In press Robinson & Schraw (eds) Current Perspectives on Cognition, Learning, and Instruction: Recent Innovations in Educational Technology that Facilitate Student Learning

How do animations influence learning?

Shaaron Ainsworth

School of Psychology and Learning Sciences Research Institute, University of Nottingham, University Park, Nottingham, NG7 2RD, UK.

Shaaron.Ainsworth@.nottingham.ac.uk

Abstract

One of the key innovations that educational technology has made available is new forms of representations, such as animation, multimedia, and virtual reality. Each new representation is initially greeted with enthusiasm and then, as research on how it impacts the processes and outcomes of learning produces mixed results, this enthusiasm wanes. In this chapter, I want to argue that to truly understand the way that different representations influence learning, we need to consider multiple interacting levels of explanation. I will present a framework that illustrates these levels in the case of one form of innovative educational representation – animation. The chapter concludes by summarising some of the advantages and disadvantages that acknowledging this additional complexity brings to our understanding of learning with animations.

Introduction

Animations are a form of dynamic representation that display processes that change over time. For example, they can show the flux of high and low pressure areas in a weather map, the results of running a computer program (algorithm animation), display blood pumping around the heart, or represent invisible processes such as the movement of molecules. Animations have been included in educational technologies with increasing frequency since the early 1980s. Their availability and sophistication continues to grow as software for their creation and hardware for their implementation develops.

In this chapter, I will apply the broad definition of animation used by Bétrancourt & Tversky (2000), i.e. animation is considered to be “series of frames so each frame appears as an alternation of the previous one” (p313). Typically, each frame exists only transiently to be replaced by subsequent frames, such that the dimension used to represent time in the representation is time. I also include animations that are under system or learner control. However, as with Mayer & Moreno (2002), video is excluded from the definition – as video shows the motion of real objects and animation is considered to show the motion of simulated objects.

Animations are used for a variety of reasons across a whole range of topics. They are often utilized when there is a need to show learners something not easily seen in the real world, such the movement of atoms in a gas (e.g. Russell et al, 2000, Figure 1), or the shifting movements of the continents (as animated in Sangin, Molinari, Dillenbourg, Rebetez, & Bétrancourt, 2006, see Figure 4). More abstract representations can also be used to represent phenomena that are not inherently visual, such as a computer algorithm (e.g. Kehoe, Stasko & Taylor, 2001), the weather in Australia (Lowe, 2003, Figure 3) or stages in a mathematical solution (Scheiter, Gerjets, & Catrambone, 2006). An increasingly common use for animation is in animated agents, where lifelike characters are animated to include gesture and expression (e.g. Johnson, Rickel & Lester, 2000, or the Microsoft agents such as Merlin Figure 2).

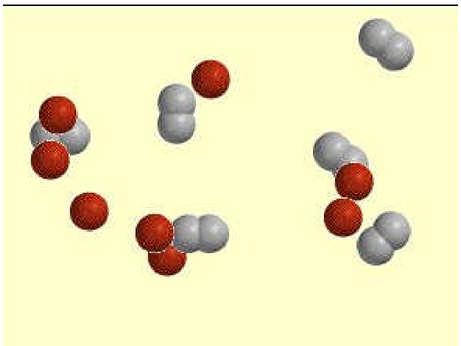

Figure 1: Chemical Animation

Figure 2: Agent animation

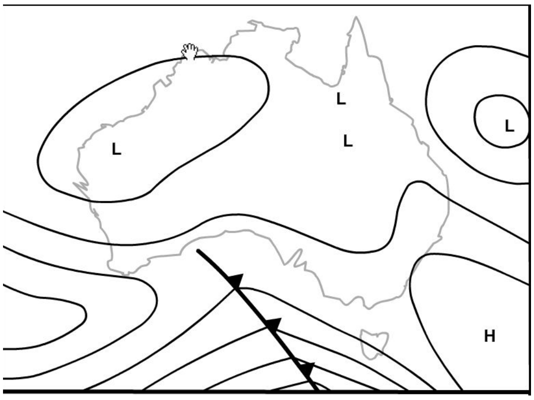

Figure 3: Weather Map Animation

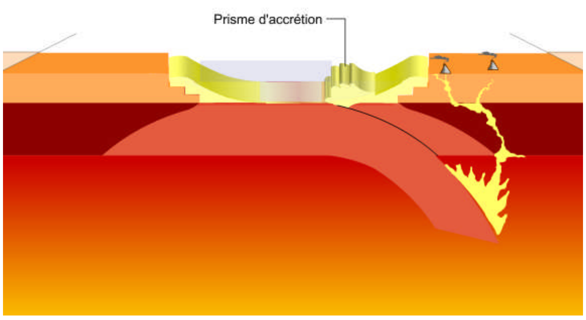

Figure 4: Geological Animation

One of the reasons animations are now found so widely is that many people believe that animations can help learners come to understand complex ideas more easily. However, the reasons that are cited for this beneficial effect tend to vary considerably. Some people believe that animations can help people learn because they are especially motivating e.g. (Rieber, 1991). Alternatively others believe there are specific computational properties of animations that match the cognitive demands of a learning task (e.g. Tversky et al, 2002). However, other people view animations with much more suspicion and recommend limiting the use of animations. Often they tend to cite the difficulties that learners can have in processing animation or in applying appropriate strategies (e.g. Lowe, 2003)

Consequently, it is not surprising that research addressing whether animation aids learners' understanding of dynamic phenomena has produced positive (Kaiser, Profit, Whelan & Hecht, 1992; Rieber, 1991), negative (Rieber, 1990; Schnotz, Böckheler & Grzondzeil, 1999) and neutral results (Price 2002; Pane, Corrbet & John, 1996). Research on animation has varied a wide range of factors, such as outcome measures, participant populations and research environment (Price, 2002) and of course, one reason for this variety of results is that animation is a general term that refers to very different forms of representation. There is relatively little in common between an animated agent, an algorithm animation and an animation of the cardiovascular system. Even within more traditional uses of animation - the display of dynamic physical processes - there are many ways that animations can be implemented. For example, Lowe (2003) identifies three variants of animation: transformations, in which the properties of objects such as size, shape and colour alter; translation, in which objects move from one location to another; and transitions, in which objects disappear or appear. Ainsworth and Van Labeke (2004) argue that animations are a specific form of dynamic representation and that the term animation should not be used to refer to all forms of dynamic representation. Figure 5 shows a simulation environment which displays three forms of dynamic representation. Time-persistent representations show a range of values over time – the dynamic time-series graph of predator-prey numbers and the table are two such representations (top left and top right of Figure 5). Time-implicit representations also show a range of values but not the specific times when the values occur, see the phaseplot of predator-prey population (middle right of Figure 5). Time-singular representations show only a single point of time, (in the example the animated rabbit and fox or the histogram) and are the classical case of animation.

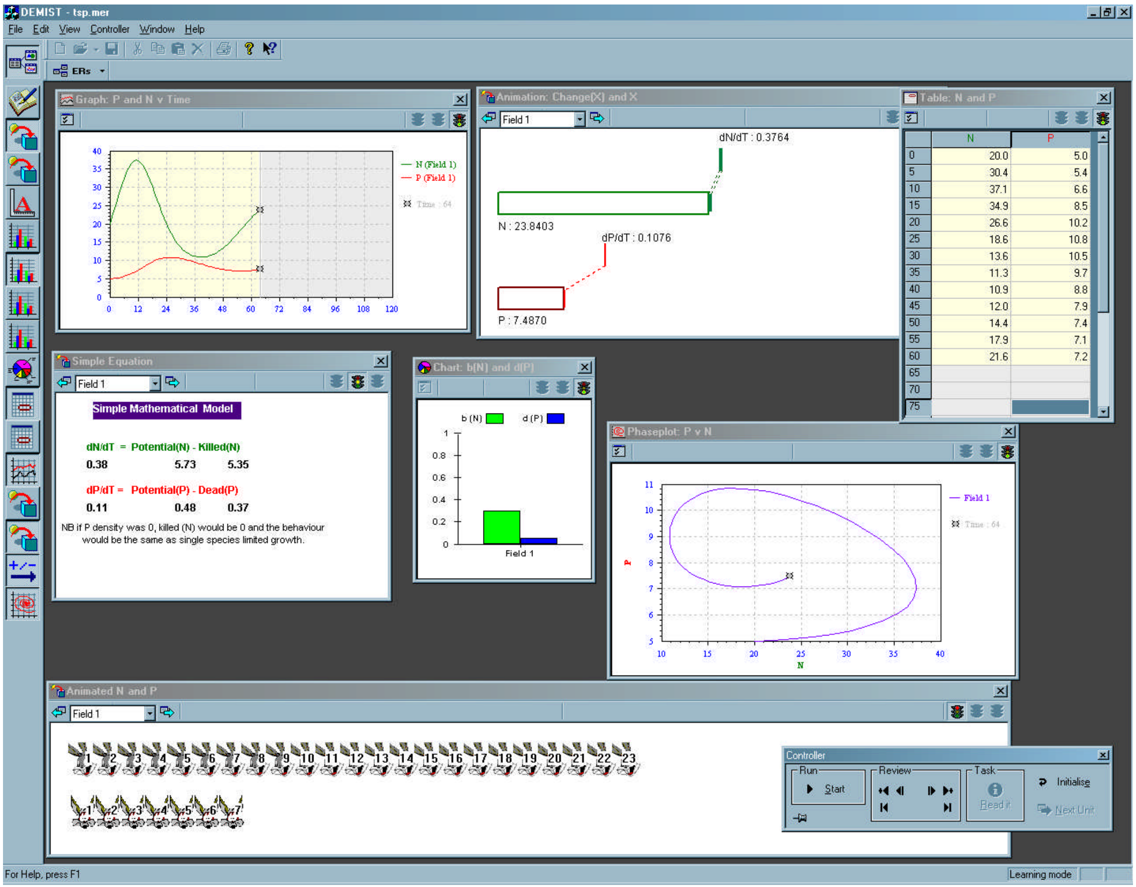

Figure 5. A simulation showing three forms of dynamic representation

What is apparent is that there are many different factors that can influence the way that people learn with animations and that the success of any particular application will depend upon the interaction of many different factors. Hence, researchers acknowledge (e.g. Tversky, Morrison, & Bétrancourt, 2002; Moreno & Mayer, 2002) that the question “do animations help learning?” is not appropriate, so the search is now on to identify the conditions under which learning with animation is helpful. Significant progress is being made in this direction: for example, we know to combine animation with narration rather than with text. However, I want to argue that this line of research needs to be supplemented by a more integrated theoretical account of role of animation, which acknowledges there are multiple levels of explanation that must be applied. Consequently, in this chapter, I will review the evidence that suggests there are at least six different levels of explanation that can and should be evoked to understand learning with animation, namely a) expressive, b) cognitive, motor and perceptual, c) affective and motivational, d) strategic, e) metacognitive and f) rhetorical. I ignore the technical level (i.e. technical devices such as computers, networks, displays), unlike Schnotz and Lowe’s (2003) three level account of representational learning, although expand their semiotic level (i.e. texts, pictures, and sounds) and the sensory level (i.e. visual or auditory modality) into six levels, from two.

The next sections in this chapter will focus on each level in turn. This order is not accidental as it builds from fundamental properties of the representation to factors that are more socially and culturally malleable. However, it should not be thought of as a fixed hierarchy with each level building solely on the ones below it. Each section follows a similar structure. They start by describing theories which have addressed that particular explanatory level (e.g. cognitive, affective) in learning with representations generally (e.g. diagrams, text) then review some of the evidence that has been collected within that explanatory framework and finally, turn to reviewing the research studies which specifically address animation. I also include studies on learning with presented animations and with constructing animations. Unsurprisingly, there is widely varying amounts of research on animation across the levels, so in some cases the review is very selective, in other cases near to exhaustive.

Expressive Explanations

This level of explanation is most associated with the work of Keith Stenning (Stenning & Oberlander, 1995, Stenning 1998). It focuses on how the inherent properties of a representation affects the degree of computation required to make inferences from it and so therefore is independent of the nature of the interpreter. In particular, Stenning argues that the benefits of many forms of representation (especially graphical ones) come from their limited ability to express abstraction. This curtails the amount of search that a learner (with a basic grasp of the semantics of the system) has to make in order to obtain the right inference. Consequently, the expressiveness of a representation will have a strong impact upon the memory and processing requirements that a learner would need to employ to be able to use the representation successfully (see cognitive level). For example, one of the reasons that people find it easier to solve logical problems when reasoning with set diagrams comes from their specificity. The text “all As are Bs” can be interpreted in two ways – that A is a subset of B (and so some Bs are not As) or that A and B are identical (and so no Bs are also not As). A set diagram of this sentence makes clear this distinction, which is hidden in the text.

However, problems can occur when an inexpressive medium is required to express abstraction. If you wanted to represent the sentence “the dog is by the cat” then it is difficult to do this graphically without committing to which side of the dog the cat is sitting (or indeed which breed of dog, colour, size etc). It is notoriously difficult for graphical representations to express disjunctions without employing “abstraction tricks”.

In the case of animation, the main issue that an expressive level of analysis makes us consider is that of temporal constraining. Temporal constraining refers to the fact that animations, as evanescent media, cannot be ambiguous with respect to time and, as a consequence, they force activities to be shown in a particular sequence. If an action is fully determined with respect to time then this can be advantageous, but if not then this can make animation a problematic form of representation. To take a simple example (from Stenning, 1998), the construction of an item of furniture which requires four legs to be attached to a table might be represented in text as “now hammer in all four legs”. However, an animation must show the legs being placed in a particular order or must use an ‘abstraction trick’ such as showing all legs being placed simultaneously. This obviously can lead viewers of the animation to misunderstand the instructions.

A related issue that considering the expressiveness of an animation reveals is the need for all aspects of the dynamic situation to be displayed simultaneously. Again the problem arises from the way that animations are fully determined with respect to time.

If an animation focuses on one aspect of the event, then learners may make erroneous inferences about what is happening in the unviewed aspect of the animation. For example, one commonly animated process is blood flow though the heart. However, if the animation were at any point to focus on only one side of the heart, a learner might draw erroneous conclusions (such as assuming that that only one side of the heart could be filled with blood at any one time or that both sides had oxygenated blood). However, if you attempt to overcome this problem by illustrating all aspects of the situation simultaneously, then the learner is left with the problem of identifying what the salient aspects of the animation are to focus on at a given point in time.

Cognitive, Perceptual and Motor Explanations

This level of explanation focuses on the interaction between the form of a representation and an individual's capacities, knowledge, and skills. Consequently, any particular case will depend both on the general constraints of human cognitive architecture and an individuals' personal experiences. Different ways of representing information tend to be seen in terms of how they can overcome the limitations of this system, particularly memory limitations, so reducing the amount of effort required learn with animations

Cognitive Explanations

The intuitive appeal of animation has, at its heart, a cognitive explanation and many researchers base their arguments on this level of explanation. Tversky et al (2002) sum it up as the Congruence Principle - the structure and content of the external representation should correspond to the desired structure and content of the internal representation (however, Scaife and Roger (1996) refer instead to this notion as the resemblance fallacy). Consequently, if you want learners to form an accurate representation of a dynamic situation (such as blood flow in the heart, or the change in high or low pressure in a weather system) then animation seems to many to be the natural choice.

Larkin and Simon (1987) describe cognitive effort in terms of: a) search operations, which seek to locate sets of elements that satisfy specific conditions; b) recognition operations, which determine whether the sought element matches the required ones; and c) inference operations, which act upon the matched elements to generate new knowledge. Consequently as diagrams preserve geometric and topological information they can exploit perceptual processes thereby reducing both the amount of search and recognition required to interpret the representation.

Zhang & Norman (1994) showed how cognitive effort can be reduced when representations have explicit constraints that are embedded in or implied by their form and so users perceive and follow these constraints without needing to internalize them. Graphical representations utilize these external perceptual processes rather than cognitive operations and so can often be more effective. For example, they explored a version of the Tower of Hanoi task which requires people to learn three rules:1) Only one disc can be transferred at a time; 2)A disc can only be transferred to a pole on which it will be the largest; and 3) Only the largest disc on a pole can be transferred to another pole. In this case, rule 3 is external and rules 1 and 2 internal. But Zhang and

Norman devised an isomorphic version where the discs and poles were replaced with cups full of coffee. Now rule 2 is also external, as no one will want to flood themselves with coffee by placing a small cup inside an already full large cup. In this version of the problem, people make fewer errors and solve the problem substantially faster.

The most extensive cognitive theory of the role of animation in learning is that of Richard Mayer (e.g. Mayer, 2001). His theory has three fundamental cognitive assumptions: 1) that there are two separate channels for processing visual and verbal representations, 2) that each of these channels can only actively process a limited amount of information at any one time and 3) that meaningful learning results from learners selecting, organizing and integrating new material with old in order to actively construct their own knowledge. Consequently, this theory predicts that narrated animations are a very effective form of a representation as they allow complex information to be presented in ways that take maximum advantage of the limited capacity cognitive system. Mayer has subsequently gone on to name this the multimedia principle “That students learn more deeply from animation and narration than from narration alone”, and has confirmed this in numerous studies. For example, a typical study (Mayer & Anderson, 1991) showed naive college students an animation concerning the operation of a bicycle tire pump. Subsequently those students who had been presented with animation and simultaneous narration did better on post-tests than those who had only heard narration.

Schnotz (e.g. Schnotz & Rasch, 2005) discusses two ways that animations might facilitate cognitive processing. The first he calls the *enabling* function of animation. Animations can provide additional information that cannot be displayed in pictures. This additional information allows for additional cognitive processing. The second is referred to as the *facilitating* function. Animations are able to help learners build dynamic mental models of situations by providing external support. In this way animations make cognitive processing easier.

Bétrancourt (2005) identified a further cognitive function that animations can play – to produce cognitive conflict. For example, famously people tend to hold naïve physical conceptions such as objects measuring different weights will fall at corresponding different speeds. However, it is hoped that if an animation showed these objects falling simultaneously, this could evoke conflict and ultimately lead to conceptual change (e.g. Chin & Brewer, 1993).

However, animations are not necessarily successful from a cognitive standpoint. Even though animations may make dynamic processes explicit, there are sufficient problems with interpreting them that this advantage can be lost (Price, 2002). Tversky et al (2002) refer to this as the *Apprehension Principle*: the structure and content of the external representation should be readily and accurately perceived and comprehended. Unfortunately, there are a number of cognitive limitations in the processing of a dynamic animation.

Many researchers have identified the problems for memory that animations promote (e.g., Stenning, 1998). Information in animations is presented transiently, so relevant previous states must be held in memory if they are to be integrated with new knowledge. As working memory has only limited capacity, animations will therefore often overwhelm this resource. In contrast, persistent media such as pictures are available to be rescanned at a learner's will and so will reduce the amount of information that needs to be held in working memory.

Cognitive Load Theory (e.g. Sweller, Van Merriënboer & Pass, 1998) pays specific attention to the way that memory resources are used in learning and it has been applied to research on learning with animation (e.g. Ayres & Paas, in press). Animations are considered in terms of three categories of cognitive load. *Intrinsic cognitive load* is the 'natural' load imposed by the information and consists of interacting elements that must be processed simultaneously to learn new material. *Extraneous cognitive load* is the load imposed by the form the instructional material takes. *Germane cognitive load* refers to the working memory resources required to acquire new information. If extraneous load is too high, learning is likely to be impeded as working memory capacity is not available to be devoted germane cognitive load. Animations are likely candidates to create conditions of high extraneous load, as they are not only transitory in nature buy they may also present a lot of information simultaneously. Empirical support for this predication is garnered from studies that have attempted to reduce extraneous load in order to improve learning. For example, segmenting animations, allowing learners to control the play of animations and directing learners' attention to important elements of an animation should reduce extraneous load (e.g. Ayres & Paas, in press) .

In Lowe's terms (e.g. Lowe, 2004) many problems of animations is that they are *overwhelming* - characteristics of the animation are such that the learner's cognitive system is unable to process all information effectively. However, Lowe also draws attention to the *underwhelming* effects of animation - where learners are insufficiently engaged so that the available information is not given due active processing. Animations that provide a direct depiction of a dynamic system may lead learners to simply observe these dynamics as they are portrayed. There is no need to carry out the intensive cognitive processing that a static depiction might require learners to perform. Given the emphasis within cognitive theories on the active construction of knowledge, this raises doubts as to the benefits of making animations of dynamic systems too direct. Empirical support for this prediction is found in the studies conducted by Schnotz and Rasch (2005). They gave learners animations of the earth rotating within specific time zones and asked them circumnavigation questions such as "Why did Magellan's companions think, upon their arrival after sailing around the world, that it was Wednesday when it was actually already Thursday?". They found that low knowledge learners' performance was better on these questions when they had been given pictures rather than animations. The researchers suggest that this was because learners did not perform the necessary cognitive processes for themselves and relied on the external support that the animation provided.

Motor Explanations

Little has been written about the role that physical action can play in learning with animations. However, there is a long tradition of considering the role of motor actions in educational and developmental theories more generally. Piaget (e.g. Piaget & Inhelder, 1969) believed that motor actions formed the basis of all learning. Infants begin with only sensorimotor representations, (at birth just simple reflexes, to deliberate sensorimotor actions to achieve effects in the world by two years). Only as children develop do they come to understand symbolic representations at first concretely and finally at eleven years they can master formal operations on abstract symbols. For Piaget, using one's body to imitate a phenomenon is fundamental to the latter development of mental symbols to stand for the phenomena.

Bruner (e.g. Bruner, 1966) also emphasises the role of action as learning is seen as progressing through enactive stages when knowledge is acquired and stored by actively engaging in manipulating objects through to iconic (mental representation of the objects) and then symbolic representations. Bruner's approach differs to Piaget's in that it is not a developmental theory but instead describes the learning of new topics at all stages of development.

These theories have recently received renewed attention as researchers have become interested in theories of embodied cognition and in the tools that new forms of haptic and tangible interfaces bring to learning. For example, Martin & Schwartz, (2005) argue that physical action can support learning in four ways; induction, offloading, repurposing and physically distributed learning. By *induction*, they argue that if learners act in stable environments that offer clear feedback and strong constraints on interpretation, then these consistencies help people uncover the structural regularities in these environments (for example, children pouring water between different shaped glasses). In *off-loading*, people rely on the environment to reduce the cognitive burden of a task and so increase their efficiency at doing the task. When *repurposing* people act upon the environment to adapt it so it can allow them to achieve their goals. For example, Kirsh & Maglio, (1994) showed that expert players of the computer game Tetris repurposed their actions so that the movements of the pieces yielded information about where each will fit (as well as to move it to the appropriate location). Finally, in *physically distributed learning* (PDL), ideas and actions of the environment co-evolve such that new ideas become possible (as in children learning fractions concepts, Martin & Schwartz, 2005).

A final area where the role of specific physical activities in learning has been explored is that of gesture. Goldin-Meadow & Wagner (2005) argue that gesture can contribute to learning by informing others about someone's current understanding. If listeners then respond to this information, they can then help the learner. There is good evidence to suggest that gestures can be extremely informative about learners' knowledge – for example Church & Goldin-Meadow (1986) found that the children who produce gesture–speech mismatches before instruction on the Piagetian conservation task are more likely to make progress on the task than children who produce matches. Furthermore, listeners can take account of this information to adapt their strategies and when they do so, learning is more successful (Goldin-Meadow & Wagner, 2005). Secondly, gesturing can support learning through externalization of some of the cognitive processes. Thus, it can reduce the demands upon the cognitive architecture in the ways described above (cognitive explanations) and make an internal representation external allowing it to be reflected upon. There is certainly evidence that people do use gesture when they need to learn something demanding, (e.g. Schwartz & Black (1996) show how people gestured when learning to solve a gears task) but still there is only limited evidence for its causal supportive role.

Consequently, there seems good reason to expect that learning with animations should be influenced by a motor level of explanation. However, there is, as yet, very little research. There may be a role for animation in physical education, with animations available to demonstrate golf swings, track and field events, weight training and swimming amongst others. It could also be the case that animated and interactive graphics allow learners to adapt the learning environments in ways that are akin to physically distributed learning. It also seems plausible (but again research is needed) that watching animations of events (such as simulations of mechanical objects or the swimming motions of fish) will encourage learners to gesture. Gesturing could then help learning by either providing models for other learners (as in Schwartz's (1995) collaborative gears problem experiment), by exhibiting a source of information for teachers to allow them to debug learners' conceptions or act as a way of externalising an individual's knowledge to reduce cognitive effort. However, it could also be the case that animations inhibit needed motoric responses. Learners working with computer animations rather than manipulating real objects may not be developing the appropriate sensory-motor schemata that theorists such as Piaget discuss.

Perceptual Explanations

Given that animations are visual images, surprisingly little has been written about the perceptual aspects animations. Indeed, it is only within a specific range of perceptual criteria (e.g. displacement, frame rate, object being animated) that a sequence of static images is seen as an animation at all. However, recently there have been calls for increased attention to be paid to the basic perceptual characteristics of animation (e.g. Schnotz & Lowe, in press).

Animations can be difficult for learners to perceive. The human visual system is extremely capable of predicting and detecting motion but yet it can still struggle to perceive interactions in fast moving displays. Perception is even more problematic when animations show complex dynamic processes, which require learners to watch simultaneously multiple events that are visuospatially separate (such as the elements on the weather map in Figure 3). Even our perception of the movement of elements within animations is strongly dependent upon the movement of other objects around them (e.g. Johansson, 1975). Furthermore, one of most significant concerns about the perception of animations is often those aspects of an animation that are easy to perceive are not necessarily those that are most important. Lowe's (2003) research on weather maps shows that learners are attracted to large and obvious changes in form or position (such as fronts and advancing highs) which may not have particular meteorological significance and can miss more subtle perceptual features (such as isobars) which do have strong implications for the weather.

Consequently, there is a need to understand how to design animations (and indeed other forms of graphical representations) to align (where possible) the features of the animations that should be attended to patterns to which the visual system is attuned (Chabris & Kosslyn, 2005; Schnotz & Lowe, in press; Ware, 2004).

Research into pattern perception has a long history, beginning with the Gestalt Psychologists in 1912. They proposed a set of laws that describe the patterns in visual displays, which remain valuable today (even if the underlying mechanisms are now disputed). Examples include Proximity (things that are closer together are seen as a group), Continuity (we construct visual entities from smooth continuous elements rather than angular ones), Similarity (similar shapes are grouped together), Symmetry (symmetrical patterns of more likely to be seen as one object), Closure (contours that closed tend to be seen as regular figures), and particularly relevant to animation Common Fate (elements which move in the same direction are perceived as a collective or unit). Principles such as these can help in the design of visualizations (e.g. see Ware 2004 for an example of how the design of node-link diagrams can be enhanced by applying Gestalt Laws).

Another related approach is to try to identify ways to make elements of interest stand out from others in their surroundings by increasing the preattentive processing of those attributes. In this way learners could be led, almost against their will, to appropriate aspects of the visualization. This could be particularly beneficial if the animation is complex and fast moving. For example, colour is preattentively processed and so in a predominantly gray, blue and green display, representing something in red will attract visual attention. Other examples of attributes that are preattentively processed include orientation, size, basic shape, convexity and motion.

Moreover, motion is processed well even in the periphery of vision and so the sudden inclusion of a moving target will draw attention even to the periphery of the screen (Bartram, Ware & Calvert, 2003). This normally leads to annoyance when viewing web pages but could be helpful in educational settings, suggesting a role for animation even in predominantly static displays.

People may also perceive continuous animations as composed of discrete steps (e.g., Tversky, et al 2002). As a consequence people perceive activities as consisting of events, each of which is a segment of time at a given location that is perceived to have a beginning and an end (Zacks, Tversky & Iver, 2001). Therefore if what is being animated is conceived of in discrete steps, it may be better to portray it in discrete steps (e.g. Hegarty, Kris & Cate, 2003). This obviously raises the question of how on-going events are partitioned into these separate steps. Zacks et al (2001) argue that this segmentation occurs due to an interaction between bottom-up perceptual processing of perceptual patterns and top-down schema driven processing. Consequently, when deciding what static pictures to use to replace an animation or where to segment long animations, knowing where people naturally perceive discrete events will be very important. Furthermore, Schnotz and Lowe (in press) argue that depending upon a learner’s goal, it may be important to segment at either macro-events (such as a horse moving from one field to another) or micro-events (such as the movements of a horse’s legs when it gallops).

Affective and Motivational Explanations

There is a tendency for all new forms of representation and technology to be greeted with naïve optimism for its affective or motivational benefits and animation has been no exception. Consequently, for many people it is self-evident that animations will help students learn because they are fun and increased fun will enhance learning. The truth is obviously more complex. Unfortunately and perhaps because of either the perceived obviousness or naivety of the claim (depending on your perspective) there are few theoretical accounts of learning with animation that evoke these explanatory constructs. However, this picture is beginning to change (e.g. Picard et al, 2004) and there is an increasing amount of empirical research exploring the affective impact of animation.

One famous exception is the work of Thomas Malone (e.g. Malone, 1981, Malone & Lepper, 1987). Malone proposed four categories of individual motivations: challenge, fantasy, curiosity and control. Of most relevance to animation are fantasy and curiosity. For example, Malone explored different versions of the computer game 'Breakout' and found that animated effects such as the breaking of a brick in the wall were seen as contributing most to the appeal of the game. Fantasy elements of games often involve animation – for example in the DARTS game that Malone explored, fantasy was created by breaking balloons with arrows. Whilst this game was popular with boys, Malone found that girls did not like playing this game and so suggested that this fantasy was inappropriate for them and was detrimental to motivation. Consequently, this research suggests that using animation to implement fantasy elements will not necessarily enhance motivation.

One positive emotion that has been linked to increased learning is that of flow (Csikszentmihalyi, 1990). Flow is considered to be the mental state in which people are fully immersed in whatever they are doing. It is characterized by a feeling of energized focus, full involvement, and success in the process of the activity – i.e. a pleasurable emotional state. A number of factors are said to enhance the possibility of creating a flow experience (such as immediate feedback, clear goals, an appropriate level of challenge) and some researchers propose that vivid and interactive presentations can also enhance flow (e.g. Chan & Ahern, 1999). If this is true, appropriate use of animation may increase flow, (although inappropriate use would also be expected to reduce it).

There is plenty of empirical evidence that people will chose animations when provided with learning environments that include them. Rieber (1991) attempted to measure the motivational benefit of different forms of computer-based representations for physics learning. After a number of lessons with an animated simulation of Newton’s laws of motion, children were given free choice of continuing to work with the animation, or to work with question and answer activity on Newton’s Law or an unrelated word-finder puzzle. He found that children preferred the animation to both of the other forms of activities. However, this may represent a preference for interacting with a simulation rather than the animation itself. Wright, Milroy, & Lickorish (1999) confirmed that compared with static diagrams, animation increased readers' willingness to study a range of graphical representations (maps, time-lines, drawings of unfamiliar objects).

Another area where animation has been extensively studied is algorithm animation (a dynamic visualization of a program's data, operations, and semantics). Again, the introduction of algorithm animation was greeted with enthusiasm but empirical reports of the benefits are mixed or missing (Kehoe, Stasko & Taylor, 2001). Consequently as well as exploring differences in learning outcomes, researchers have interviewed students about their experiences of working with animations. Stasko, Badre & Lewis, (1993) report that students feel they help them learn and Kehoe et al (2001) report that students typically respond positively that they are "*relaxed, more confident in their knowledge and more open to learning*", p 282).

A third area where the impact of animation upon emotion and motivation is receiving attention is that of animated pedagogical agents - an animated agent that cohabits a learning environment with students to help them learn (Johnson, Rickel & Lester, 2000). Animation in this case is used to demonstrate how to perform actions, locomotion, gaze, and gestures are used to focus the student's attention, and head nods and facial expressions can provide feedback on the student's behaviour. They report a persona effect - because lifelike characters (in their case, an animated character called Herman the Bug) have an enchanting presence, they can significantly increase students' positive perceptions of their learning experiences. However, there is also contradictory evidence about the benefits of animated agents on motivation. Baylor, Ryu, & Shen (2003) asked students interacting with either animated or non-animated agents questions concerning self-efficacy, disposition, and satisfaction (as measures of motivation). They found that presence of animation negatively affected both satisfaction and self-efficacy. Baylor et al speculated that agent animation distracted learners, making them feel less confident and satisfied, and propose that if the learner's expectation toward the agent's capabilities and human-likeness are too high (e.g., human voice with animation) or too low (e.g., machine-generated voice and no animation), this could negatively impact motivation.

Strategic Explanations

It is known that different representations can both evoke and require different strategies* to be used effectively. This is true both for when people are presented with representations and when they construct their own representations.

Zhang & Norman's (1994) analysis of the impact of presenting different forms of representation shows how they change learners' behaviour and the likelihood of them discovering particular strategies for solving problems. For example, if the problem "twenty one multiplied by seventeen" is represented as "21 * 17" or "XXI * XVII" then it dramatically changes the strategies that are available to solve this problem. Zhang, Johnson & Wang (1998) observed how different forms of the game tic-tac-toe (noughts and crosses in the UK) changed the likelihood that people would discover the optimal strategy for playing the game. The three isomorphs were: a) Line – getting three circles on a straight line is a win; b) Number -getting three numbers that exactly add to 15 is a win; and c) Color -getting three big circles that contain the same colored small circle is a win. The most effective strategy for winning this game they called

* In this chapter I will use strategy in a very general way to mean methods by which students learn.

"Even-even" based on its form in the number game and requires players to pick two even numbers to start (or two places in the board, etc). They found that the Line isomorph (because of the way it externalized information) led to the development of the even-even strategy first. Moreover, transfer behaviour was also affected with the Number representation leading to a more specific form of the strategy which led to positive transfer and Color leading to a more general strategy which increased negative transfer when students then played the Line game.

Ainsworth & Loizou (2003) also found evidence that presenting information as either text or pictures impacted upon whether learners used an effective learning strategy – self explanation (Chi, Bassok, Lewis, Reimann, & Glaser, 1989). A self-explanation is additional knowledge generated by learners that states something beyond the information they are given to study. For example, if learners read "*The heart is the muscular organ that pumps blood through the body*", a typical self-explanation might be "*so it's got to be a muscle that is strong enough to pump blood around the whole body*". Students were trained to self-explain and then given either text or diagrams describing the structure and function of the cardiovascular system. Students in the diagrams conditions learnt more than students in the text condition. Moreover, diagrams students gave over one and a half times more self-explanations than student given text. It seems therefore that diagrams are more successful than text at inducing an effective learning strategy. Furthermore, learning outcomes correlated with the amount of self-explanation only in the diagrams condition. This suggests that successful learning with diagrams rather than text may depend more on effective strategies.

There is also evidence that constructing representations of different forms is associated with different strategies. Tabachneck, Koedinger & Nathan (1994) also found that students' spontaneous construction of different representations were associated with different strategies. College students were asked to solve typical word problems (such as "A man has 3 times as many quarters as he has dimes. The value of the quarters is one dollar and 30 cents more than the value of the dimes. How many dimes does the man have?"). They found that students used six different representations, verbal propositions, verbal arithmetic, verbal algebra, diagrams, written arithmetic, and written algebra, which were associated with four different strategies. In some cases, a representation was used solely with one strategy (algebraic representation) but in other cases the same representation was used with more than one strategy (verbal math). There was no particular strategy which led to success; rather the use of multiple strategies was correlated with better performance.

A small number of studies have looked at the relation between effective learning from animations and learning strategies. Lewalter (2003) looked at the strategies students used when learning about a complex astrophysical topic from text accompanied either by a picture or by an animation. He categorized learners' behavior into either rehearsal strategies (such as simple memorization techniques), elaboration strategies (which help learners connect new knowledge to existing knowledge) and control strategies (which refer to metacognitive strategies aimed at assessing one's own comprehension – see the next section). Information about which strategies learners were performing was elicited by using verbal protocols. He found that learners used rehearsal strategies significantly more often when learning with pictures rather than animations, but no difference for either elaboration or control strategies which were both rarely used. Animations were not found to be significantly better than pictures at supporting learning in this study, potentially because students did not engage in effective elaboration strategies.

Lowe (1999, 2003, 2004) has studied the strategies that novice learners use to search for relevant information in weather map animations. He considers both spatial strategies, which refer to the area and location of the search and temporal strategies that look at when the search is conducted. Temporal strategies are defined as either: a) confined strategies that concentrate on a small and highly localized section of an animation; b) distributed strategies that also concentrate on a small proportion of the total animation but involve frames that are spread throughout the whole time period; c) abstractive strategies that survey the animation for occurrences of a particular feature to try to abstract a general principle; and d) integrative strategies that seek out combinations of feature events that change in association with each other.

Lowe (2004) explored learners' strategies by examining their drawings, interaction with the animation and spoken commentary and gesture about the animation. He found that evidence that learners mostly used low level strategies that addressed only isolated aspects of the animation. As a result, they were unsuccessful at producing integrated predictions across the weather map overall. This strategy is seen as strongly related to the overwhelming cognitive factors discussed above. Consequently, he warns that simply providing interactive features will not by itself overcome the problems associated with animations.

A final aspect of learners' strategies with animation that might be considered is whether there is evidence that the underwhelming characteristics of animations may also impact upon the strategies learners choose to use. This will be considered as a failure of metacognition and so discussed in the next section.

Metacognitive Explanations

Metacognition is often simply defined as the process of "thinking about one's own thinking" and involves active control over the processes engaged in learning. Learning behaviors that are associated with metacognition include planning how to perform a task, monitoring how well you are learning and evaluating whether you are close to solving a problem. The relationship between metacognition and representation is most often evoked in terms of how these metacognitive activities can be enhanced by encouraging students to create their own representations, for example, by drawing diagrams, writing notes, or by annotating the existing representation. Less is written about the relationship between metacognition and presented representations – do different forms of representations themselves help or hinder learners to engage in metacognition. Furthermore, the boundary between metacognitive and strategic accounts of learning is fuzzy, as metacognition also emphasise use of appropriate strategies to help learners regulate their learning better.

Arguments for the presumed relationship between representation and metacognition for the most part are extrapolated from the relationship between representation and cognition, i.e. appropriate representations can enable metacognition by overcoming the limitations of the cognitive system and so enabling learners to devote cognitive effort for metacognition. For example, Kirsh's (e.g. Kirsh, 2005) distributed cognitive approach to understanding how representation influences metacognition is very similar to that of Zhang and Norman's described above in the Cognitive Section. For Kirsch, good representations display cues and constraints to bias users towards appropriate metacognitive actions, making planning, monitoring and evaluating easier. For example, the size of a font might cue learners that this section of the text is important and they should plan to read it first or that material presented in both text and diagrams is important and learners should closely monitor their understanding of it. Thus, learners can perceive and follow these constraints without needing to internalize them.

If graphical representations are typically more cognitively effective than textual ones for the reasons reviewed above then we would expect graphical representations to also be more metacognitively effective and there is some limited evidence to support that statement (e.g. Ainsworth & Loizou, 2003). However, this does not mean that animations are likely to prove more effective in promoting appropriate metacognition. Because of the problem that animations create for working memory, it is reasonable to worry that learners will engage in less metacognition with animations than with other forms of representation.

One of the first researchers to explore the relationship between the form of representation and metacognition was Salomon (*e.g.* Salomon, 1984). He studies the amounts of invested mental effort (AIME) learners were prepared to expend upon their learning. Learners with good metacognition skills should be investing the appropriate amount of effort when learning. This should vary with how difficult they find the material to learn, with greater expenditure of effort when processing material that is complex, ambiguous or novel. However, this was not always the case with learners' AIME being affected by both individual differences and the medium of the material. For example, he found that children invested less mental effort in comprehending materials on television than they did in textual materials. Television was perceived as entertainment whereas text was seen as informing and educating. This is also likely to be the case for animation (see affective explanations above). If it is the case that television and animations require less cognitive effort than text, then this could be considered to be metacognitively appropriate. However, the research reviewed above suggests this is not the case and as a result learners will not appropriately monitor and evaluate their learning with animations as they will falsely perceive them as easy. A number of empirical studies have confirmed this prediction. For example, Schnotz and Rasch (2005) (described in the cognitive section) suggest that learners only engage in superficial processing of animations of the earth. Hübscher-Younger & Narayanan (2001) found a similar illusion of understanding problem with algorithm animations.

Lewalter (2003) (first introduced above in the Strategy section) in his study of astrophysical animations also explored metacognitive actions which he called control strategies, i.e., those behaviors which plan and regulate learning or which monitor the learner's actual level of comprehension. He found evidence of reducing planning with animations compared to static pictures which suggests that learners were not as metacognitively successful. However, he also found that animations increased the amounts of positive monitoring statements that learners made and as this correlated with learning outcomes, it is presumably an accurate metacognitive activity. Cromley, Azevedo & Olson (2005) explored the processes of self-regulated learning that learners engage in (e.g. planning, metacognitive monitoring and control) when learning from a multimedia environment on the circulatory system that included animation. Compared to other forms of representation, learners engaged in less self-regulation with the animation. However, if they summarized the information in the animation as they watched they did learn more (perhaps analogous to the self explanation strategy, see above)

There is also some evidence that training can help students use learning environments which include animations. Azevedo & Cromley (2004) trained students in the techniques of self-regulated learning including planning, metacognitive monitoring and control, and compared their performance to students who had not been trained when using multimedia environment. Trained students gain much greater conceptual understanding than untrained students. Similarly, students who had access to a human tutor who scaffolded their self-regulation also learnt more (Azevedo, Cromley and Seibert, 2004).

Rhetorical Explanations

The final level of explanation considered is how animations can influence learning when people are learning in social situations. Learning is acknowledged to be a participatory process in which people learn by constructing knowledge though interactions with others. Representations play a fundamental role in mediating social learning and there are a number of different roles that representations can serve. Suthers & Hundhausen (2003) suggest they can: a) lead to negotiation of meaning as when individuals act upon representations they may feel the need to obtain agreement from others; b) serve as the basis for non-verbal communication as collaborators can point to representations to make points; and c) serve as group memory, reminding the participants of previous ideas, which hopefully encourages elaboration on them. There is evidence that learners who construct representations together create representations that are different from those they create individually. Schwartz (1995) found that collaborating dyads produced representations that were more abstract than learners completing the same task individually. This may be evidence that pairs of learners had negotiated a form of representation that encompassed both their views.

Furthermore, full participation in a community of practice requires fluid use of representations. Tabachneck, Leonardo & Simon (1994) describe how an economics professor used multiple representations when explaining complex concepts, interspersing the construction of visual representations with spoken explanation. When prevented from constructing the visual representation or referring to it, he was simply unable to do so. In contrast, novice's use of representations was fragmentary and unintegrated. Kozma and Russell in a number of studies in both artificial and natural situations studied how experts and novice chemists use representations. Kozma & Russell (1997) gave experts and students various chemical tasks (such as sorting representations and transforming them from one to another) and found that novices used the surface features of the representations to try to build their understanding of the chemical phenomena they represented which limited their understanding and their ability to see the relations between representation. Experts by contrast saw deep principles embodied with representations and were easily able to move across different representations and use them together to express their understanding of chemical phenomena. This analysis was confirmed by observations in chemical laboratories. Kozma, Chin, Russell, & Marx, (2000) observed fluid and coordinated construction and interpretation of representations as experts went about their professional practice. In particular, representations were used to support social interaction. An expert chemist and his assistant used the spontaneous construction of a structural diagram, the interpretation of a NMR spectrum and diagrams in a reference book to progress through disagreement to a shared understanding of their activity. Consequently, Kozma and Russell (2005) reserve the highest level of representational competence for those who can use representations effectively within social and rhetorical contexts.

However, use of external representations does not guarantee the success of collaborative learning. For example, Fischer & Mandler (2005) found that providing learners with external representation tools did not help them share information more effectively. Similarly, Munneke, van Amelsvoort & Andriessen, (2003) also found that providing visual representations did not help collaborative argumentation based learning.

There is relatively little work exploring the role of animations in social learning situations. However, there is a small body of work that is looking at collaborative learning with either presented animations (e.g. Sangin et al, 2006, Schnotz et al, 1999) or constructed animations (e.g. Hübscher-Younger & Narayanan, 2003; Gelmini & O'Malley, 2005). Views about the likely effectiveness of animation tends to fall into either the optimistic camp, with animation seen as likely facilitate to collaboration as they enhance the possibilities for interaction and exploration, or pessimistic camp, with researchers worried about the cognitive and perceptual problems that animations present.

There is mixed evidence for the impact of collaborating around presented animations. Schnotz, Böckheler and Grzondziel (1999) explored an interactive animation of the earth rotating within specific time zones in both individual and collaborative conditions and contrasted it with static pictures. In the individual situation, questions about time differences (e.g." What is the time in Anchorage, if it is Thursday 9 o'clock p.m. in Tokyo?") were answered better by learners who had studied animations than those who had worked with static pictures. However, in the collaborative setting, learners with static pictures answered those questions better. In this case, therefore animations inhibited collaborative learning. However, studies performed in the CLEAP project (Collaborative Learning with Animated Pictures) have found that collaborative learning is enhanced by animations. The researchers picked domains (the transit of Venus and plate tectonics) that should be most likely to be facilitated by animations as they are intrinsically dynamic and where understanding benefits from the representation of microsteps (see Figure 4 for an example of their animation). Rebetez et al (submitted) found that animations in this case benefited learners in both individual and collaborative conditions. Furthermore, when learning was analyzed separately in terms of retention and inference questions, inference questions in particular benefited from collaborative use of animations. The authors suggest that collaboration helped learners overcome the underwhelming effect discussed above. It is difficult to know what leads to the contradiction between the studies as different learners, topics, animations and task instructions were employed, however, Rebetez et al point out the Schnotz et al's (1999) animation was interactive (perhaps closer to a simulation) and their animation was in more traditional form. In an attempt to understand more about how animations impact upon the process as well as the outcomes of collaborative learning, Sangin et al (2006) studied the impact of animation on learners' dialogues. They found no impact on the amount or quality of the discussion. Furthermore, in a version of the animation that also provided static snapshots of key frames to overcome the memory problems associated with a lack of permanence, the amount of relevant content-related dialogue was reduced.

Hübscher-Younger & Narayanan (2003) explored the benefits of constructing animation for understanding algorithms in ways that mixed individual and collaborative learning. Learners first constructed a representation of an algorithm, and then exhibited it to their peers who evaluated it upon a number of dimensions before finally participating in a collaborative discussion about the representations. Learners who created representations did tend to learn more than those who simply critiqued and observed. Learners had been free to create a wide variety of representations including text, graphics and animations. What was apparent was that the construction of animations, although popular with learners at the beginning of the study, was increasingly abandoned in favor of simpler text and graphics as time went on. This tendency was also supported in learners' judgments of others' representations with ultimately the highest ratings for a visualization going to a simple text-based (and humorous) representation.

Gelmini & O'Malley (2005) studied children using KidPad - a shared drawing tool that enables children to collaborate synchronously by drawing images, hyperlinking them, zooming in and out and creating animations. They examined the effectiveness of KidPad for supporting the process of telling a story in small groups of children. Twelve groups of three children (ages six -seven) used KidPad to create a story together and then tell it to an audience. The children in one condition worked with the basic tool and those in the experimental condition were able to use the hyperlinking, zooming and animating tool. The stories told in the experimental condition featured richer characterizations of the characters, the overall structure of the stories was more articulated and the experimental children made more effective communicative effort towards the audience. The researchers also found social differences suggesting that collaboratively creating animations and negotiating their meanings and relevance to the story elicited a stronger sense of collective responsibility towards the ultimate narrative production.

A final way that animations can be used within social learning situations is to replace one of the collaborators with an animated agent. The aim is to use lifelike autonomous characters which cohabit learning environments with students to create rich, face-to-face learning interactions. For example, Steve (described in Johnson et al, 2000) works with teams with to solve complex naval training tasks such as operating the engines aboard Navy ships. The team can consist of any combination of Steve agents and human students; each assigned a particular role in the team (e.g., propulsion operator). The agent can be configured with its own shirt, hair, eye, and skin color.

Animated agents can then help learners by demonstrating tasks, reacting to their responses (by nodding when they understand a communication) and helping learners navigate complex virtual worlds.

Conclusion

This chapter has so far presented evidence that there are (at least) six levels of explanations that are relevant to explaining learning with representations and particularly animations.

- The *expressive* characteristics of animations resulted from the need to represent activities in a specific sequence. This could be advantageous for learners when the dynamic activity represented does need to be understood as one fully determined sequence but problematic when this is not the case.
- An analysis of *cognitive, motor and perceptual* consequences of learning with animations showed that whilst they may make dynamic information explicit, which should reduce the amount of cognitive effort required to learn about dynamic systems, they also introduce significant problems for perceptual processing and memory because of their transient nature.
- *Affective* accounts of learning with animations suggest that although learners may often report increased satisfaction and motivation as a result of using animations, this is not invariably the case.
- The *strategies* that learners use when studying with animations are crucial for their ultimate understanding. Unfortunately, most of the research indicates that

novice learners do not easily develop and apply effective strategies for learning with animations.

- Similarly, there is little evidence to suggest that learners are helped to achieve effective *metacognition* by animations and some evidence to suggest instead that animations may produce an illusion of understanding that can interfere with successful learning.
- Finally, evidence concerning the *rhetorical* functions that animations can serve in supporting social learning is mixed with some researchers reporting increasing effective communication and some decreased.

In this final section, I will try to draw out some implications of this approach, discussing the benefits and costs of such increased complexity. The first thing that is apparent from this discussion is that these levels are not independent from one another. It can be precisely because of the properties of representation at one level, that their impact is felt at another. For example, Stenning (1998) argues that it is the expressive properties of animation, with their necessary determinism with respect to time, which causes such difficulties for memory. There is also a very strong relation between strategic and metacognitive explanations with many researchers referring almost exclusively to metacognitive strategies. The strategies that learners apply to learning with animations depend upon the availability of cognitive resources, their motivation to expend their effort on effective learning strategies and their metacognition concerning the appropriateness of particular strategies.

The levels interrelate such that changing the way information is represented to take account of factors at one level will almost certainly change its properties at another. For example, a number of researchers have considered whether adding learner control to animations to reduce the cognitive costs of processing animations will help learning (e.g. Boucheix & Guignard, 2005; Mayer & Chandler, 2001). However, doing so may well also have an impact upon affect - learners may like these animations better if they have control over them (e.g. Malone, 1981). The strategies learners need to apply will change and there is evidence that simply adding interactive features does not help learners apply effective strategies (Lowe, 2004). There are metacognitive consequences – learners now need to decide if they have understood the animation in order to decide how to use the interactive controls. It is also likely to change the way learners talk about animation. For example, they now need to discuss how to use the interactive features. This may also influence the process of using the animations (e.g. stopping the animation to talk to one another - see Sangin et al, 2006 for a similar effect from adding extra still frames to an animation).

This interrelation and interdependence is problematic if we are looking for straightforward and simple answers about learning with representations such as animation. If we add an animation to study material or change the features of an existing animation, how can we be certain that the explanation we propose for the effect is the right one (or ones)? Moreover, it is perfectly possible for design features to be advantageous at one explanatory level but disadvantageous at another. For example, what if changes to an animation add extra interactivity, which the research suggests should increase learners' motivation, but, as a result, learners are required to use more sophisticated strategies that they do not possess or have difficulty monitoring when to apply? This situation may be very common and this could help explain some of the very mixed results reported for effectiveness of animations. But it raises a whole host of other questions. Is it more important to design an animation in ways that are cognitively successful but affectively less so? Are some explanatory concepts more powerful than others (for certain learners, in specific contexts, learning particular tasks), and so designing animations with respect to those needs should be considered of paramount importance?

Acknowledging this complexity makes life more difficult. It suggests that some of the acknowledged truths of the field may need revaluation. Can we be certain that the effects studied with one level of explanation actually owe their results to that level? It suggests that simple answers will be hard to find. Designers and teachers asking researchers “Should I use an animation” may well be greeted with “it all depends” and so assume that research is not helpful to them.

However, it also opens up new possibilities as well. Researchers from many different traditions can become involved in asking questions about learning with animation. At the moment, a review of the literature reveals the vast majority of researchers interested in animation come from a cognitive background, and unsurprisingly therefore most of our knowledge about the effects of animation is also framed in cognitive terms. Whilst there is little doubt about the importance of cognitive accounts of learning with animations, more research is needed elsewhere as relatively little is known in comparison about expressive, perceptual, affective, strategic, metacognitive and rhetorical levels of explanation. This may mean that completely new types of study are needed to seek out this knowledge at these underexplored levels. For example, animations are rarely studied in real rather than artificial contexts (but see Kozma et al, 2000) It also suggests that new methodologies should be used to explore learning with animation. For example, only a very few studies make use of protocol data (e.g. Lewalter, 2003, Sangin et al, 2006) or compare expert and novice users of animations (e.g. Trafton, Marshall, Mintz,& Trickett, 2002) or make use of behavioral logs of interaction (e.g. Lowe, 2004) or use eye-tracking (Boucheix, Lowe, & Soirat, 2006). Furthermore, different methodologies may also reveal new explanations that we might need to take into account, for example, researchers in cognitive psychological traditions are increasingly adopting neuroscientific methods and models – a level not even addressed in this framework. Researchers working specifically within one level of explanation could be encouraged to routinely collect data at others (e.g. an experimental cognitive study could be followed by interview and questionnaire about motivation and affect, or studies of learners' preferences for certain animations could probe if this was due to cognitive factors).

This chapter has attempted to review and, as far as possible, integrate research on animation conducted at a number of different levels. As a result, it is acknowledged that this brings a complexity to the question of "how do animations influence learning" that many people may find unwarranted. However, for others it may suggest a more rewarding way to begin to answer the question.

Acknowledgements

Very many thanks to Mireille Bétrancourt, Ric Lowe, and Joel Russel for providing screens from their animations.

References

Ainsworth, S., & Loizou, A. T. (2003). The effects of self-explaining when learning with text or diagrams. *Cognitive Science, 27*(6), 937-937.

Ainsworth, S., & VanLabeke, N. (2004). Multiple forms of dynamic representation. *Learning and Instruction, 14*(3), 241-255.

Ayres, P., & Paas, F. (submitted). Learning from animations: A cognitive load approach. *Applied Cognitive Psychology.*

Azevedo, R., & Cromley, J. G. (2004). Does training on self-regulated learning facilitate students' learning with hypermedia? *Journal of Educational Psychology, 96*(3), 523-535.

Azevedo, R., Cromley, J. G., & Seibert, D. (2004). Does adaptive scaffolding facilitate students' ability to regulate their learning with hypermedia? *Contemporary Educational Psychology, 29*(3), 344-370.

Bartram, L., Ware, C., & Calvert, T. (2003). Moticons: detection, distraction and task. *International Journal of Human-Computer Studies, 58*(5), 515-545.

Baylor, A., Ryu, J., & Shen, E. (2003). *The effects of pedagogical agent voice and animation on learning, motivation and perceived persona.* Paper presented at the World Conference on Educational Multimedia, Hypermedia and Telecommunications 2003, Honolulu, Hawaii, USA.

Bétrancourt, M. (2005). The animation and interactivity principles. In R. E. Mayer (Ed.), *Handbook of multimedia learning*. Cambridge: Cambridge University Press.

Bétrancourt, M., & Tversky, B. (2000). Effect of computer animation on users' performance: a review. *Le Travail Humain, 63*(4), 311-330.

Boucheix, J. M., & Guignard, H. (2005). What animated illustrations conditions can improve technical document comprehension in young students? Format, signaling and control of the presentation. *European Journal of Psychology of Education, 20*(4), 369-388.

Boucheix, J.-M., Lowe, R., & Soirat, A. (2006). *On line processing of a complex technical animation: Eye tracking investigation during verbal description.* Paper presented at the EARLI Text and Graphics Comprehension Meeting, Nottingham.

Bruner, J. (1966). *Toward a Theory of Instruction.* Cambridge, MA.: Harvard University Press.

Chabris, C. F., & Kosslyn, S. M. (2005). Representational correspondence as a basic principle of diagram design, *Knowledge and Information Visualization: Searching for Synergies* (Vol. 3426, pp. 36-57).

Chan, T. S., & Ahern, T. (1999). Targeting motivation - adapting flow theory to instructional design. *Journal of Educational Computing Research,, 21*(2), 151-163.

Chi, M. T. H., Bassok, M., Lewis, M. W., Reimann, P., & Glaser, R. (1989). Self-Explanations - how students study and use examples in learning to solve problems. *Cognitive Science, 13*(2), 145-182.

Chinn, C. A., & Brewer, W. F. (1993). The Role of Anomalous Data in Knowledge Acquisition - a Theoretical Framework and Implications for Science Instruction. *Review of Educational Research, 63*(1), 1-49.

Church, R. B., & Goldin-Meadow, S. (1986). The Mismatch between Gesture and Speech as an Index of Transitional Knowledge. *Cognition, 23*(1), 43-71.

Cromley, J. G., Azevedo, R., & Olson, E. D. (2005). Self-regulation of learning with multiple representations in hypermedia. In C-K. Looi & G. McCalla & B. Bredeweg & J. Breuker (Eds.), *Artificial intelligence in education: Supporting learning through intelligent and socially informed technology* (pp. 184-191). Amsterdam, The Netherlands: IOS Press.

Csikszentmihalyi, M. (1990). *Flow: The Psychology of Optimal Experience*. New York: Harper and Row.

Fischer, F., & Mandl, H. (2005). Knowledge convergence in computer-supported collaborative learning: The role of external representation tools. *Journal of the Learning Sciences, 14*(3), 405-441.

Gelmini, G., & O'Malley, C. (2005, August 2005,). *Computer Support for Collaborative Storytelling'*. Paper presented at the 11th Biennial Conference of the European Association for Research on Learning and Instruction,, Nicosia, Cyprus.

Goldin-Meadow, S., & Wagner, S. M. (2005). How our hands help us learn. Trends in *Cognitive Sciences, 9*(5), 234-241.

Hegarty, M., Kriz, S., & Cate, C. (2003). The roles of mental animations and external animations in understanding mechanical systems. *Cognition and Instruction,, 21(4)*, 325-360.

Hubscher-Younger, T., & Narayanan, N. H. (2001). How undergraduate students' learning strategy and culture effects algorithm animation use and interpretation, *Ieee International Conference on Advanced Learning Technologies, Proceedings* (pp. 113-116).

Hubscher-Younger, T., & Narayanan, N. H. (2003). Authority and convergence in collaborative learning. *Computers & Education, 41*(4), 313-334.

Johansson, G. (1975). Visual motor perception. *Scientific American, 232*,(6), 76-89.

Johnson, W. L., Rickel, J., & Lester, J. C. (2000). Animated pedagogical agents: Face-to-face interaction in interactive learning environments. *International Jounral of Artificial Intelligence in Education, 11*, 47-78.

Kaiser, M., Proffitt, D., Whelan, S., & Hecht, H. (1992). Influence of animation on dynamical judgements. *Journal of Experimental Psychology: Human Perception and Performance., 18*, 669-690.

Kehoe, C., Stasko, J. T., & Taylor, A. (2001). Rethinking the evaluation of algorithm animations as learning aids:An observational study. *International Journal of Human-Computer Studies,, 54*, 265-284.

Kirsh, D., & Maglio, P. (1994). On Distinguishing Epistemic from Pragmatic Action. *Cognitive Science, 18*(4), 513-549.

Kozma, R., Chin, E., Russell, J., & Marx, N. (2000). The roles of representations and tools in the chemistry laboratory and their implications for chemistry learning. *Journal of the Learning Sciences, 9*(2), 105-143.

Kozma, R., & Russell, J. (2005). Modelling students becoming chemists: Developing representational competence. In J. K. Gilbert (Ed.), *Visualization in Science* *and Education* (pp. 121-146). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Kozma, R. B., & Russell, J. (1997). Multimedia and understanding: Expert and novice responses to different representations of chemical phenomena. *Journal of Research in Science Teaching, 34*(9), 949-968.

Larkin, J. H., & Simon, H. A. (1987). Why a diagram Is (sometimes) worth 10000 words. *Cognitive Science, 11*(1), 65-99.

Lewalter, D. (2003). Cognitive strategies for learning from static and dynamic visuals. *Learning and Instruction, 13*(2), 177-189.

Lowe, R. (2004). Interrogation of a dynamic visualization during learning. *Learning and Instruction*, *14*(3), 257-274.

Lowe, R. K. (1999). Extracting information from an animation during complex visual learning. *European Journal of Psychology of Education, 14*(2), 225-244.

Lowe, R. K. (2003). Animation and learning: selective processing of information in dynamic graphics. *Learning and Instruction, 13*(2), 157-176.

Schnotz, W., & Lowe, R.K. (in press). A unified view of learning from animated and static graphics. In R.K. Lowe & W. Schnotz (Eds.) Learning with animation: Research and design implications. New York: Cambridge University Press

Malone, T. W. (1981). Toward a theory of intrinsically motivating instruction. *Cognitive Science*, *5*(4), 333-369.

Malone, T. W., & Lepper, M. R. (1987). Making learning fun: A taxonomy of intrinsic motivations for learning. In R. E. Snow & M. J. Farr (Eds.), *Aptitute,* *Learning and Instruction III* (pp. 223-253). Hilsdale, NJ: Lawrence Erlbaum Associates.

Martin, T., & Schwartz, D. L. (2005). Physically distributed learning: Adapting and reinterpreting physical environments in the development of fraction concepts. *Cognitive Science, 29*(4), 587-625.

Mayer, R. E. (2001). *Multimedia Learning*. Cambridge: Cambridge University Press.

Mayer, R. E., & Anderson, R. B. (1991). Animations need narrations: An experimental test of a dual-coding hypothesis. *Journal of Educational Psychology, 83*(4), 484-490.

Mayer, R. E., & Chandler, P. (2001). When learning is just a click away: Does simple user interaction foster deeper understanding of multimedia messages? *Journal of Educational Psychology, 93*(2), 390-397.

Mayer, R. E., & Moreno, R. (2002). Animation as an aid to multimedia learning. *Educational Psychology Review, 14*(1), 87-99.

Munneke, E. L., Amelsvoort, M. A. A. v., & Andriessen, J. E. B. (2003). The role of diagrams in collaborative argumentation-based learning. *International Journal of Educational Research 39*, 113-131.

Pane, J. F., Corbett, A. T., & John, B. E. (1996). Assessing dynamics in computer-based instruction., *Proceedings of ACM CHI'96 Conference on Human Factors in Computing Systems.* Vancouver.

Piaget, J., & Inhelder, B. (1969). *The Psychology of the Child*. New York: Basic Books.

Price, S. J. (2002). *Diagram Representation: The Cognitive Basis for Understanding Animation in Education* (Technical Report CSRP 553): School of Computing and Cognitive Sciences, University of Sussex.

Rebetez, C., Sangin, M., Bétrancourt, M., & Dillenbourg, P. (in press). Learning from animation enabled by collaboration. *Instructional Science*.

Rieber, L. P. (1990). Using computer animated graphics in science instruction with children. *Journal of Educational Psychology, 82*(1), 135-140.

Rieber, L. P. (1991). Animation, incidental learning and continuing motivation. *Journal of Educational Psychology, 83*(3), 318-328.

Russell, J., Kozma, R., Zohdy, M., Susskind, T., Becker, D., & Russell, C. (2000). SMV:Chem (Simultaneous Multiple Representations in Chemistry). New York: John Wiley.

Salomon, G. (1984). *Interaction of media, cognition and learning*. Hillsdale, NJ: LEA.

Sangin, M., Molinari, G., Dillenbourg, P., Rebetez, C., & Bétrancourt, M. (2006). Collaborative learning with animated pictures: The role of verbalizations, *Proceedings of the Seventh International Conference of the Learning Sciences*. Bloomington, USA.

Scaife, M., & Rogers, Y. (1996). External cognition: How do graphical representations work? *International Journal of Human-Computer Studies, 45*(2), 185-213.

Scheiter, K., Gerjets, P., & Catrambone, R. (2006). Making the abstract concrete: Visualizing mathematical solution procedures. *Computers in Human Behavior, 22*(1), 9-25.

Schnotz, W., Böckheler, J., & Grzondziel, H. (1999). Individual and co-operative learning with interactive animated pictures. *European Journal of Psychology of Education, 14*(2), 245-265.

Schnotz, W., & Lowe, R. (2003). External and internal representations in multimedia learning - Introduction. *Learning and Instruction, 13*(2), 117-123.

Schnotz, W., & Lowe, R. K. (in press). A unified view of learning from animated and static graphics. In R. K. Lowe & W. Schnotz (Eds.), *Learning with animation: Research and design implications*. New York: Cambridge University Press.

Schnotz, W., & Rasch, T. (2005). Enabling, facilitating, and inhibiting effects of animations in multimedia learning: Why reduction of cognitive load can have negative results on learning. *Educational Technology Research and Development*, *53*(3), 47-58.

Schwartz, D. L. (1995). The emergence of abstract representations in dyad problem solving. *The Journal of the Learning Sciences, 4*(3), 321-354.

Schwartz, D. L., & Black, J. B. (1996). Shuttling between depictive models and abstract rules: Induction and fallback. *Cognitive Science, 20*(4), 457-497.

Stasko, J., Badre, A., & Lewis, C. (1993). Do algorithm animations assist learning?: an empirical study and analysis, *Proceedings of the INTERCHI '93 conference on Human factors in computing systems* (pp. 61-66). Amsterdam, The Netherlands: IOS press.

Suthers, D. D., & Hundhausen, C. D. (2003). An experimental study of the effects of representational guidance on collaborative learning processes. *Journal of the Learning Sciences, 12*(2), 183-218.

Sweller, J., van Merrienboer, J. J. G., & Paas, F. (1998). Cognitive architecture and instructional design. *Educational Psychology Review, 10*(3), 251-296.

Tabachneck, H. J. M., Koedinger, K. R., & Nathan, M. J. (1994). *Towards a theoretical account of strategy use and sense making in mathematical problem solving.* Paper presented at the 16th Annual Conference of the Cognitive Science Society, Georgia Institute of Technology, Atlanta, Georgia.

Tabachneck, H. J. M., Leonardo, A. M., & Simon, H. A. (1994). *How does an expert use a graph ? A model of visual & verbal inferencing in economics.* Paper presented at the 16th Annual Conference of the Cognitive Science Society, Georgia Institute of Technology, Atlanta, Georgia.

Trafton, J. G., Marshall, S., Mintz, F., & Trickett, S. B. (2002). Extracting explicit and implicit information from complex visualizations. In M. Hegarty & B. Meyer & H. Narayanan (Eds.), *Diagrammatic Representation and Inferenence* (pp. 206-220). Berlin Heidelberg: Springer-Verlag.

Tversky, B., Morrison, J. B., & Bétrancourt, M. (2002). Animation: can it facilitate? *International Journal of Human-Computer Studies, 57*(4), 247-262.

Ware, C. (2004). *Information visualization: Perception for design*. San Francisco: Morgan-Kaufmann.

Wright, P., Milroy, R., & Lickorish, A. (1999). Static and animated graphics in learning from interactive texts. *European Journal of Psychology of Education, 14*(2), 203-224.

Zacks, J. M., Tversky, B., &, G. (2001). Perceiving, remembering, and communicating structure in events. *Journal of Experimental Psychology-General, 130*(1), 29-58.

Zhang, J. J., Johnson, T., & Wang, H. (1998). Isomorphic Representations Lead to the Discovery of Different Forms of a Common Strategy with Different Degrees of Generality, *Proceedings of the 20th annual conference of the Cognitive*.

Zhang, J. J., & Norman, D. A. (1994). Representations in distributed cognitive tasks. *Cognitive Science, 18*(1), 87-122.