The multiple representations principle in multimedia learning

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Abstract

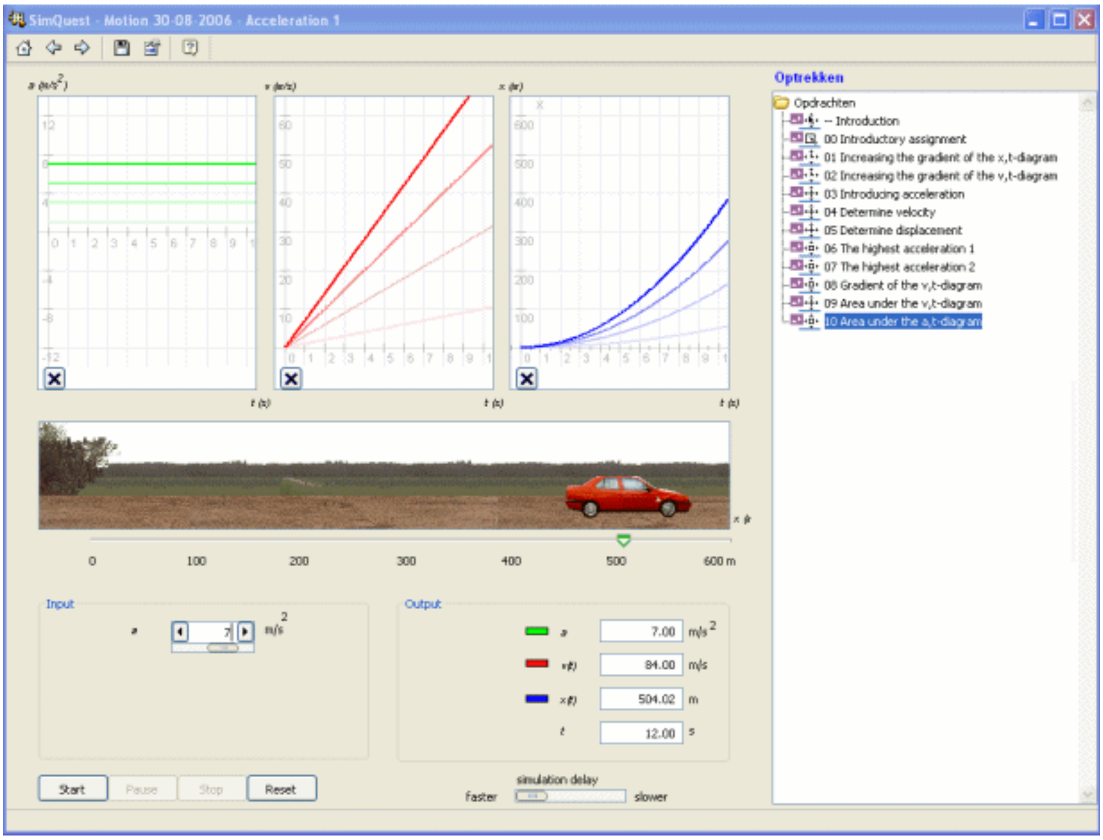
This chapter argues that to understand the ways that multiple representations should be designed to support learning, we need to consider the pedagogical functions that they play alongside their structural form. Multiple representations play a complementary role when learners exploit differences in computational properties or information by switching between and selecting the appropriate representation for the task at hand. Constraining benefits can be achieved when learners understanding of a second representation is supported by relating it to a familiar representations. Learners can construct deeper understanding when they abstract over multiple representations to achieve insight about the nature of the representations and the domain. The chapters reviews studies that have used multiple representations for these purposes and identifies some of the circumstances that influence the effectiveness of using multiple representations in these ways.

What Is the Multiple Representation Principle in Multimedia Learning Principle?

Open a page in a typical textbook and, in addition to text, you will find photographs, diagrams, graphs, maps, pictures, concept maps and a host of specialized graphical representations (such as evolutionary trees, timelines, cartograms or electrical circuit diagrams). In the digital world, there are even more possibilities with animations, videos, and simulations now commonplace and augmented reality and haptic representations becoming increasingly available. And of course learners are not only 'consuming' the representations they are provided with but also creating new ones of their own. They may be talking to peers, writing notes, drawing a sketch, uploading a video they have created or summarizing their understanding in a mind map. In other words, students are constantly engaged in learning with multiple representations, which come is a dazzling array of different formats. Given this diversity of form, can we understand enough about how students learn with multiple representations to make sensible choices about the design of multimedia material and the tasks that learners should perform when engaged with them? The answer proposed in this chapter is that to understand the effectiveness of specific combinations of representations for learning it is not enough to understand the properties of these representations, we must also understand the functions for which they are employed.

What Is an Example of the Multiple Representation Principle in Multimedia Learning Principle?

In understanding the functions that multiple representations can play in supporting learning, it is helpful to start with an example. Figure 1 shows a screenshot from SimQuest (van Joolingen & De Jong, 2003). Like many simulation environments, it describes a concrete situation (in this case the motion of car) and illustrates this with multiple representations that show different aspects of the situation. There is an animation of a car moving forward, three graphs (distance-time, velocity-time and acceleration-time) which show the most recent run of the simulations as well as two earlier ones, the current states of certain variables in numerical displays, and sliders to control the simulation. Simulation environments such as these are now very common, particularly in science, economics and medicine. They are used to allow students to engage in inquiry learning by encouraging learners to change the values of the input variables and to observe the results in the variety of representations provided by the simulation (e.g. de Jong & van Joolingen, 1998; Rieber, 2005). In addition to the representations shown in Figure 1, they often include photographs or textual descriptions to describe and contextualize the phenomena as well as tables of values and dynamic equations that result from running the simulation.



Input

a 7 m/s²

Output

a 7.00 m/s²

v(t) 84.00 m/s

x(t) 504.02 m

t 12.00 s

Figure 1. A screenshot from SimQuest showing multiple representations

There are a number of ways we can describe the representations included in this example. The first type of approach emphasizes the structural aspects of these representations. For example, this could include their modality (e.g. visual or textual; e.g. Mayer, 2005); their dynamism (e.g. static or animated) or their abstraction (e.g. descriptions or depictions (Schnotz, 2002) or symbol, icon or index (Peirce, 1906)). Other researchers appeal to a more fine-grained structural taxonomy of representations such as that of Bertin, (1983) or Lohse, Biolsi, Walker, & Rueler (1994). For example, Lohse et al.'s experimental approach resulted in 11 major categories of static 2d visual representation (graphs, tables, graphical tables, time charts, networks, structure diagrams, process diagrams, maps, cartogram, icons and pictures). In all of these cases, a single representation is the unit of analysis. However, it is also possible to describe the system as a whole and then researchers might speak about this as a multimedia, multi-representational or multimodal system.

A second common approach is to analyze the functions that these representations might support. Again a number of taxonomies have been proposed. For example, Cheng (1996) analyses the functions that diagrams can serve in supporting reasoning and identifies 12 key roles including showing physical assembly, displaying values or encoding sequences. There are also functional taxonomies that analyze the roles that multiple representations play. One of the most frequently cited is that of Levin, Anglin, and Carney (1987), which identifies five functions that pictures can serve when included with text. Firstly, decorational picture simply decorate the page with little relationship to the text and have often been implicated in the seductive details effect (Harp & Mayer, 1997) where learners' understanding of the text can be impaired when presented with such pictures. Representational pictures aim to show all or part of the text they are presented. Organizational pictures provide a structural framework that should help learners understand the content of text whereas interpretational pictures aim to elucidate any difficult aspects of a text. Finally transformational pictures aim to help learners remember texts by providing more concrete referents for the represented text.

The functional taxonomy that serves as the basis of this chapter is one first proposed in Ainsworth (1999) and refined in Ainsworth (2006) as part of the DeFT framework for learning with multiple representations. It suggests that there are three main functions that multiple representations play when supporting learning, namely complementary, constraining, and constructing functions.

Complementary multiple representations support learning by taking advantage of the differences between representations. Representations used in such ways may either represent different information or they may refer to the same information but show it in different ways. By combining these representations, it is envisaged that learners will benefit from the unique properties of each one.

When information is distributed over representations rather than being combined into one representation it becomes possible to simplify each individual representation. For example, in Figure 1, the three numerical displays of the current values of acceleration, velocity and distance refer to information that is on different scales and which uses different units and arguably for this reason, are best they are left as distinct representations. In this form, they are simple to identify and to interpret. However, as they only reference the current state of the simulation they are perhaps of limited value for a learner; previous values must be remembered and they provide little basis for predicting future states.

Multiple representations support complementary processes when the representations have different computational properties (e.g. Larkin & Simon, 1987). Representations that are computationally non-equivalent refer to the same information but differ in the ease and speed with which the inferences can be drawn. Much research has been conducted to explore the different computational properties of individual representations and in many different fields (see Card, Mackinlay, & Shneiderman, 1999; Hegarty, 2011; Kress & Van Leeuwen, 1996; Reed, 2010; Scaife & Rogers, 1996; Tversky, 2011; Ware, 2008). Thus we know that in the ideal case diagrams allow us to utilize perceptual processes which, compared to text, makes search and recognition easier. Typically diagrams group together spatially related information and can use other perceptual clues such as color or connection. Together these design features allow learners to decrease their reliance on complex cognitive actions and replace them with relatively easy perceptual processes. However, it is important to recognize that graphical representations are not inherently superior – accidently subscribing to what Green (Green, Petre, & Bellamy, 1991) has called "graphical superlativism" as for other tasks alternative representations can be more efficient. For example, when reading exact values, comparing values or reading maximum/ minimum values, tables are often found to be more efficient than graphs (Meyer, Shinar, & Leiser, 1997). Thus, in Figure 1 we can suggest that one reason for including multiple graphs is to benefit from the computational processes they support. The straight slope of the velocity-time graph shows that velocity is increasing at a constant rate and the flat line of the acceleration-time graph allows one to simply read off this constant value for acceleration. Of course, the slope of the velocity-time graph also provides the value for acceleration but even assuming the learners know this, it requires calculation to determine the gradient and so it is a slower and more error prone activity.

Table 1. DeFT: The functions of multiple representations

	Complementary	Constraining	Constructing
Function	Using two or more representations when each offer either unique information or supports different inferences.	Using a familiar or easier representation to support understanding of a second complex one.	Using two or more representations so when learners integrate them they achieve deeper understanding of the domain.
Example	Using tables, equation and graphs in a simulation.	Using a concrete animation to support a dynamic graph.	Relating velocity and distance time graphs to understand more about functions and derivatives.
Relating Representations	Not required	Crucial but can be supported through dynalinking relatively easily	Crucial but learners often struggle to achieve this and potentially supporting features such as dynalinking not as helpful as hoped.
Evidence	Plentiful for different computational properties; less research on distributing information.	Plentiful for dynamic graphs and constraining representations; less research on other pairings.	Evidence tends to be elusive with novices often not benefiting in the ways designers intend.

The second common reason to use multiple representations relies on learners noticing the relationships between representations. Multiple representations can provide constraints on what learners understand. In this case, although constraint has a somewhat negative connotation, it is meant positively. Often learners can find a novel representation (or familiar representations used for novel tasks) difficult to understand. Consequently, they may need support to understand this representation and although this could be provided in many ways (such as explicit instruction), one common option is to provide a more familiar and easy to understand representation on which to anchor their understanding of the less familiar representation. In this sense, the first representation constrains understanding of the second and so can limit learners' misunderstandings of it. Simulation environments such as the one shown in Figure 1 often provide a simple animation either of a concrete situation to which the model could apply or to a simplified abstraction. So in this case, it is intended that animation of the moving car will help constrain understanding of the less familiar graphs and those reduce the possibility that learners will misinterpret them. Learners could be less susceptible to seeing graphs as pictures when they are used in this way. For example, they may be less likely to interpret a horizontal line on a velocity-time graph as meaning no motion, or consider that a negative gradient implies negative motion; or see a "hill" on velocity-time graph as showing the object is slowing down over the crest of a hill (Leinhardt, Zaslavsky & Stein, 1990).

Accordingly, the constraining function of multiple representations can only be achieved if the learners understand the relationship between the two representations. In Figure 1 for example, if the learners did not perceive the relationship between the car animation and the motion graphs, then the benefits of providing a familiar or easy to understand representation to help in the interpretation of the less familiar one would not be achieved. The constraining representation may also come with some unwarranted implications with may limit the way it can support learning of the second representation. The car in Figure 1 may encourage learners to apply their understanding from real world experience and, in this example, this could lead to confusion as the impact of friction is not being modeled in the simulation and so shown on the graphs. Given these difficulties, it cannot be taken for granted that the benefits of using constraining representations will always be achieved in the ways that designers intend. Moreover, the representation that is intended to perform the supporting role in constraining interpretation may often not be necessary if the learner has understood the second representation. In this case (and unlike the complementary and constructing functions) DeFT makes a clear prediction of an expertise reversal effect (Kalyuga, Ayres, Chandler, & Sweller, 2003) – that constraining representations are good for novices and either unnecessary or even inhibiting for experts.

The final function considered in the DeFT framework is using multiple representations to help learners construct deeper understanding. It is argued that when learners integrate information from multiple representations they can, in the right circumstances, achieve insight that it would be difficult to achieve with only a single representation. In particular, by so doing they can identify what are the shared invariant features of a domain and what are the properties of the individual representations (Dienes, 1973; Kaput, 1992). Consequently, learners must come to understand how the representations relate to one another. This understanding is neither automatic nor straightforward and in many cases constructing deeper understanding with multiple representations necessitates learners spending much time and effort to develop this knowledge. They often will require support such as dyna-linking the representations where one acts on one representation and sees the results on another (Kaput, 1992; Van Labeke & Ainsworth, 2002) or explicit instruction (Seufert, 2003).

In the example shown in Figure 1, one rationale for providing the three different motion graphs could be to encourage learners to explicitly connect these forms of representation. For example, learners may know how to interpret the distance-time graph and the velocity-time graph. In both cases, this knowledge can develop separately and is useful in answering specific questions (e.g., to answer how far the car has travelled can be read off the final value from the position graph; the speed of the car is the current value on the velocity-time graph). However, it is hoped that learners may come to understand more about kinematics and more about rates of change in general if they can connect these representations. Thus, understanding why the velocity on velocity-time graph provides the gradient of the line on a distance-time graph may help students eventually understand the relation between a function and its derivative. However, as many researchers indicate this is often difficult for learners, even at quite advanced levels (Leinhardt, Zaslavsky, & Stein, 1990). Arguably one way to help this to situate these graphs in multiple contexts (e.g. motion of cars, motorbikes, skaters) and increasing attention has been paid to representing the motion of learners themselves (Kaput, 1998; Nemirovsky, Tierney, & Wright, 1998).

Finally, two complications should be remembered when analyzing the functions that multiple representations can play in supporting learning. Firstly, combinations of representations often serve multiple functions simultaneously. For example, the multiple graphs in Figure 1 allowed both for complementary processes in that different inferences could be drawn more or less easily from each representation and they may also support learners to construct deeper understanding of kinematics and calculus if learners can come to understand the relationship between them. The simple numerical representations of position, velocity, and acceleration are useful to provide the current information in a very efficient way. However, they could also support learners by constraining their understanding of the graphs as current value of velocity may help students decide whether to read the slope or height of the velocity-time graph something that even undergraduate students of physics have been reported to find difficult (McDermott, Rosenquist, & van Zee, 1987). Secondly, the actual function that multiple representations play is crucially dependent upon the learners' prior knowledge and their current goals. If learners know how to read a velocity-time graph, then they will not need the current value display to constrain their interpretation. In this case, they may simply use the numerical displays to answer questions concerning the current value of the simulation and then swap to the graphs when they need to understand the simulation behavior in the past (or make predictions about the future). Equally, if learners do not understand the relationship between the representations they are shown, or choose not to translate between them, then neither the constraining or constructing roles of multiple representations can be achieved. Thus, what is important is not only the designers' intent but what the students actually do.

What Do We Know about the Multiple Representation Principle in Multimedia Learning Principle?

So far we have considered the functions that multiple representations can play around a concrete example, but this analysis has rested on a conceptual analysis rather than on evidence. Consequently this section reviews studies that have examined the complementary, constraining and constructing functions of multiple representations.

Complementary functions

The research literature leaves no doubt that different forms of representation have different computational properties (e.g. Card et al., 1999; Hegarty, 2011; Kress & Van Leeuwen, 1996; Larkin & Simon, 1987; Reed, 2010; Scaife & Rogers, 1996; Treagust & Tsui, 2013; Tversky, 2011; Ware, 2008). Experimental evidence for this assertion can be found in many studies. For example, Bibby and Payne, (1993) found that in learning to operate a simple device, participants who had studied tables and diagrams identified faulty components faster than ones provided with the same information expressed as specific verbal rules. Thus, participants given tables and diagrams identified faulty components faster than one given verbal rules and these representations influenced task performance even when they were no longer present. However, these did not mean that diagrams were generally superior; when the task required finding out which switches were misaligned, participants who had learned from verbal rules were quicker.

Schnotz and Kuerschner, (2008) compared learners' performance with rectangular pictures, which represented the earth along a time axis, to learners who had seen similar information but represented as a circle. Again, neither representation was better overall. However, those participants who had learnt with a rectangular pictures answered questions concerning time differences better than those who learnt with circle pictures, whereas those who learnt with circle pictures answer questions about circumnavigation better than those learned with rectangular pictures. Moreover, these task and representation interactions do not just apply to different modalities of representation; relatively subtle differences within types of representation can give rise to these effects. For example, line graphs help people make judgments about trends whereas bar charts facilitate the reading of individual points or making discrete comparisons (Shah & Freedman, 2011). These effects can be so strong that line graphs influence people to make trend interpretations even when they information they describe is clearly discrete (Zacks & Tversky, 1999). As Hegarty (2011) points out even much maligned representations such as pie charts can be more effective than commonly preferred alternatives such as bar charts when the task requires complex rather than simple comparisons.

Furthermore, there are studies that show that in the right circumstances learners can indeed benefit from combining representations with these different complementary properties. For example, Hegarty and Just (1993) examined learners' performance when presented with simple drawings of pulley system, their textual descriptions or both representations. Their results showed that learners given both representations scored significantly higher on comprehension tasks concerning kinematics rather than those concerning configuration.

Stieff, Hegarty and Deslongchamps (2011) developed three interactive visualizations for teaching molecular mechanics and within each showed four different representations: an equation of the general mathematical model; a specific numerical example of the equation; a graph of this equation; and a well known chemistry specific pictorial representation (a ball-and-stick model) of the molecular system. They designed tasks for students that required students to select different combinations of representations. They also took both verbal protocols and eye-movement data to explore the process of learning. They found that the majority of participants were able to select the representations that were most appropriate for the specific tasks (using the pictorial model for tasks that required 3d spatial relationships whereas the graph was used more extensively to reason about 2d relationships). However, this should not be taken to mean their understanding was faultless; it was clear that students rarely selected equations for their answers even when they would have provided useful insight.

Parnafes and Disessa (2004) used a similar methodology to explore how learners used multiple representations in a simulation environment called NumberSpeed. NumberSpeed supports student understanding of kinematics by asking them to create various scenarios and provides feedback by using two different representations. The first is a concrete animation of racing turtles along with current position and velocity information, which provides immediate and visual feedback on students' actions. The second is a number list representation, which is essentially a tabular representation of position and velocity at different points in time and which supports efficient interpretation and comparison of magnitudes. By analyzing the verbal protocols of pairs of students interacting with NumberSpeed, the researchers showed that different types of reasoning were strongly associated with different types of representation. They describe an approach based on satisfying single constraints at a time based on a local means end analysis and found it to be strongly associated with number list representations. In contrast, more holistic model-based reasoning where a qualitative plan addressing multiple dimensions simultaneously was strongly associated with the concrete animation. Both types of reasoning proved useful and as a result the representations supported complementary cognitive processes that the learners cycled between.

There is less research that has studied people learning with representations that are deliberately designed to provide complementary information. In fact, much research seeks to approach information equivalence in order to understand the role that computational properties play. However, there are a few studies that do address this issue explicitly.

One rationale for distributing information is to explore whether complex information can be better understood when separated into multiple simpler representations rather than combined into one complex representation. For example, Ainsworth, Bibby, and Wood (1997) studied primary school children learning computational estimation where feedback on the accuracy of their estimates included both direction information (either higher or lower than the exact answer) and magnitude information (how close). For some children, this information was integrated into more complex representations and for others it was represented separately. They found that in this case children improved their understanding of estimation faster when the feedback was provided in multiple simpler representations. Ainsworth and Peevers (2003) explored this issue in more depth by considering how the computational properties of representations (tables, text and diagrams) and informational properties of representations (one complex; four simpler) influenced learners' understanding of the best way to operate a complex device. Their results were not straightforward but they found that participants with either the text representation or single complex representation were more likely to find the optimal solution to the problem but at the cost of significantly increasing the time spent studying the instructions. The authors concluded that as this task demanded information to be integrated in order to operate the device most effectively, separating this information added an additional burden. Although there is too little research in this area to safely draw firm conclusions, it does seem reasonable to suggest that when the task that students are learning allow them to focus on separate aspects of it sequentially, then multiple simple representations may be preferred. However when the task requires integration of information combining this information into fewer but more complex representations will be most beneficial (see also Chapter 13) .

A second reason to use multiple representations to split information across representations is when certain information is best represented in alternative ways. This is often straightforwardly because the information is displayed in different units. Whilst tabular representations can accommodate this with ease, this is not the case for many forms of graphical representation (for example, see the three motion graphs in Figure 1). Zhang (1996) produced a thoughtful analysis of the need to match the scale (i.e. nominal, ordinal, interval, ratio) of the represented information with the scale of the representation displaying this information. He argues that the most effective representations match these scales whereas displays with too much information (e.g. use interval display to represent nominal information) are likely to cause learners to over-interpret the information and displays with too little information (e.g. relying on nominal representations to display interval information) increase the demands on learners to internalize and remember these hidden conventions. Thus, it follows from this argument (at least on retrieval and comparison task, if not integration) that performance will be enhanced by distributing information over representations such that the scale of information is matched to the scale of the display.

Similarly it may be that different aspects of a complex system are best represented in different modalities. Bivall, Ainsworth, and Tibell (2011) taught postgraduate biochemists about protein ligand recognition and, in particular, focused on dynamic aspects of this process. In this case, the attractive and repulsive forces between the molecules were represented using haptic feedback. They found the compared to learners who did not receive this information (as there is no simple way to represent the stochastic nature of the process visually), learners given this additional information both learnt more about the complex molecular interactions and tended to demonstrate less misconceptions about protein-ligand interaction.

In summary, the overwhelming message of studies reviewed is that no representation is universally the best; instead representations most help learning when their design (either in the choice of informational complexity or computational properties) is matched to the needs of the task. Consequently, using multiple representations can provide the opportunity to achieve these representation–task matches.

Constraining functions

There is good evidence that multiple representations can serve constraining functions (i.e. when a familiar and easy to understand representation helps learners understand a second representation). For example, Mokros and Tinker, (1987) and Brasell (1987) studied that children significantly increased understanding of graphs when working with computer software (micro-computer based labs in their term) to learn science concepts. They argued this was due to the pairing of real-time experiences and the students' control over them (Beichner, 1990) with the simultaneous graphing of them on the variables on more abstract kinematics graphs. Over both short periods of time (single lessons) as well as longer periods (3 months) it was found that children significantly reduced their misunderstandings about graph interpretations (such as slope and high confusion) as well improved their understanding of kinematics.

Research by Van der Meij and de Jong (2006; 2011) explored the use a complex multi-representational simulation to help learners develop their understanding of moments. It included complex and unfamiliar representations such as dynamic equations and graphs and supported learners' interpretation of these abstract representations by providing dyna-linked concrete animations and simple numerical displays. Studies found improvements in learning domain knowledge and in seeing similarity across representations (especially when supported by dyna-linking, integrating representations or specific prompts to integrate representations) . However the researchers found little evidence of transfer or the learners' understanding of how to transform one representation to another (although these were short interventions). Thus, it seems the environment succeeded in helping learners to develop their understanding through constraining interpretation but did not succeed at helping them to construct deeper understanding.

The constraining use of multiple representations are not only limited to computer environments. For example, Prain and Waldrip (2006) studied how teachers used multiple representations when teaching science topics such as electrical circuits and focused particularly on students' construction of representations such as drawings, writing, role play as well as physical construction of circuits. They argue that teachers introduced representations to students in ways designed to complement and to constrain with some degree of success. However, just using multiple representations did not guarantee success. Students with weaker underlying knowledge did not always benefit from the constraining opportunities the representations provided. Madden, Jones, and Rahm (2011) in the studying undergraduate chemistry observed that many students tended to prefer to work with single representations. Yet with more proficiency, they began to introduce new representations utilizing the constraining benefits of a familiar and well understood representation to help them interpret the new ones.

However, as noted above that the benefits of using one representation to constrain interpretation of another are only needed if learners require such support. This point is illustrated in the work of Scheiter, Gerjets, Huk, Imhof, and Kammerer (2009) who compared students learning about conceptual and visual aspects of mitosis with realistic or schematic dynamic representations. One question addressed was whether presenting the simpler schematic representation first would guide learners when they subsequently saw a realistic representation (which it was hoped would help in the recognition the phases of mitosis when depicted in a microscopic image). However, there was no differential benefit for any task of the realistic representation nor did the combination of schematic and realistic representation help learning. Consequently, it would seem that the schematic representation is sufficient for the task and the additional realistic representation does not provide further benefits. However it could also be the case that, given the profound difficulties that learners can experience when integrating multiple representations, (Ainsworth, Bibby, & Wood, 2002; Kozma, 2003; van der Meij & de Jong, 2006), that these expected advantages did not arise as learners did not see the relationship between the representations.

Constructing functions

The final rationale that was advanced for multiple representations is that this provides opportunities for learners to abstract over multiple representations and gain a deeper understanding of a domain and representations. There is abundant evidence that expertise in many disciplines, especially STEM disciplines, is associated with fluent and coordinated use of multiple representations. For example, Kozma (2003) employed both experimental and ethnographic methods to describe how expert chemists transform representations from one to another (such a NMR spectra, text, and self constructed diagram) and how this supported their understanding of chemistry. They found that such knowledge is fundamental to inquiry processes of professional chemists as they practice their science and moreover, it is fundamental to the way that knowledge is constructed across multiple collaborators. In contrast, students were focused on surface features of single representations, they failed to construct representations to help them think or talk with one another, and they manifested difficulties in making connections across different representations. Similar observations have been made in disciplines such as Physics, Economics and Medicine (Anzai, 1991; Boshuizen & van der Wiel, 1998; Tabachneck, Leonardo, & Simon, 1994).

Accordingly studies have explored whether learners can be provided with multiple representations and encouraged to relate them in order to support the development of such expertise. Stull, Hegarty, Dixon, and Stieff (2012) showed that providing students with physical models with which they could interact helped learners translate between different diagrams of molecular structure. Olympiou, Zacharias, and deJong (2012) provided learners with ray diagrams and simulations of real world objects to allow student to design experiments to understand optics. For simple mechanisms providing the additional representation did not improve learning. However, for more difficult concepts it did and the researchers argue that providing multiple representations had allowed the learners to abstract the mechanism under investigation. This approach need not only be taken when students work individually. For example, White and Pea (2012) in the area of function theory and Furberg, Kluge, and Ludvigsen (2013) in the area of heat and energy transfer describe how multiple representations can support collaborating students to slowly coordinate, refine and deepen their understanding.

Many computer environments have been developed to help learners' construct deeper understanding through multiple representations. For example, SMV Chem (Russell, Kozma, Becker, and Susskind, 2000) shows simultaneous linked macroscopic, microscopic and symbolic chemical representations. Others such as SimCalc or SimQuest use dyna-linking such as a learners action on one representation is reflected upon others (Hegedus & Roschelle, 2013; van Joolingen & De Jong, 2003). However, even with such support learners can struggle to see the relationship between representations (Schoenfeld, Smith, & Arcavi, 1993; van der Meij & de Jong, 2006). Consequently attention has more recently turned to providing scaffolding for learners as they relate representations either by requiring them to actively integrate representations (Bodemer, Ploetzner, Bruchmuller, & Hacker, 2005; Bodemer, Ploetzner, Feuerlein, & Spada, 2004); to self explain these relationships (Berthold, Eysink, & Renkl, 2009; van der Meij & de Jong, 2011); informing learners about the functional roles that relating representations can play (Hilton & Nichols 2011; Schwonke, Berthold, & Renkl, 2009) or by providing direct instruction or worked examples concerning how one representation relates to another (Hilton & Nichols, 2011; Rau, Aleven, Rummel, & Rohrbach, 2012; Seufert, 2003). Typically these approaches are found to improve learning outcomes for students, although these benefits are often influenced by learners' prior knowledge (Corradi, Elen, & Clarebout, 2012; Seufert, 2003).

Another issue that has been received more attention recently has been to explore how learners develop deeper understanding of a domain when they don't simply interpret multiple representations but construct them for themselves. For example, Gobert and Clement, (1999) and Van Meter, Aleksic, Schwartz, and Garner (2006) have found that leaners who construct their own drawings from text develop deeper understanding of the domain. Zhang and Linn (2011) found that asking learners to draw whilst studying a dynamic visualization of hydrogen combustion was even more effective at enhancing learners understanding that interacting with the simulation. Finally, work within the RiLS project (Representations in Learning Science) has focused explicitly on using multiple representations and student constructed representations to deepen understanding of a variety of science topics such as forces and evaporation. This research is more qualitative in its approach focusing on teachers' practices as well as student learning, but is finding consistent evidence of increased understanding of science concepts as well as increasing sophistication in children's use of representations (Hubber, Tytler, & Haslam, 2010; Prain & Tytler, 2012).

In summary, there is evidence that providing (or asking learners to generate) multiple representations that learners must systematically relate to one another can indeed help learners construct deeper understanding of phenomena under investigation. However, both the experimental studies and qualitative accounts of students' sense making show that this process is difficult one and that learners need both time and support if this is to occur.

What Are the Implications for Cognitive Theory?

The main implication of taking this approach to understand multimedia and multi-representational learning is that we must do more than analyze the cognitive aspects of multiple representations. Of course, we must continue to deepen our understanding of the perceptual, attention and memory characteristics of multimedia but such an analysis should be integrated with an account of what are the pedagogical functions we wish the representations to play for learners. Essentially, this position argues that the functions of multiple representations may be one of the important boundary conditions when we consider such issues as whether to use both text and graphics (i.e., multimedia principle; see Chapter 7), whether representations which contain redundant information will harm learning (i.e., redundancy principle; see Chapter 10), or whether the relationship between representations should be indicated (i.e., signaling principle; see Chapter 13). A second significant implication is the finding that to gain the benefits of multiple representations, learners must be proficient in many, often complex, cognitive tasks. Multi-representational learning is not necessarily easy or automatic and takes many years for learners to achieve representational competence (Kozma & Russell, 2005). Throughout the reviewed literature, learners did not always achieve the intended benefits of multiple representations. In particular, many studies found that learners find relating representations difficult. Future research that focuses on the processes by which learners relate representations and the factors that make this more or less difficult would be welcome.

What Are the Implications for Instructional Design?

Ainsworth (2006) argued that there are a number of design implications that follow from this perspective. Rather than considering all of those here we focus on two central issues: the number of representations and how representations should be coordinated.

Although multiple representations can bring many benefits, research shows that such learning is demanding. Consequently, one simple implication for design is to use the minimum number of representations necessary to achieve the instructional goals. Of course, this does not mean only use one representation nor does it automatically mean integrating all information into one representation, although the research does often find that to be beneficial (see Chapter 13). What it does mean is more caution in assuming that learners will gain benefits from additional representations. For each representation included in a system then learners must come to understand it syntax and semantic; they made need to know how to select between representation or how to construct them; and for constraining and constructing functions of representations, they need to know how they relate to one another. Consequently, adding extra representations should only be done after careful consideration. We must consider the properties of representations both separately and together; the task requirements, the nature of the learners such as their prior knowledge and personal learning goals, and indeed how new knowledge will be used and assessed in future.

A second implication concerns whether the system should be designed so that learners are encouraged to relate representations. When learners use multiple representations to construct deeper understanding, they need to relate representations. There is now significant evidence that simply providing learners with multiple representations is not a particularly helpful way to achieve this understanding nor does dyna-linking provide as much benefit as was initially hoped. Consequently, research suggests that effortful learning activities supported by teachers or peers may be required.

When multiple representations are used to constrain interpretation, again they must be related. This might mean that the environment should be designed to remove constraining representations as learners' expertise develops. There is also evidence that learners can use their prior knowledge of one representation to build understanding of a second or take advantage of signaling, interactivity or dyna-linking. Finally, if multiple representations are used solely to achieve complementary benefits, then it may be sufficient to switch between them as appropriate without encouraging learners to relate them. However, it should be remember that multiple representations are often used for more than one purpose and so how they are designed may change as a consequence of the task or learners' goals and experience. For example, initially one might simply encourage a learner to switch between the complementary benefits of graph and a table to understand a car motion (using the table for accurate read off and the graph to identify patterns). However, as learners' familiarity with the system grows them one might encourage them to relate these representations to see how velocity is represented in both forms. Finally, it is worth remembering that the designers' intentions are only one part of the story when determining the effects of learning with multiple representations. Presenting learners with multiple representations does not mean they will choose to attend to all of them (Schwonke et al., 2009) and their own learning goals will strongly influence whether or how they relate multiple representations or use features such as dynalinking (Van Labeke & Ainsworth, 2003).

What Are the Limitations of Current Research and What are Some Implications for Future Research?

Research concerning learning with multiple representations has matured. As Goldman (2003) points out it is now firmly second generational in nature as researchers have moved from asking whether multiple representations help learning to trying to more precisely characterize when multiple representations help learn and what conditions should be in place for this to be more effective. One recent trend has been the inclusion of broader theoretical frameworks; for example papers by de Vries, (2006), Furberg et al (2013), Waldrip, Prain, and Carolan, 2010 and White and Pea (2012) draw on both cognitive and socio-cultural perspectives and this is deepening our understanding of the issues involved.

There is less convergence on a methodological level with most research either providing detailed descriptions of the processes involved with learning with multiple representations over the longer term or reporting on the outcomes of short term experiments that have manipulated key variables of interest. More research that integrates both process and outcome measures would be welcome. These could include analysis and data-mining of system interaction (Rau et al., 2012), eye-movements (Schwonke et al., 2009), verbal protocols (Ainsworth & Loizou, 2003) or combination of these measures (Stieff, Hegarty, & Deslongchamps, 2011).

In arguing for both process and outcome data, this also raises the question of how multi-representational learning should be assessed. Researchers are increasingly aware that if we are understand and demonstrate the benefits of multi-representational learning then assessments must be aligned to this goal (Lowe, Schnotz, & Rasch, 2010). Thus, we see researchers using a variety of outcome measures which go beyond textual outcomes to includes such issues as understanding the form of representations, how to relate representations them or how to construct them. Indeed, researchers are increasingly arguing that we cannot hope to understand what students know in many domains without such multi-representational assessments (Madden et al., 2011). Moreover, we now recognize that the ability to interpret, construct, transform and explain multiple representations is often what counts as knowing in a domain (Kozma & Russell, 2005). Unfortunately, this is at odds with much of school practice where the dominant modes for both learning and assessment are still written and mathematical (Yore & Hand, 2010). Thus, if we are supporting students to learn with multiple representations but their real world assessments do not require this knowledge we may both be underrepresenting the value of multiple representations for learning and even more crucially, misassessing the fundamental ways of knowing a domain (Lemke, 2004).

Another lesson that qualitative and observational studies have taught us that is not being well integrated into the experimental literature is the recognition of just how long multi-representational learning takes. Consequently, it is hard to avoid the conclusion that too many studies are describing not learning **with** multiple representations but learning **of** multiple representations. Future work should aim to provide learners with more realistic periods of time to develop their knowledge of multiple representations.

Finally, if we are to understand more about the functions that multiple representations play in supporting learning, it would be helpful if researchers themselves were more explicit about their choice of representations. In many papers, neither the representations themselves nor their intended role are described in sufficient detail for other researchers to make best use of the existing research or teachers or policy makes know how to implement the findings. We are slowly moving to a world where multimedia does not form only the focus of how work but is the way we can publish it as well (through these use of e-books and supplementary online materials). Therefore, the next generation of research with multiple representations could be based on a much richer picture of the current research if we take advantages of these new publishing opportunities.

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