Chapter 9
The Educational Value of Multiple-representations when Learning Complex Scientific Concepts

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Abstract When people are learning complicated scientific concepts, interacting with multiple forms of representation such as diagrams, graphs and equations can bring unique benefits. Unfortunately, there is considerable evidence to show that learners often fail to exploit these advantages, and in the worse cases inappropriate combinations of representations can completely inhibit learning. In other words, multiple representations are powerful tools but like all powerful tools they need careful handling if learners are to use them successfully. In this chapter, I will review the evidence that suggests that multiple representations serve a number of important roles in science education. I will also consider why the research on the effectiveness of multiple representations shows that all too often they do not achieve their desired educational goals and I consider what can be done to overcome these problems.

Introduction

The use of external representations to help learners come to understand complex scientific concepts is now commonplace. Typical interactive environments such as the three shown below offer learners many different ways to visualize scientific phenomena including video, animations, simulations, and dynamic graphs. SMV-Chem (Russell, Kozma, Becker, & Susskind, 2000) provides examples of real experiments and shows the experimental phenomena with molecular-scale animations, graphs, molecular models, and equations (Fig. 9.1). Connected Chemistry (Stieff, 2005) is a "glass box" simulation which provides a graphical representation of simulated molecules as well as dynamic graphs describing their behaviour and simple numerical displays of system variables (Fig. 9.2). DEMIST (Van Labeke & Ainsworth, 2001) is a domain-independent multi-representational simulation environment. The example shown in Fig. 9.3 is of simulating predator-prey relationships and shows dynamic graphs such as time-series graphs, histograms and phaseplots, animations, a table and an equation.

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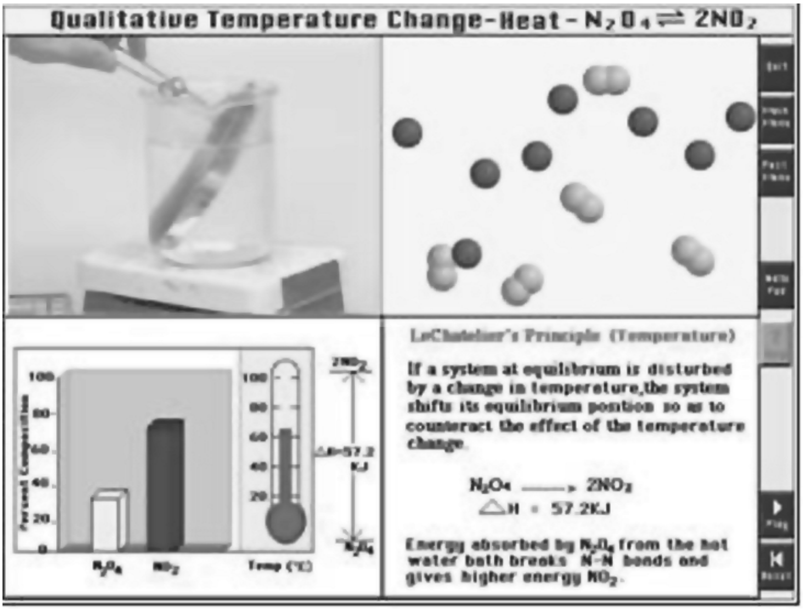

Fig. 9.1 SMV chem

Each environment was designed for different, equally important, educational reasons. They can help learners come to understand the complex forms of visualisations required for professional and expert practice (e.g., phaseplots in DEMIST). They can be designed to give learners indirect experience of phenomena that it is

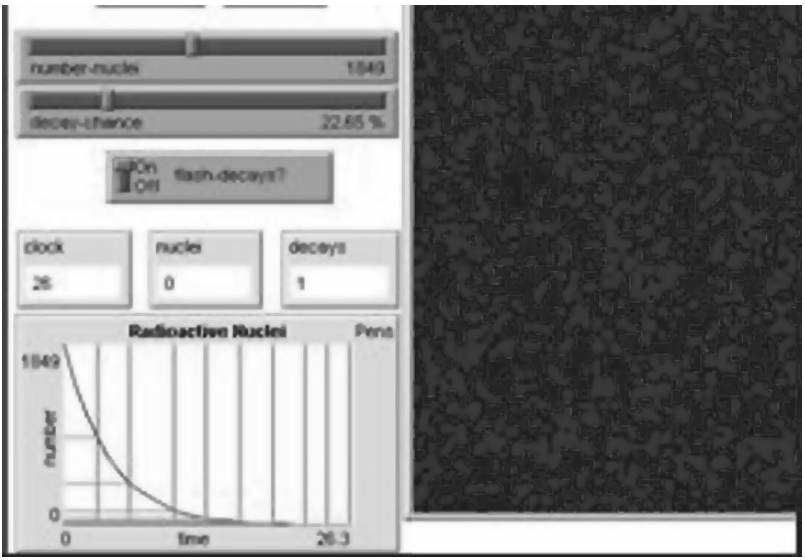

Fig. 9.2 Connected chemistry

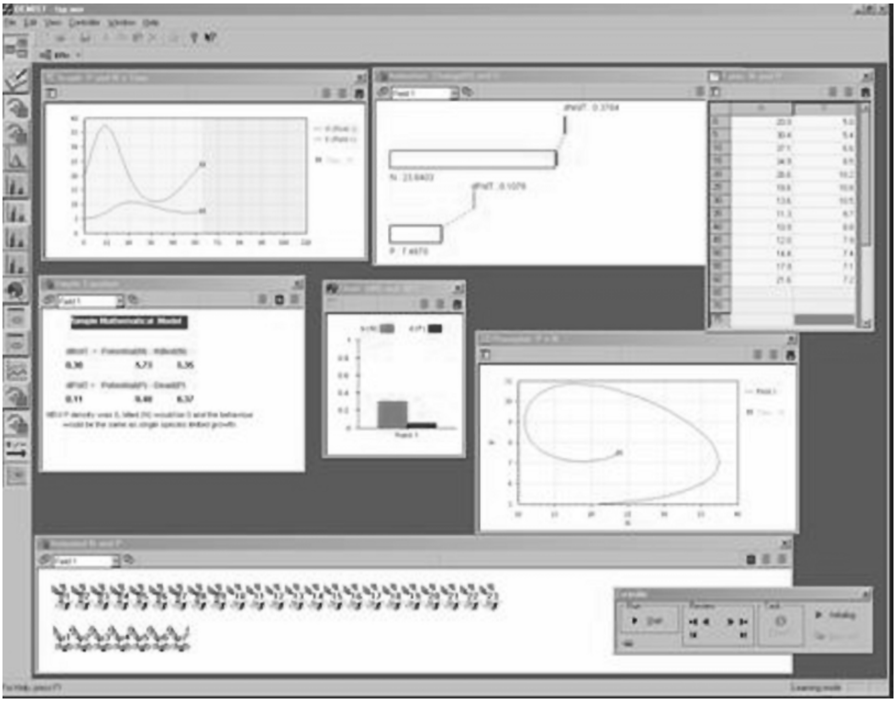

Fig. 9.3 DEMIST

difficult to experience directly in educational settings (such as the video of experiments in SMV-CHEM). They can provide visualisations of phenomena that are impossible to see in the real world yet whose experience will provide understanding that is it difficult to achieve without such representation (e.g. molecular simulations in Connected Chemistry). However, all have one thing in common – they don't just provide a single visualisation: instead they provide multiple representations simultaneously. The purpose of this chapter is to argue that using multiple representations in science education, though commonplace, has particular advantages and disadvantages that should be acknowledged. It will suggest that there are many good reasons behind the decision of designers to include multiple representations but that so doing comes at a cost and that cost can be paid by learners as they become overwhelmed with many new learning demands. It will conclude by considering ways to maximise the benefits of multiple representations without succumbing to these costs.

Advantages of Learning Scientific Concepts with Multiple representations

Multiple representations of scientific concepts are provided for good educational reasons. In this section, the potential advantages of multiple representations will be reviewed, before a later section turns to the complexity that multiple representations can bring to learning.

In the United Kingdom, children learning science in Secondary (High) School follow a National Curriculum that specifies both methods (e.g. Scientific Enquiry) and concepts (e.g. Physical Process). To take one example, children studying science at the ages 14 to 16 might cover the topic of Forces and Motion, which requires them to understand:

- how distance, time and speed can be determined and represented graphically
- factors affecting vehicle stopping distances
- the difference between speed and velocity
- that acceleration is change in velocity per unit time
- that balanced forces do not alter the velocity of a moving object
- the quantitative relationship between force, mass and acceleration
- that when two bodies interact, the forces they exert on each other are equal and opposite

There are many multi-representational learning environments which are designed to help students learn these sorts of topic: two are described below. SimQuest (van Joolingen & De Jong, 2003) is an authoring environment designed to allow researchers and teachers to create instructional simulations for their students. The screenshot of a typical Force and Motion Learning Environment, (Fig. 9.4), uses many different representations to help learners understand the topic. It provides a photograph of the phenomena to be described (top right), a concrete animation of the simulated motorcycle (bottom left), a dynamic time-series graph of the motorcycle's

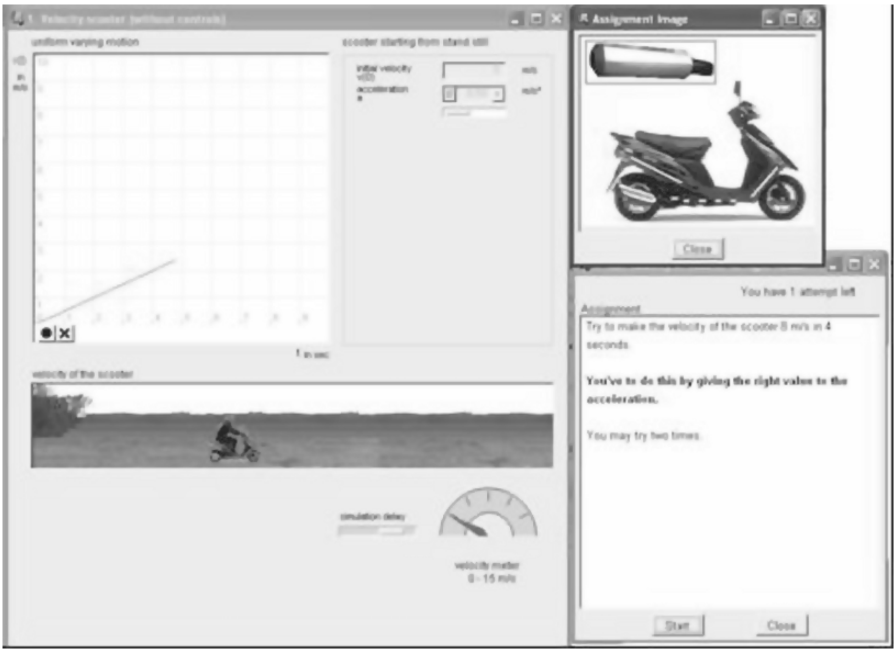

Fig. 9.4 An example of a SimQuest Learning Environment for Force and Motion

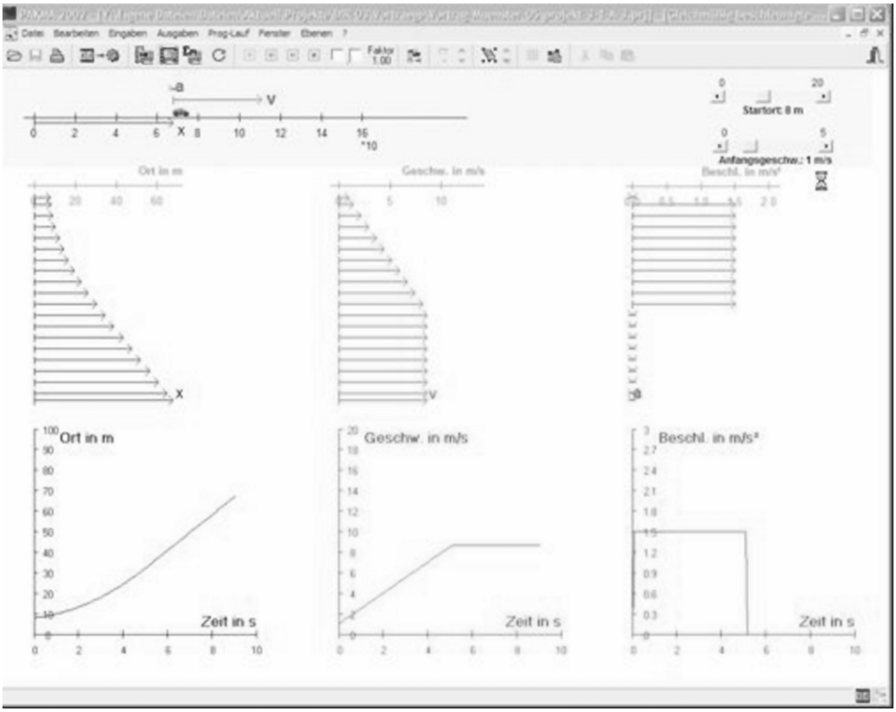

Fig. 9.5 An example of the PAKMA Environment for Force and Motion

velocity (or distance) (top left), and simple numerical displays of the motorcycles current velocity and acceleration (top centre).

PAKMA (Heuer, 2002) is an interactive simulation program that can be used to model force and motion. Fig. 9.5 shows it representing an object's distance, velocity and acceleration. It provides a concrete animation (top left), which is overlaid with vectors to represent the various kinematics concepts (top left), stamp diagrams, which show the object's motion (distance, velocity and acceleration) at previous slices of time (middle row), and dynamic time-series graphs of distance, velocity and acceleration (bottom row).

I proposed a functional taxonomy of multiple representations Ainsworth (1999, 2006) and argue that multiple representations can serve a number of distinct functions for learning (and communication). I will use this functional taxonomy to illustrate the advantages of multiple representations used in the SIMQUEST and PAKMA environments for Force and Motion.

Complementary Roles

The functions of multiple representations fall into three broad classes. Firstly, multiple representations can support learning by allowing for complementary information or complementary roles (see Fig. 9.6).

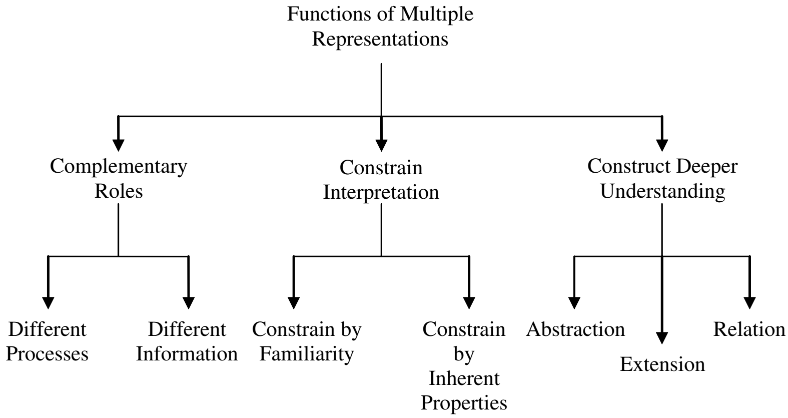

Fig. 9.6 Functions of multiple representations (Ainsworth, 1999, 2006)

The simplest illustration of complementary information in our Force and Motion example would be displaying values for mass, force, friction and velocity. Each representation, be it a graph, an equation, a numerical display, is representing different aspects of a simulated body. The choice of which form of representation to use is therefore likely to depend on the properties of the represented information to be provided. For example, mass might be represented as a simple numerical display as it does not change as the simulation runs, whereas velocity might be represented in a dynamic graph or a table because these representations are time-persistent (Ainsworth & Van Labeke, 2004) and so show how velocity has changed over time. If all this information had to be included in a single representation, then this would either mean that it was represented in ways that were inappropriate to its form (e.g. mass on a time-series graph), at the wrong scale or in the simplest possible way (for example, numerical displays or tables of all the values). So, multiple representations in this case allow different information to be represented in ways that are most appropriate to the learners' needs.

Using multiple representations to support complementary processes rests on the now extremely well known observation that even representations that are informationally equivalent still differ in their computational properties (Larkin & Simon, 1987). For example, diagrams can exploit perceptual processes by grouping together relevant information so making search and recognition easier. Tables make information explicit, emphasise empty cells, allow quick and accurate readoff (of single values) and can highlight patterns and regularities. Equations show compactly the quantitative relationship between variables and invite computational processes.

In forces and motion examples of SIMQUEST and PAKMA, consider the case of trying to determine whether the vehicle is accelerating. If the learner was given a numerical value (e.g. –2) then it is very simple to decide that it is slowing down. It is still easy to see at glance if on object is accelerating, constant, or decelerating from the gradient of the velocity-time graph or simply reading off a single value in an acceleration-time graph. Trying to make this determination in a table requires learners to look at least two entries and then perform a fairly simple mathematical comparison (is the latest value higher, the same, or lower than the previous value?). Whereas if the learner had been given only this equation, $s = ut + \frac{1}{2}at2$ and the current values of s (distance) and u (initial velocity) they would need to first solve the equation for acceleration, $(a=(s–ut) / \frac{1}{2}t2)$ and then substitute values into the equation.

All these solutions require the learner to understand how to interpret the representation (see later) and even the simplest of these still require knowledge. For example, when reading off from a numerical display requires a learner must know the "–" convention for deceleration or how to interpret the downward slope on a velocity-time graph. But, assuming for now that learners know how to interpret these forms of representations, it is obvious that their different computational properties can make this task either trivially easy or extremely complicated (for example, in the equation example).

Consequently, as learning to understand force and motion requires many different tasks to be performed, skills developed and concepts understood, then providing learners with multiple representations with different computational properties presents many possibilities to support learning different aspects of the phenomena.

Constraining Interpretation

Secondly, multiple representations can be used so that one representation constrains interpretations of another one. Often learners can find a new form of representation complex and can misinterpret it. In this case one might use a second, more familiar or easy to interpret, representation to support learners' understanding of the new complicated representation. The role of this simple representation is to constrain the interpretations that learners make of the new representation. In the SIMQUEST example, the constraining representation is the concrete animation of the motorcycle. It moves across the screen to show the learner an object's velocity. This can then constrain interpretation of other more abstract representations. For example, a common misinterpretation of the velocity-time graph is that a horizontal line means that the object is at rest. However, if the learner can see the moving motorcycle at the same time as the velocity-time graph, then may help them understand that a horizontal line means uniform motion rather than no motion.

In the PAKMA example, the stamp diagrams could be considered to be the constraining representation. Each stamp diagram uses the vector arrow overlaid on the animation to show the object' properties in a coordinate plane at defined points in time. Consequently, it is hoped that will help learners understand the corresponding line graphs which are interpolations of these stamp diagrams (see Ploetzner, Lippitsch, Galmbacher, & Heuer, 2006).

The second way that constraining interpretation can be achieved is to rely on the inherent properties of one representation to help learners develop the intended interpretation of the second representation. A number of researchers have drawn attention to the differences between depictions and descriptions. For example, Schnotz (2002) discusses the way that descriptive representations are symbolic in nature whereas depictive representations are iconic. Thus, depictive representations are most useful to provide concrete information and are often efficient as specific information can be more simply readoff.

In our example, a description in text of an objects' motion might be "the motorcycle moved from left to right". However, a depiction would have to be more specific and complete with regard to specific class of information. An animation or a video of a motorcycle would have to commit to a velocity and acceleration for the motorcycle as well. This can be advantageous if you want learners to form a specific understanding of a more descriptive representation and hence constrain interpretation of the description. However, it must also be managed carefully as depictions also have to commit to represent information that may not be important. In this example, one can see the colour of the motorbike, that it is bring ridden by someone with a helmet, etc. Not necessary perhaps for understanding but not especially damaging to understanding either unless the learner decided that Newton's laws are only true for motorcycles with yellow stripes being ridden by men in red jumpers (see later). However, it is also apparent that the motorcycle is going along a road, with trees and with a city in the background. This may encourage learners to apply the intuitive physics they have from real world experience and, in this example, this could lead to confusion as the impact of friction is not being modelled. Consequently, it can be seen that constraining interpretation through the use of depictive representations can be successful but that care must be taken when so doing.

Constraining interpretation by the use of multiple representations is quite different to using multiple representations because they have complementary roles. One implication is that the representation that is designed to perform the supporting role in constraining interpretation is not necessary if the learner has understood the second representation. This might mean that the environment should change to remove constraining representations for different learners or as a learner's expertise grows. In contrast, if the representations are genuinely complementary then one would always expect to be using multiple representations, irrespective of a learners' expertise. It also has implications for the demands facing learners and we will return to this later.

Constructing Deeper Understanding

Multiple representations can support the construction of deeper understanding when learners relate those representations to identify what are shared invariant features of a domain and what are properties of individual representations. Kaput (1989) proposes that "the cognitive linking of representations creates a whole that is more than the sum of its parts". There are many different theoretical accounts of learning that emphasise this use of multiple representations. Cognitive flexibility theory highlights the ability to construct and switch between multiple perspectives of a domain as fundamental to successful learning (Spiro & Jehng, 1990). Dienes (1973) argues that perceptual variability (the same concepts represented in varying ways) provides learners with the opportunity to build abstractions about mathematical concepts. It also can be the case that insight achieved in this way increases the likelihood that it will be transferred to new situations (Bransford & Schwartz, 1999).

Abstraction is the process by which learners create mental entities that serve as the basis for new procedures and concepts at a higher level of organization. Learners can construct references across representations that then expose the underlying structure of the domain represented. In the examples above, abstraction might be supported by providing multiple situations to model. For example, SIMQUEST could illustrate issues of force and motion with motorcycles, cars, skaters, etc. This would allow learners to see that the relationship between the kinematic concepts was not tied to a specific context.

Extension can be considered as a way of transferring knowledge that a learner has from a known to an unknown representation, but without fundamentally reorganizing the nature of that knowledge. For example, learners may know how to interpret the velocity-time graph provided by PAKMA in order to determine whether a body is accelerating. They can subsequently extend their knowledge of acceleration to the other representations.

Finally, relational understanding is the process by which two representations are associated, again without reorganization of knowledge. In the PAKMA example, it may be the case that learners know how to interpret the distance-time graph and the velocity-time graph in isolation. However, they might not know that if they read the velocity from the velocity-time graph then this gives them the gradient of the line on a distance-time graph. The goal of teaching relation between representations can be an end in itself. For example, much emphasis is placed on learning how to construct a graph given an equation.

The differences between these functions of multiple representations are subtle. In extension, the learner starts from understanding one representation well and extends that knowledge to an unknown. In relational understanding, both representations are (partially) known, but the relation between them is unknown. These constructing functions also differs from constraining functions of representations in that all representations contribute to helping learners understand the domain, whereas in the constraining situation the function of one representation is to support understanding of the second.

It should be noted that what functions the representations serve often depends upon learners' knowledge not a designer's intent. For example, one learner coming to PAKMA may be familiar with velocity-time graphs and so extend their knowledge to distance time graphs (extension), but another may already be familiar with both but not have considered their relationship (relation).

Multiple Roles of Multiple Representations

The last section has argued that multiple representations can offer three main advantages for supporting the learning of complex scientific concepts such as force and motion. Furthermore, it has shown that the roles that representations can play depend not only upon the designer's intent but also upon the learner's knowledge and goals. One further factor that should be considered is that any particular combination of representations may also be serving multiple roles simultaneously. An environment may represent velocity through the use of a table, equation, a numerical display, an animation and a graph. In so doing it is allowing for the advantages provided by the different complementary properties of these forms of representation and the different information (e.g. changes over time) they provide It may be taking advantage of the ease of interpretation and familiarity of the numerical display and animation to help learners understand an unfamiliar representation by constraining how they can interpret it Finally, it may be helping learners construct a deeper understanding of force and motion by helping them form abstractions over multiple cases, or relate and extend their knowledge from tables to graphs for example.

Complexity of Learning Scientific Concepts with Multiple Representations

These potential advantages of multiple representations for learning force and motion concepts can only be achieved if learners manage the complex learning tasks associated with their use. This section will review what learners need to know understand about representations in order to learn successfully.

Understanding the Form of a Representation

The most basic competency that learners must develop is to understand the representational syntax. They must understand how a representation encodes and presents information, sometimes called the format of the representation (e.g. Tabachneck-Schijf & Simon, 1998). For example, in the case of the velocity-time graph shown in Fig. 9.4, the format includes attributes such as line on the graph, the labels (what does m/s mean) , and axes (that velocity in metres per second is represented on the Y axis and time (in seconds) on the X axis. They must also learn what the operators are for the representations. Again for the velocity-time a graph, operators to be learnt include how to find the gradients of lines, determine maxima and minima, calculate the area bounded by the line and the axes, etc.

Understanding the form of the representation is not easy for learners, and much research has shown how difficult this is (e.g. Friel, Curcio, & Bright, 2001). For example, Preece (1993) reports that 14–15 year old children found some pupils had trouble with reading and plotting points on graphs, they interpreted intervals as points, and confused gradients with maxima and minima. Scanlon (1998) also found that negative slopes and negative values on velocity-time graphs caused particular problems.

Additionally, the operators of one representation are often used inappropriately on another representation. The most famous example with velocity-time graphs is when they are interpreted using operators appropriate for pictures (e.g. Leinhardt, Zaslavsky, & Stein, 1990). When learners are asked to draw a velocity-time graph of a cyclist travelling over a hill, they should select a U shaped graph, yet many show a preference for graphs with a hill shaped curve. Elby (2000) proposes that this is because learners tend to rely on intuitive knowledge – what-you-see-is-what-you-get and that this is cued by the most compelling visual attribute of a representation (e.g. straight lines mean constancy, hill shape means hill). Learning to correctly apply operators for a representation can therefore involve learning to ignore this intuition.

Understanding the Relation Between the Representation and the Domain

Even if learners understand the form of the representation, they still need to understand how this representation relates to the specific topic it is representing. Evidence suggests that learners do not build domain – independent models of representation but instead use interpretation as an inherently contextualised activity (e.g. Roth & Bowen, 2001), strongly affected by learners' conceptions of and familiarity with the domain.

One key problem that learners face is trying to determine which operators to apply to a representation to retrieve the relevant domain information. In the Force and Motion domain, learners often examine the height of line, rather than its gradient when attempting to determine the velocity of an object from a distance-time graph (Leinhardt et al, 1990). Scanlon (1998) suggests that many learners have developed over-generalised rules for selecting operators (e.g. gradient equals "something", the area under a graph equals "something"). She found that pairs of students interpreting motion graphs would therefore use these general rules irrespective of the particular graph (distance, velocity, acceleration) they were interpreting. For example, they would determine the gradient of the graph and state it as the average velocity if they were working with a velocity-time graph as well as correctly with a distance-time graph. In other cases, however, the rules for these operators were overly selective. For example, Scanlon cites the example of a learner who believed that you could only apply "distance = area under the velocity-time graph" when the graph did not go through the origin.

These problems do not only arise with abstract representations. There is considerable evidence suggesting that even concrete representations (such as fingers when children learn to count) still need to be related to the domain. For example, in the PAKMA environment, the iconic representations of the arrows and stamp diagrams were introduced to provide an intermediate representation between the animation and the abstract graphs. However, Ploetzner et al. (2006) compared students learning about kinematics with either just the animation and the line graphs, the animation, line graphs and arrows, or the animations, line graphs, arrows and stamp diagrams. The students given the additional representations did not perform any better than those without these representations and for harder concepts, even did worse.

Finally, it is worth remembering that one of the main reasons that learners are provided with multiple representations is that they have limited knowledge of the domain that we wish to help them develop. Experts, by contrast, have the advantage of their subject matter knowledge when faced with the task of relating a new representation to the domain (e.g. Chi, Feltovich, & Glaser, 1981). This knowledge will be organised around deep structural knowledge and principles, will be rich and connected to situations where it can be applied and will be available with little effort. However, learners are often seduced by surface features of problems, their knowledge is fragmented and they do not have fluid access to it. Consequently, learners are at particular risk of misrelating new representations to the domain as they have neither the representational knowledge nor domain knowledge to provide support for this task.

Understanding how to Select an Appropriate Representation

In many multi-representational environments, not all representations are available at the same time. In this case, learners have to select the most appropriate representations for their needs. If this is the case, they may have to consider what goal they are seeking to achieve, what representations are available and what are their individual preferences. For example, when solving Force and Motion problems, learners may need to focus on the task they are solving. If their current task is to find out the position from which an object started and they are currently working with a velocity-time graph, they should learn to select the distance-time graph. However, if they need to determine acceleration, they should learn that the distance-time graph is not ideal. They may also need to identify the nature of their personal preferences, for example, do they prefer to learn from tables or graphs? If so, would it be a good idea at this time for them to stay with their preferred form of representation or would it be good to try to focus on their least preferred representation to learn its value?

Understanding how to Construct an Appropriate Representation

In the examples shown above, learners were presented with representations and then required to interpret them. However, learners may also be required to construct the representations themselves. They may be given specific instructions of the representation to construct such as “draw a velocity-time graph of a body which starts with an initial velocity of 0ms and then continues to accelerate at the rate of 9.8 m/s2 for 30 seconds. Find the average velocity” Alternatively, they may be presented with a problem such as “a body starts with an initial velocity of 0 ms and then continues to accelerate at the rate of 9.8 m/s^2 for 30 seconds, find the average velocity” which does not tell them which representations would be helpful. A further possibility would be to give learners the velocity-time graph of this situation and then ask them to construct other representations such as an acceleration time-graph or a table of velocity against time. In the first case, learners must know how to construct the appropriate representation, in the second case, they must know how to select an appropriate representation to construct before interpreting it correctly and in the third case, they must know how to interpret the first representation and the construct a second representation on this basis.

There is a lot of evidence that knowing how to interpret a representation does not mean that you know how to construct a representation correctly (e.g. Cox, 1996). Furthermore, knowing how to construct a representation does not guarantee that you can then use it to solve the problem you constructed it to solve. For example, Scanlon (1998) found that some learners solving a problem like the first one described above could use the area under the velocity time graph and divide by the time or take the mid point of the graph. However, just as many then ignored the constructed graph and used their knowledge of the motion equations and further learners misused equations or as described earlier then used the wrong operators.

There are many educational benefits from encouraging learners to construct their own representations, not least that we want learners to be able to do so – imagine a world where people could read but not write. In addition, it may be the case that constructing your own representations leads to better understanding than interpreting a given representation (see Van Meter & Garner, 2005). Grossen and Carnine (1990) found that children learned to solve logic problems more effectively if they drew their responses to problems rather than selected a pre-drawn diagram. Another innovative use of construction was explored by Schwartz and Martin (2004) who allowed students to invent representations to help them understanding descriptive statistics and compared them to students who had been given solution and allowed to practice them. No student in the invented condition developed the correct solution. However, when comparing which group of students could then learn from a standard lecture and apply the solution to novel problems, the group who had invented solutions were better than the group who had practiced with the correct solution. Consequently, we need to consider allowing students construct their own representations, even if these representations are not ultimately the ones they will go on to use.

Understanding how to Relate Representations

If learners are working with an individual visualisation, then they still need to master the cognitive tasks outlined above. However, there is one process that is unique to learning with more than one representation – that of relating different representations. Unfortunately, there is good evidence that this can be extremely difficult for learners, yet it is a fundamental characteristic of expertise (e.g. Kozma, Chin, Russell, & Marx, 2000). For example, Tabachneck, Leonardo and Simon (1994) report that learners of economics did not attempt to integrate information between line graphs and written information when both interpreting and constructing graphs. Similarly, Yerushalmy (1991) examined fourteen year olds understanding of functions after an intensive three month course with multi-representational software. In total, only 12% of students gave answers which involved both visual and numerical representations. Combining inappropriate representations can even completely inhibit learning. Ainsworth, Bibby and Wood (2002) contrasted children learning estimation with two representations, either mathematical, pictorial or a mixed system of one pictorial and mathematical representation. By themselves, picture and mathematical representations helped children learn but those children who studied with the combination knew no more at the end of the study than they had at the beginning.

It is also difficult to know how to support this process. For example, whether it is beneficial to teach learners to relate representations may depend upon a learner's prior knowledge. Seufert (2003) found that only learners with an intermediate amount of prior knowledge benefited from help with translation between representations. High prior knowledge learners did not benefit as presumably they could make these links for themselves. Low prior knowledge students also did not benefit because they became overwhelmed by too much new information.

Other approaches to helping learners relate representations include making sure they use common labels and conventions, for example, always using blue to indicate distance, green to represent velocity and red for acceleration (as in PAKMA), refer always to distance or position but not distance and position, etc. It may also be the case that the order in which representations are introduced to learners is crucial. For example, Ploetzner (1995) built a cognitive model of how to solve 1-D motion problems with constant acceleration. He then compared the results of his cognitive model to learners' behaviour to show how qualitative knowledge needs to be coordinated with quantitative knowledge for successful problem-solving performance to result. Ploetzner, Fehse, Kneser, and Spada (1999) then tested this prediction by examining collaborating pairs taught with different sequences of qualitative and quantitative representations. Those learners who had first learnt qualitative knowledge were able to gain more from collaboration than those who had first learnt quantitative knowledge. Moreover, software tools that are designed to help in this process may not do so. One common approach is known as dyna-linking – where you act upon one representation and see the results of those actions in another. Dynamic linking of representations is assumed to reduce the cognitive load upon the student – as the computer performs translation activities, students are freed to concentrate upon their actions on representations and their consequences in other representations. However, direct evidence for the benefits of dyna-linking are hard to find. Van der Meij and de Jong (2006) compared different versions of a SIMQUEST environment for teaching moments, which varied whether the system dyna-linked the representations. Overall, there was little evidence for the benefits of dyna-linking.

The inescapable conclusion of this research is that relating representations is an extremely complicated task. Little is currently known about how learners achieve this integration (Reed, 2006) and attempts to help learners do so by providing instructional support or software tools are far from proving invariably successful. Furthermore, failure to relate representations can leave learners without the additional benefits that the multiple representations were designed to provide and can even completely inhibit learning.

Conclusion

This chapter has reviewed evidence to suggest that the learning of complex scientific topics is commonly, even invariably, supported by the use of multiple representations.

It has argued that there are many roles that different combinations of representations can play in supporting learning. However, it has suggest that the benefits of multiple representations do not come for free – learners are faced with a number of complex tasks and as the number of representations increases so do these costs.

So, what is the system designer to do when faced with deciding how to use multiple representations to support the acquisition of complex scientific knowledge? A number of possible frameworks exist and some researchers suggest design principles (e.g. Mayer, 2001). However, that for many of the complex representational systems used to support science learning we may not yet at the point of producing definitive principles – instead there are a number of heuristics that could be used to guide design.

The first heuristic is to use only the minimum number of representations that are you can. So, if you can use one representation do so. But, if you can't consider whether the representations that you think are necessary really are required.

Secondly, carefully assess the skills and experience of the intended learners. For example, do they need support of constraining representations to stop misinterpretation of unfamiliar representations or would this extra representation not provide any new insight without a great deal of work by the learner. Alternatively, they may be so experienced that the constraining representation is not needed and just adds additional work for no tangible benefit.

Thirdly, consider how to sequence representations in such a way to maximise their benefits. Even if you have eight informative ways to visualise a concept, don't introduce all eight simultaneously. Allow learners to gain knowledge and confidence with fewer representations before introducing more.

A fourth heuristics is to consider what extra support you need to help learners overcome all the cognitive tasks associated with learning with multiple representations. Are there help files or exercises to ensure that learners know how to understand the form of the representation? Is the topic to be learnt familiar to the learners or do learners need additional help in relating the representation to the domain? Has the system been designed to help learner see the relation between representations? For example, are consistent labels, colours and symbols used and are representations that need to be related placed close to one another.

Finally, consider what pedagogical functions the multi-representational system is designed to support. If the primary goal is to support complementary functions, then it may be sufficient that learners understand each representation without understanding the relation between them. The task for the learner is to identify when to select particular representations for particular tasks. Learning may be hindered if they spent considerable time and effort in relating representations unnecessarily and so designers may consider ways to either discourage learners from doing this (e.g. by not making representations co-present or by automatically relating representations). If the goal is to constrain interpretation it is imperative that the learner understands the constraining representation. Consequently, designers must find ways of signalling the mapping between representations without overburdening learners by making this task too complex. If the goal is for learners to construct a deeper understanding of a domain, if they fail to relate representations, then processes like abstraction cannot occur. Moreover, although learners find it difficult to relate different forms of representations, if the representations are too similar, then abstraction is also unlikely to occur. Consequently, it is difficult to recommend a solution to this dilemma. But if you need learners to abstract over multiple representations then you should provide considerable support for them to do so, by providing focused help and support on how to relate representations and giving learners sufficient time to master this process.

Multiple representations are powerful tools to help learners develop complex scientific knowledge. But like all powerful tools, they require carefully handling and often considerable experience before people can use them to their maximum effectiveness. Beginners using powerful tools do not achieve the same results as experts and so we should consider how these tools can be designed to allow learners to develop their expertise. Moreover, beginners do not learn without support from others, either peers or teachers. Although this chapter has focused upon what system designers can do to create powerful learning environments, we also need to consider how the learning environment is embedded within particular social contexts.

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