text and verbal explanations.

In addition to the classroom observations, the researchers interviewed students in pairs, audio recorded and transcribed the interviews, and compared and checked all data. The authors used a deductive-inductive data mining approach to identify students' learning strategies and understanding of the underlying concepts. Students also completed items on the breathing mechanism from a two-tier diagnostic test previously developed by Mann and Treagust (1988). An example of a diagnostic test item is shown in Figure 4.

Each lung is a large hollow sack that is like a balloon that expands and contracts to get air into and out of the lung

- A. True B. False

The reason for my answer is:

- There is a model that shows the lungs as two balloons in a cavity. The balloons expand to let air into them and get smaller to push air out of them.
- The lungs are composed of lots of little sacks and the air entering them makes them expand.
- The lungs are made up of a lot of tiny sacks and the lungs expand and contract as the thoracic (chest) cavity changes its volume.
- The lungs are two hollow bags and their volume changes because the diaphragm pushes and pulls on them.
- Other reason

Figure 4. Diagnostic Test Item on the Human Breathing Mechanism from Mann and Treagust (1988)

In this research, we adapted Ainsworth's framework to analyse the pedagogical functions of different representations used by students to explain their understanding of the human respiratory system, namely, to determine how different representations complemented information and cognitive processes, or constrained the interpretation/

misinterpretation of phenomena, or evaluated their learning showing a deeper understanding and reasoning.

In the research paper by Won et al. (2014), three distinct ways were identified in which students used four multiple representations (model, diagram, text, and verbal explanation) to build their concept of the human breathing mechanism. One group of students showed a critical understanding of the nature of each of the representations and developed a coherent, scientific explanation. In such cases, the model of the bell-jar and the lung diagram in the textbook were used by students in a complementary manner, representing different aspects of a concept. Further, students with this level of understanding were able to recognise the limitations of the model in relation to the explanation in the textbook.

Another group of students developed mostly correct explanations but had an incomplete understanding of the different representations. These students were able to explain the concept using one representation but they demonstrated some minor problems in interpreting another representation (the lung diagram) or in transferring their interpretation of one representation (the bell-jar model) for another (the lung diagram). Students with this understanding, the verbal text constrained their interpretation of the model.

A third group of students searched for a one-to-one correspondence between one representation (the bell-jar model) and another (the lung diagram), resulting in incorrect explanations. While understanding the analogous nature of the bell-jar model, they did so without critical evaluating the different representations and did not consider the limitations of the model or the differences between the two representations. Further in the diagnostic test, they displayed naïve conceptions that their teacher in his oral presentation to the whole class explicitly described and warned them about.

This study provided clear evidence about the different approaches that students used to interpret multiple representations for learning about the human breathing mechanism. An analysis of these different approaches can be used by teachers and students to help learning outcomes with multiple representations.

Summary

Multiple representations are ubiquitous in science education teaching and learning. For example, science textbooks often show more than one representation on a single page. A textbook having text adjacent to one or more representations as photographs, drawings, diagrams, models, charts, tables, or equations is common, almost the norm. The reader needs to be able to make sense and analyse why, say, a paragraph about increased heart rate during exercise also has a heart rate - time graph and a picture of a track athlete. The graph can provide information complementary to the text and provide deeper understanding of the concept or it could constrain the meaning of the text. The photograph of the athlete is likely to provide the context and/or is intended to be motivational. To learn science concepts with these different representations, students need to analyse them in order to make judgements about their utility in helping make scientific explanations. To increase students' interest in science, teachers and curriculum specialists provide experiments or demonstrations as well animations and simulations. In every case, without appreciating the vantage point of the different representations, a full understanding of science may not be possible and learning opportunities may be reduced.

References

Adadan, E. (2013). Using multiple representations to promote grade 11 students' scientific understanding of the particle theory of matter. *Research in Science Education, 43*(3), 1079-1105.

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

Eilam, B. & Poyas, Y. (2010). External visual representations in science learning: The case of relations among system components. *International Journal of Science Education, 32*(17), 2335-2366.

Gilbert, J. K. & Treagust, D. F. (Eds.). (2009). *Multiple representations in chemical education*. Springer.

Johnstone, A. H. (1993). The development of chemistry teaching. *Journal of Chemical Education, 70*(9), 701-704.

Kohl, P. B. & Finkelstein, N. (2017). Understanding and promoting effective use of representations in physics learning. In Treagust, D. F., Duit, R. & Fischer, H E. (Eds.). *Multiple representation in physics education* (pp. 231-254). Springer.

Mann, M., &Treagust, D. F. (1998). A pencil and paper instrument to diagnose students' conceptions of breathing, gas exchange and respiration. *Australian Science Teachers' Journal, 44*(2), 55-59.

Opfermann, Schmeck and Fischer (2017). Multiple representations in physics and science education – why should we use them? In Treagust, D. F., Duit, R. & Fischer, H E. (Eds.). *Multiple representation in physics education* (pp. 1-22). Springer.

Treagust, D, F &, Tsui, C-Y. (Eds.). (2013). *Multiple representations in biological education*. Springer.

Treagust, D. F., Duit, R. & Fischer, H E. (Eds.). (2017). *Multiple representation in physics education*. Springer.

Van Someren, M. W., Reimann, P., Boshuizen, H.P.A., de Jong, T. (Eds.). (1998). *Learning with multiple representations*. Amsterdam: Elsevier.

Won, M., Yoon H. & Treagust, D. F. (2014). Students' learning strategies with multiple representations: Explanations of the human breathing mechanism. *Science Education, 98*(5) 840–866.