Chapter 2
The 'Ins' and 'Outs' of Learning: Internal Representations and External Visualizations

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Abstract Science classrooms teach complex topics by exposing students to information through a variety of methodologies, including lectures, discussions, readings, lab experiences, and representational experiences. The goal of these activities is to help students build internal representations for course content – information stored in memory that students can retrieve to generate inferences, solve problems, and make decisions. But what are these internal representations like, and what does the nature of these representations suggest for the design of learning methodologies such as external representations? This chapter is an introduction to current and contemporary work on mental representations. In particular, we emphasize theoretical and empirical views that have focused on links between perception and action, and what those links imply for learning. In this way, basic research on the nature of memory can provide pragmatic suggestions with respect to the design, implementation, and assessment of what are commonly called 'visualizations' (i.e., external visual representations of processes) as tools for science learning.

The 'Ins' and 'Outs' of Learning

What remains in student memory after a successful learning experience and how is that information used in future learning situations? Learning is usually defined as acquiring some knowledge and, presumably, being able to use that knowledge to solve problems (e.g., Kintsch, 1998). But this definition tells us little about what students actually represent 'in their heads,' and even less about what constitutes the fabric of that knowledge. Learning, in this way, reveals little as to whether stored memories are composed of images, or words and sounds, or some more abstract form that isn't easily described. The measures we use to assess learning are also of limited utility in describing internal representations of knowledge. While we can evaluate a student's understanding of course content using tests, term papers, or discussion questions, these assessments provide little insight into the *nature* of

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students' knowledge. Even our personal introspections about effective teaching and learning reveal relatively little about the way information is coded in memory.

Nevertheless, philosophers and scientists have discussed, debated, and, using cleverly designed experiments, developed hypotheses about the nature of memory for hundreds of years. Some of these hypotheses have suggested that memory is composed of mental models, conceptual schemas, and semantic networks (Johnson-Laird, 1980; Minsky, 1975; Newell & Simon, 1972). Each of these constructs is useful for suggesting how memory is organized and utilized to generate inferences, solve problems, and make decisions. But each of these constructs has its own inherent ambiguity, and thus the question of what constitutes the 'residue' of learning remains an open one.

We focus on these thorny issues as a means of contextualizing the challenges involved in discussing and investigating mental representations. Despite these challenges, researchers in fields such as cognitive science and the learning sciences have managed to provide important insights into what people retain after a successful learning experience. Beyond epistemological inquiries about the nature of memory, this work also has implications for thinking about the conditions that might facilitate learning. Consider that if we have some notion of how information is represented in memory, we can attempt to design learning experiences that align with and contribute to the development of such representations. An underlying assumption of this view is that external presentations should match, in some way, what we wish students to encode into memory. If information that is gathered from a learning experience is too abstracted from the situation(s) it is related to, it may be too difficult for novice students to recognize that the information is useful for reasoning and problem solving.

Science education is a domain in which teaching methodologies have often relied on matches between learning activities (i.e., external presentations) and the knowledge we wish students to acquire from their lessons (i.e., internal representations). Lab-based activities, active learning assignments, and task-driven coursework all help students learn about scientific topics through active participation rather than passive viewing or listening. External representations ('visualizations') have emerged as a methodology that, in many ways, relies on similar principles to facilitate learning. A visualization can be thought of as the mental outcome of a visual display that depicts an object or event. Science-based 'visualizations' in particular have become ubiquitous in classrooms; by this, we mean there are many 'visualizations' available, and in actual classroom use, for the principles, theories, and concepts that students might learn in traditional k-12, college, and adult education courses. Their popularity and implementation is a function of many factors, but generally, those factors have remained separate from evidence-based assurances of actual learning benefits (e.g., Rapp, 2005; Rapp & Uttal, 2006).

A realization of the need to assess the effectiveness of 'visualizations' in science classrooms has led to increased interest in the impact of their use. We believe, though, that it is possible to tackle the issue using a slightly different approach. Psychological investigations of learning and memory can provide useful suggestions as to when and how 'visualizations' might function as effective learning tools (see

Rapp, Taylor, & Crane, 2003, for similar discussion with respect to digital media). One way to pursue this issue is to consider, as described earlier, whether the mental activity necessitated by visualization-based tasks effectively engenders the construction of mental representations. To adopt this approach, researchers must, necessarily, possess at least a basic understanding of the nature of the mental representations that students may develop during learning experiences.

Thus, the current chapter has two goals. The primary goal is to introduce the topic of mental representations so as to address our initial question: What do students glean from external representations and how do they internalize and manipulate that information? A second, but equally important goal is to relate this work to educational situations, to derive practical implications that can help inform the development of effective visualization experiences, and potentially help students internalize those visualizations. Some of our own work has involved developing such implications for the Earth Sciences, and more generally, for instances involving procedural and skill-based learning; however, these implications, we believe, should be generalizable beyond particular science domains as well as across other content areas.

The chapter is organized as follows. We begin with a general description of mental representations and 'visualizations', to develop common ground for our discussion and to better codify the distinction between internal and external representations. We briefly review attempts to broadly qualify the contents of mental representations, and specifically attend to perspectives that emphasize their perceptual and abstract qualities. We next constrain these perspectives to consider modality-specific representations – those derived from visual- or verbal-only experiences. We also consider work investigating the multi-modal nature of mental representations. These reviews allow us to consider how theories of mental representations might be applied to foster knowledge acquisition. We conclude by deriving some general recommendations for the development and implementation of effective educational methodologies, and specifically for visualizations, in classroom settings, as a function of our review. The chapter, then, is intended as a basis for translating empirical research on mental representations into pragmatically oriented design implications for instructional visualizations.

Internal and External Representations

A representation is a likeness or simulation of some idea, concept, or object. We construct and comprehend representations throughout the day, taking for granted the degree to which the phrase 'what you see is what you get' often fails to ring true. For example, a photo of the Chicago skyline is a representation of that skyline; it is not the actual skyline reduced in size and transposed onto a two-dimensional surface, but only a copy of what the skyline looks like from a particular vantage point. Similarly, if you have ever been to Chicago and can envision what the skyline looks like, from whichever perspective you wish, you are relying on a mental representation of that skyline. The skyline is not physically in your head, but rather a 'mental copy' of the skyline accessed from memory. Some representations can be quite detailed and convey meaning in a very direct way, as exemplified by the intricate renderings of an architectural blueprint or the delicate brushstrokes of a painting. Other representations can be more abstract, and interpretations of such work must be derived in ways that rely less on surface characteristics. Consider the meanings (e.g., views and beliefs) associated with the flags of a nation, or the geometric shapes that, taken together, convey emotion in cubist artwork. Words themselves, whether spoken or written, are also a type of representation. The changes in air pressure that make up speech, and the ink blots and pixels that make up the words we see, are not meaningful things unto themselves but are instead imbued with meaning by cultural groups. These acoustic and visual stimuli are representations of ideas, concepts, and objects, including concrete items (e.g., the word 'chair') and more abstract notions (e.g., the word 'luxury').

These examples allow us to introduce a useful dichotomy for classifying representations – external vs. internal. An external representation is one that is available in the environment, like the aforementioned skyline, flag, or blueprint. These representations often stand for or correspond to additional concepts or notions, such as a flag both being an object itself and a symbol of some geographical region, group of people, or sociocultural perspective. A variety of external representations have been developed specifically to convey particular ideas, and in many situations, to specifically help individuals learn. Maps and graphs are examples *par excellence* of external representations for learning. They organize data into presentations that are more easily interpretable than their raw forms (e.g., the collected numbers that comprise a bar graph) by summarizing concepts in salient, systematic ways.

Internal representations are not available in the environment, but are instead held in the viewer or learner's mind. The traditional term in cognitive science for an internal representation is a mental representation, which designates it as part of our private thoughts, derived through mental activity. Our memory for a happy childhood experience, our recall of the number of windows in our house or apartment, and our expectations for the events that traditionally take place when we visit a restaurant are all examples of mental representations. Unlike external representations, we have no direct evidence for their existence. We cannot physically manipulate mental representations to assess their validity. Nevertheless, our phenomenological experience of mental representations remains quite vivid, and their importance for our moment-to-moment functioning is quite obvious.

With respect to visualizations, internal representations can be divided among at least three categories; visual memory, visual imagery, and knowledge representations. There are at least two forms of visual memory. One is a short lived record of the perceptual experience that persists in working memory for a few seconds (Sperling, 1960) and is essentially a veridical copy of what was seen. Another form of visual memory is memory of what something looks like as recalled from long term memory. The 'mental copy' of the Chicago skyline discussed above is an example of visual memory. This long term visual memory is in many ways similar to visual imagery. A visual image is an internally generated 'visual' experience viewed in what has been metaphorically referred to as the mind's eye. Visual images can be of something mundane such as an apple or something completely novel such as hitting a baseball into outer space. The labeling of these images as visual is appropriate given that, in addition to describing the subjective experience of imagery, visual images are created by partially engaging the brain regions involved in visual perception (Behrmann, 2005; Kosslyn, 1994). Visual images are constructed based on our knowledge of the object or event of interest.

Knowledge representations are in many ways more complex than visual memory and imagery (Barsalou & Hale, 1993; Markman, 1999). In addition to how something looks, knowledge representations for objects contain a variety of attributes and their relationships, and usually also include attributes of the situations in which they are used (e.g., time, location, events, goals; Barsalou & Hale, 1993). Consider a screwdriver for example. Knowledge of this object may include information about category membership (tools), non-visual features such as weight and function (fastening), situational information such as activities associated with use of the object (replacing a broken hinge), and emotions or beliefs linked to the object and its relevant activities. Events are represented in a similar way except that the focus of these representations is typically on situational information such as the agents typically involved in the event (the agent *officer* is typically involved in the event of *arresting*; Ferretti, McRae, & Hatherell, 2001; Wiemer-Hastings & Xu, 2005). It is the student's knowledge representation that we hope to influence in some way with 'visualizations'. For example, by making visually explicit a certain process, we may facilitate a student's ability to make new links between concepts in their knowledge representations, understand new uses for objects, and so on.

The dichotomy between external and internal representations is both theoretically and practically interesting because these two types of representations necessarily interact throughout our daily experiences in a variety of ways. Consider first how often we must convert our mental representations *into* external presentations. Communication, and specifically language, is the best example of this conversion process. When we sit down to write a scientific paper, compose an e-mail, or prepare a grocery list, we are retrieving our internal representations and attempting to reproduce them in some external form. Next, consider that we also continually attempt to develop mental representations *from* external presentations. Readers studying textbook explanations, perusing their e-mail inboxes, and carefully double-checking their shopping lists are transducing external stimuli into mental representations. These activities, the production of internal and external representations, and the comprehension of those internal and external representations, are far from trivial. Many core perceptual and motor processes are necessary for successful language production (e.g., writing) and language comprehension (e.g., reading). Additionally, individual differences across readers and writers, as a function of expertise, learning preferences, and motivation, among other factors, guide those processes (e.g., Chi, Glaser, & Farr, 1988; Dunn & Dunn, 1978; Dweck, 1986; Levelt, 1989). In fact, the degree to which mental and external representations successfully coalesce into mutually-agreed upon, meaningful constructions is quite remarkable (Clark, 1996). Quite clearly, our everyday activities are continually marked by interactions between what is inside and outside our heads.

'Visualizations' as External Representations

Given the above classifications, the 'visualizations' we discuss in this chapter should be thought of as one type of external representation. Science 'visualizations' in classrooms, for example, present data in novel ways to foster student comprehension. These 'visualizations' might include a simulation of a scientific law, a novel grouping of information that makes elements of a scientific explanation more salient, or an innovative method of organizing data that relies on readily familiar grouping principles or conceptual frameworks (e.g., using color as an indicator of temperature). Examples of scientific 'visualizations' include dynamic multimedia demonstrations of physics principles like the swing of a pendulum or gravitational force, animated explanations that use voiceovers to describe the causal antecedents and resulting consequences of seasonal change, and manipulable three-dimensional images of the human brain that can be overlaid with detail to indicate neural and vascular substrates. Each of these visualizations, to name key characteristics, (a) conveys information that would not be easily seen (or is actually impossible to see) with the naked eye, (b) uses symbolic cues like color, icons, and sound to help students identify which elements are key to comprehending the underlying scientific issues (e.g., Tversky, Zacks, Lee, & Heiser, 2000), and (c) likely acts as a simulation that students can review, and in some cases manipulate, to test hypotheses and potentially solve problem sets (e.g., Taylor, Renshaw, & Jensen, 1997). Not all 'visualizations' share these characteristics but we point them out to exemplify some of the elements that may be integral to any potential effectiveness for the methodology.

In line with their label, 'visualizations' are most often visual. However, 'visualizations' can also convey information by necessitating the use of other sensory modalities for their presentations. Sound and proprioceptive feedback, for example, are perceptual cues that could be used to convey critical concepts. Acoustic stimuli might be employed in a 'visualization' of national parks by including songbird calls to indicate the avian species found in local habitats. Raised relief globes rely on touch to deliver scalar information about the surface topography of the Earth. Thus 'visualizations' can include solid physical objects (e.g., desk globes) or immaterial light projections (e.g., holographic images) that utilize images, sounds, text, textures, and other perceptual modifications to convey complex information.

Whatever the format or modality, 'visualizations' depend upon the notion of scaffolding to facilitate learning. Scaffolding is the idea that existing knowledge can be used as a support to guide the understanding of new information. If students know that particular colors are associated with particular temperatures (e.g., red as hot and blue as cold), they can use that information to quickly understand the meaning of color cues in a depth-related water temperature diagram. Or if students want to revisit a particular video demonstration in an interactive 'visualization', the functional controls necessary to rewind or fast forward through the animation would be most effective if they mapped onto those used with traditional VCR and DVD players. 'Visualizations' often rely on interface or content-based metaphors to help students successfully navigate through and understand elements of a novel presentation. In many cases, these scaffolding cues can be quite powerful. Consider that arrows or underlining used to point out key components in a presentation are an excellent method of attracting and maintaining user attention (Heiser & Tversky, 2006). Obviously advertisers use scaffolding cues to promote their products in commercials and in-store displays. For science 'visualizations', though, designers and instructors use these cues to help students not just take notice, but to develop a deeper conceptual understanding of scientific principles. These cues can be used to help individuals understand the causal and associative relationships between elements of a 'visualization' presentation along with the concepts that underlie their activity, as necessary for comprehending complex explanations and processes in science.

Thinking About Mental Representations (Visualizations)

We now focus on the nature of mental representations, beginning with a broad examination of some of their features. One important thing to consider at the outset is that mental representations are not as complete as one might suspect. Evidence has convincingly demonstrated that, in general, human memory is hardly infallible (e.g., Loftus, Miller, & Burns, 1978; Loftus & Palmer, 1974). Not surprisingly, then, mental representations can be characterized as piecemeal and incomplete (e.g., Franco & Colinvaux, 2000; Norman, 1983; Rapp, 2005; Tversky, in press). What this means is that a student with some knowledge of a concept, like how lightning forms, does not simply retrieve a holistic mental replica of that knowledge from memory (e.g., the text they read or the lecture they attended). Instead, the student retrieves elements of the partial representation he or she has stored of that material, and those fragmented sets of memories must be reassembled in some form. That partial representation, only partially retrieved, is reconstructed during problem solving tasks (e.g., answering a test question about lightning or explaining what one knows about lightning to others).

Besides the limits of our mental representations, a host of other factors constrain our reconstructive processes, and hence our resulting problem solving and decision making activities. Factors such as the nature of a task, the immediate context, our arousal level, and general mood can influence the ways in which we build meaning from our partial knowledge structures. Thinking about mental representations in this way is much different than everyday notions of memory retrieval. Consider the degree to which instructors describe their students as 'remembering what they studied' for an exam or 'calling upon what they had read' to answer questions in class. It is important to mention that underspecified, piecemeal representations describe both novices' and experts' mental representations. The advantages experts enjoy in solving problems derive from qualitative and quantitative differences in what they know, as well as from their practice piecing together important representational elements in their domains of expertise (Chi, Feltovich, & Glaser, 1981; Ericsson, Krampe, & Tesch-Römer, 1993; Reimann, & Chi, 1989).

Understanding the piecemeal nature of mental representations, while useful for thinking about the limits of memory, tells us relatively little about the format of our knowledge. A simple way of conceptualizing this issue is to ask what a memory *looks* like (although the word *looks* should not limit us to thinking about mental representations as visual in nature). While we may feel as if we can build images in our heads, perhaps our mental representations are not visual, or at least not only visual. Surely we can easily imagine the smell of fresh cut grass or our favorite foods. Do these sensory-based phenomenological experiences provide insight into mental representations? Certainly some of our memories appear to resemble complex multimedia presentations. For instance, if you were asked to recall your last argument with someone, or the last time you rode a roller coaster at an amusement park, you might feel as if you could see the situation unfolding like a movie, hear the voices, smell the smells, and even feel your pulse begin to race. Our memories, like this one, can seem quite vivid.

While our introspections about memory suggest certain qualitative features that 'feel right,' we must be careful in ascribing any explanatory validity to them. Consider the following analogy: Computer printers do not contain words and sentences pre-stored in their systems. Rather, computer peripherals like printers rely on a language of binary digits that are translated into the patterns we interpret as printed language. The 'internal representations' of a printer (i.e., 0s and 1s), are quite unlike the external representations that are produced (i.e., words and images). Looking at a printout, we would never gain insight into the units (0s and 1s) comprising the printer's internal programming language. Similarly, we cannot rely on introspections (our verbal productions, or printouts, if you will) to gain insight into the basic components of memory. What, then, does research and theory actually suggest about the underlying nature of our mental representations?

Amodal vs. Perceptual Views of Mental Representations

To date, notions of what mental representations are like can be categorized into two general views. Each view has obtained evidence for their basic proposals, and current debates as to the validity of each view continues unabated (although, as will become clear from our discussion, one view has gained considerable support for its tenets from neural, behavioral, and philosophical investigations). We now discuss these two general perspectives, as they provide the foundation for thinking about how visualizations, and really a broad variety of educational experiences, may be represented in memory.

The *amodal* view of mental representations likens knowledge to a set of nodes in memory. These nodes hold information in some abstract form, composed of arbitrary symbols (which we will refer to as amodal symbols) that are not related in any systematic way to our real-world experiences of them (Anderson & Lebiere, 1998; Graesser & Clark, 1985; Newell & Simon, 1972; Pylyshyn, 1981; Van Dijk & Kintsch, 1983). An appropriate analogy might be to think about the way most words are related to their underlying concepts. Some words have some form of relationship with their associated concept, as in the case of onomatopoeia (i.e., 'pow,' or 'purr'), but the majority of English words do not. The word 'dog' does not have any inherent relationship to the concept of dog, but is set of symbols that, in English, has been selected to convey that concept. Similarly, amodal symbols have no inherent relationship to the concepts they represent. Amodal views, however, go further by suggesting that the underlying 'language' of mental representations need not bear similarity to any known communicative or perceptual form. Amodal theories assume that knowledge is represented as the association of these arbitrary symbols in node-based networks (Newell & Simon, 1972). Thought, then, involves the manipulation of these amodal symbols using rules, propositions, and processing procedures (cf. Harnad, 1990).

Why should we believe that amodal symbols are a viable description of how information is stored in memory? Some researchers have argued that amodal symbols provide a good explanation of abstract thought and reasoning; that is, reasoning that does not or could not involve actual experience (Pylyshyn, 1981). For example, Pylyshyn (2002) argues that people can easily imagine situations they could never experience. Consider, again, a situation wherein a baseball player hits a ball hard enough to launch it into outer space. While we have little difficulty considering such a situation, it is not based on any previously experienced event. Thus, we must somehow be able to store and construct this situation in our heads without any directly suitable perceptual analogs. In addition, many theories of text comprehension assume that the mental representations readers build during reading are, in general, composed of propositions and arbitrary symbols (e.g., Kintsch, 1998; Van Dijk & Kintsch, 1983). The theoretical underpinnings of this issue are beyond the scope of this chapter; however, the general notion is that readers comprehend sentences by decomposing them into their propositional idea units, and those units are amodal in nature.

Amodal symbols, as a description of how we represent knowledge, have much to recommend them. Because of their abstract nature, amodal symbols are amenable to computation, and as such, can potentially describe the ways in which we process information. If all knowledge is stored in an amodal format, it need not matter whether experiences are verbal, visual, or imagined, because in the end, all experiences would be coded in the same abstract format. Additionally, an amodal code could be combined and reconstituted in countless ways. In other words, the 'common code' underlying amodal representations affords an easy way for memory nodes, regardless of how or when they were encoded, to interact and communicate. All that would be required is that the human processing system understand the computations underlying the transformations from real experience to abstract code (e.g., from what we hear to what is stored in memory) and from abstract code to output (e.g., from what is stored in memory to what we say or do).

However, potential problems for amodal accounts quickly emerge when we consider the ontogeny of those symbols. How do our processing systems *learn* an amodal symbols code? Harnad (1990) used the well-known Chinese Room problem, introduced by Searle (1980), to describe one inherent challenge facing purely amodal explanations. Imagine you are in a foreign country and do not speak the language. As an aid, you carry a dictionary published in the language of that country, but unfortunately, you possess no translation of the contents of that dictionary into your own native language. When you hear a word in the foreign language, you attempt to look it up in your dictionary to understand it. Even if you could find the appropriate entry, the dictionary only defines that word using the same incomprehensible (to you) language. How could you hope to eventually figure out that foreign language? The amodal symbols view falls victim to an analogous problem: Without appropriate links to direct meaning, amodal symbols are inherently untranslatable, and hence uninterpretable, to the human processor. One way to solve the Chinese Room problem is to ground some aspect of the dictionary to elements of the real world that are readily understood. For example, the Chinese Room problem could be at least partially resolved by looking at a storefront displaying a sign in the foreign language, assessing what it sells, finding words that were contained in the sign within the dictionary, and assuming that the words and meanings in the relevant dictionary entries are somehow related to the store's wares. Unfortunately, amodal theories in general provide no mechanism for such grounding to occur in memory, as they are based purely on abstract symbols. Thus, a problem for this view of mental representations is that it does not provide an adequate and necessary account of how mental representations are formed.

In response to this problem, recent *perceptual* theories of knowledge representation have suggested that the brain systems involved in perception and action are central to cognition (Barsalou, 1999; Glenberg, 1997; Zwaan, 2004), and hence, knowledge acquisition. Thus, when we think of a concept, we conduct mental simulation (Kahneman & Tversky 1982) that reactivates the brain systems recruited during actual perception. These simulations are, then, mental reenactments of the perceptual experiences associated with some concept or experience. Perceptual theories of knowledge assume that representations are modality specific – visual experiences lead to representations that are imagistic; tactile experiences lead to representations that encode touch in some way. When representations from different perceptual sources are combined, which is nontrivial since different representations presumably have different perceptual codes, they potentially become multimodal. Despite the translation problem inherent to combining representations, perceptual views, unlike amodal views, can describe how representations develop. Our mental representations are embodied, in the sense that they are precisely linked to the real world concepts and sensory perceptions we have experienced (Barsalou, 1999; Glenberg, 1997; Hesslow, 2002; Lakoff & Johnson, 1980; Svensson & Ziemke, 2004; Zwaan, 2004).

Most importantly, a growing body of evidence has supported perceptual rather than amodal accounts of mental representation. This evidence is based on both neuropsychological research and behavioral studies. For example, Martin, Haxby, Lalonde, Wiggs, and Ungerleider (1995) found that the cortical regions proximal to those involved in color perception were activated when participants named the colors associated with objects. In addition, other areas of the cortex associated with the perception of motion were activated when participants were required to name actions associated with objects (see also Martin, Wiggs, Ungerleider, & Haxby, 1996). Similarly, Kellenbach, Brett, and Patterson (2001) found activation in cortical areas associated with audition when participants retrieved information about the sound properties associated with objects. More generally, motor regions of the brain appear to activate when participants are shown pictures of tools and objects that can be manipulated (Chao & Martin, 2000; Gerlach, Law, & Paulson, 2002; Grafton, Fadiga, Arbib, & Rizzolatti, 1997; Kellenbach, Brett, and Patterson, 2001; Martin & Chao, 2001). Across all of these studies, tasks that require individuals to simply think about particular objects or concepts seem to recruit the neural systems responsible for actual perception of those objects or concepts.

Behavioral studies have also provided support for the notion that perceptual simulations underlie cognition, and in particular, language comprehension (Stanfield & Zwaan, 2001; Zwaan, Stanfield, & Yaxley, 2002). For example, Zwaan, Madden, Yaxley, and Aveyard (2004) demonstrated that readers simulate the motion depicted by language. In their experiments, participants were presented with sentences that implied an object was moving either toward or away from the reader. For example, the sentence 'You threw the baseball to the catcher' implies motion moving away from the reader. After reading a sentence, participants were next presented with two sequential pictures of a single object (e.g., a baseball), in which the second picture was either slightly smaller or larger than the first. Consider that objects appear smaller as they move away from us, but larger as they approach. Participants took longer to determine whether the two sequential pictures were of the same object when the pictures depicted movement (as a function of a change in size) in a direction opposite to that suggested by the sentence. For our example sentence, in which the ball is described as moving away, participants were slower to identify the baseball pictures as depicting the same object when the baseballs appeared to grow in size, in contrast to when they appeared to diminish in size. These results, as well as other studies looking at matches and mismatches between text descriptions and their perceptual correlates, suggest that the mental representations responsible for our comprehension of language likely involve perceptual simulation of those descriptions ((Fincher-Kiefer, 2001; Glenberg & Kaschak, 2002; Horton & Rapp, 2003; Kaschak et al., 2005; Pecher, Zeelenberg, & Barsalou, 2003; Stanfield & Zwaan, 2001; Zwaan et al., 2002; Zwaan & Yaxley, 2004, 2005).

Modality-specific Representations

Based on empirical evidence, the prevailing view is that our mental representations are, to a large degree, embodied by our actual experiences with the external world and its external representations. In fact, this general philosophical view has been invoked, if not explicitly then implicitly, in classic theories of memory processes from the cognitive sciences. These earlier theories of memory processing under gird perceptual views of mental representation. But in contrast to perceptual views, which focus on the degree to which mental representations as a group tend to share certain inherent characteristics, these classic memory theories have focused more specifically on how mental representations develop as a function of the particular characteristics of a learning experience. Such theories were intended to describe how different types of memory processes, structures, and products are a function of different tasks, activities, and stimuli. This early work aligns nicely with our interest in what memory looks like as a function of learning methodologies. In this section, we describe how learning modalities influence what we store in memory, by discussing classic theories of memory processes.

Individuals can learn with different types of materials, including descriptive texts, detailed illustrations, engaging verbal descriptions, and immersive multimedia simulations. Not surprisingly though, not all learning experiences are created equal. By this we do not mean to suggest that specific methodologies are always more or less likely to succeed in some objective way (an issue, it turns out, that is particularly important to educational researchers, e.g., Woolfolk, 2004), but rather that these different experiences may result in different types of mental representations. This view derives from research on conditions that improve and impede memory, much of which has focused on the ways in which individuals learn lists of information (e.g., words or word pairs).

One view based on this work suggests that individuals can mentally represent information in at least two different formats: a visual code and a verbal code. Paivio's dual-coding theory (1971, 1986) suggests that when individuals encounter some word, they may elect to store that information in memory by imagining what it looks like (i.e., reading or hearing the word 'tiger' and imagining a tiger) or based mainly on the verbal stimulus (i.e., what the word 'tiger' sounds like or the letters in 'tiger' look like). A dual-coding view suggests that information can be represented in these formats, depending on a variety of factors. In fact, evidence suggests that the nature of the to-be-remembered stimuli often determines, at least in part, the particular format that information might be encoded in, as well as the likelihood that the information will be available for later retrieval (Paivio, 1983). What are some of the critical factors in this process?

Words can differ in a variety of ways, but one oft-studied variable is the degree to which words convey concrete or abstract concepts. According to Paivio, the concrete or abstract nature of concepts influences the ways in which they are encoded. Consider concrete words such as 'cat,' 'telephone,' or 'ball.' These words can be encoded into a visual format, relying on an image-based representation of the objects based on our prior experiences with them in the real world, and/or a verbal format, relying on the phonological, orthographic, and acoustic properties of the words. Abstract words such as 'freedom,' 'perplex,' and 'species,' in contrast, are not easily imagined and are instead encoded in a verbal format. For example, it is harder to establish an exemplary image for the notion of 'freedom' without invoking other concrete objects and thus abstract concepts like this one are less amenable to visual representation.

Evidence for differential memory effects as a function of a concept's concrete-abstract qualities comes from work on the picture-superiority effect (e.g., Nelson, Reed, & Walling, 1976; Paivio & Csapo, 1973). When participants are asked to study words for later recall, they are more likely to remember concrete than abstract words. This is, presumably, at least partially a function of the degree to which concrete words can be represented in visual and verbal formats, while abstract words are restricted to the verbal format. In sum, the degree to which a particular concept is visualizable can confer a memory advantage for later recall. This important evidence reinforces our earlier statement that different stimuli may afford different types of representations, with concomitant effects on memory retrieval as a function of those representations. Again, the dual-coding view aligns nicely with perceptual views of mental representation. Learning benefits accrue as a function of how easily we can develop a visual image of to-be-studied information, a notion that relies directly on the perceptual (in this case, visual) properties associated with some concept.

We note that there has been some criticism of dual coding theory. Some have argued that the picture-superiority effect is mainly due to tendencies to devote deeper processing to pictures than words. That is, it may not be the visual code itself that facilitates memory but rather individuals’ propensities for how they elect to process visual information. Indeed, the recall benefits enjoyed by concrete words as compared to abstract ones can be reduced with instructions asking individuals to process abstract words more deeply (Paivio, 1991). Regardless of why memory for pictures is better than words, the dual-coding findings suggest that the use of pictures over words whenever possible may be beneficial in enhancing memory.

Another influential view that has suggested individuals can code information based on modality-specific features is derived from Baddeley’s working memory model (Baddeley, 1986). Working memory exemplifies the storehouse in which we maintain attentional focus for things we are currently thinking about, whether those thoughts are driven by information from the environment or concepts we have retrieved from prior knowledge. Baddeley’s model of working memory goes further to describe both the underlying mental structures that comprise working memory, as well as the processes involved in its activity (e.g., Baddeley, 1992). According to the model, working memory is made up of three components, each devoted to the operation of the human memory and information processing system (Baddeley, & Lieberman, 1980; Baddeley & Logic, 1999).

Two working memory components, termed subsystems, are devoted to the processing and storage of information in a particular modality (and hence can be considered modality specific). The *phonological loop* is responsible for acoustic stimuli, generally. When we listen to a lecture, and mentally imagine hearing particular words or phrases from that lecture, we are maintaining the spoken stimuli in this storage subsystem. Maintaining information in this loop involves the mental rehearsal of sound stimuli. In contrast, the *visuospatial sketchpad* is responsible for visual and spatial stimuli, generally. We rely on this subsystem to think about the shapes and colors of objects, and their locations in space. This subsystem is the mental workspace necessary for considering the relationship between two spatial regions, such as when we attempt to figure out the fastest route from home to work. Taken together, the phonological loop and the visuospatial sketchpad are structures that allow us to keep information active during moment-by-moment comprehension.

The third working memory component, the central executive, is responsible for coordinating activities between the two subsystems. The central executive acts as a control processor, allocating precious mental resources to each subsystem. An account of how resources are allocated to each subsystem is necessary to explain both the successes and failures of the human processing system. In particular, failures provide important insight into the nature of working memory. In Baddeley's view, and as supported by considerable research evidence, each subsystem can be taxed depending on the qualitative and quantitative difficulty of a particular task (Baddeley & Hitch, 1974). When tasks continue to tap a particular subsystem, the potential for overload increases, and performance suffers. In contrast, when tasks allow individuals to rely on both subsystems, overload can be avoided. So, one way to decrease the likelihood of one type of learning failure is to provide information in multiple formats, allowing individuals to rely on both subsystems during processing.

The views offered by Paivio and Baddeley, while focusing on different elements of everyday experiences, share some critical characteristics for this review. Note, as with Paivio's view, that the subsystems of Baddeley's model are organized around the perceptual qualities of an experience; the acoustic and visual characteristics of stimuli are critical factors in determining whether and how information remains active in working memory (and eventually accrues enough attention and rehearsal to facilitate encoding into more permanent, long-term memory). Also like Paivio's dual-coding model, Baddeley's working memory model suggests that learning benefits can result when information is encoded in more than one format. These theories, while focusing on the modality-specific characteristics of memory, seem to suggest that the construction of a multi-modal representation can foster effective learning. We turn to this issue next.

Mental Representations in Multiple Modalities

Both Baddeley's and Paivio's work on the systems responsible for maintaining mental representations, and the underlying nature of those representations, have been incredibly influential in describing the basic cognitive processes and structures involved in human memory. But just as importantly, this work has had a considerable impact on our practical understanding of conditions that might foster effective learning. That is, these scientific models have had a great degree of applied value for education. Most obviously, both of the views have been taken to suggest that learning experiences should be presented to students in a form that fosters the development of multimodal representations in memory.

Recall that concrete concepts allow individuals to build both verbal and visual representations, and coding information in these two formats increases the likelihood of successful encoding into memory and successful retrieval at a later time point. Similarly, information that is coded in both of these formats can utilize the separate subsystems in working memory, reducing the likelihood of single subsystem overload. Thus, information should be presented in multiple modalities to ensure that individuals will remember the contents of a learning experience.

The complementary nature of a well-designed multi-modal presentation can help consolidate working memory resources, provide conceptual redundancy, and encourage students to make connections across presentation modalities, all in the service of facilitating memory for the material in presentations (Mayer, 2001). For example, students demonstrate better memory for simple procedural tasks (e.g., how to put together a small object) after viewing multimodal (e.g., text and picture) rather than single modality (e.g., text or picture) presentations (Brunyé, Taylor, Rapp, & Spiro, 2006). Multimodal representations presumably result from multimodal or multimedia experiences, and the benefits are quite compelling.

Researchers have built up a considerable literature on this issue by specifically examining both how and why multimedia presentations foster the development of multimodal representations in memory. These investigations have, to a large degree, had a particularly educational focus; they have considered the conditions under which students will most effectively learn complex topics. For instance, Mayer and colleagues (e.g., Mayer & Anderson, 1992; Mayer, Heiser, & Lonn, 2001; Mayer & Moreno, 2003; Mayer & Sims, 1994; Moreno & Mayer, 1999) have focused on the ways in which multimedia presentations that include pictures, sounds, and text can help or hinder students’ understanding of complex scientific explanations. In their work, participants are asked to view multimedia presentations that describe, as examples, how lightning forms, how brakes operate, and how air pumps function (Mayer, 2001; Mayer, 2003). By manipulating, again as examples, the degree to which information in one format (e.g., a text description) is complementary or redundant with another format (e.g., an illustration), or whether information in the two formats is presented simultaneously or sequentially, this work has assessed the qualities of multimedia presentations that prove most effective for learning.

Most importantly, the hypotheses generated in these studies have relied directly on theories of mental representations. Again, consider what dual-coding and working memory research suggests about multimedia presentations. Mayer (2001), in line with these views, argues that if individuals experience both visual and verbal presentations, they are more likely to remember that information later, in contrast to single-format presentations. This does not mean that multimedia presentations are a panacea; certainly a poorly designed multimedia presentation is going to have little positive impact on a student’s acquisition of knowledge. But the nature of memory is such that, with appropriate design, careful organization of material, and a consideration of the content that would be best presented in a visual or verbal format, we might expect educational methodologies to potentially benefit from multimedia experiences.

The issues inherent to the viability of multimedia presentations as effective learning tools, and the findings derived from the above cited studies, are certainly appropriate for thinking about the conditions that foster learning, and what those conditions suggest for effective educational design and implementation. We now turn to a brief review of current research that examines matches between the perceptual nature of representations, and the activities required to learn various concepts. We follow this discussion with some brief recommendations for the use of educational methodologies, including visualizations, as informed by work on mental representations and memory.

Implications for Learning Experiences

Earlier in this chapter we discussed the nature of mental representations by considering both amodal and perceptual views. Classic theories of memory align with current perceptual views, given their mutual reliance on sensory systems during memory encoding and retrieval. And recent work suggests that perceptual views, as compared to amodal views, provide a better account of the extant biological and behavioral data with respect to performance on memory, decision making, and comprehension tasks. The accumulated findings suggest that participants draw upon perceptual representations to understand situations, and that the mental representations we build from an experience rely on the perceptual features of those situations. One of the most exciting elements of this work is that a framework focused on the importance of the perceptual qualities of experiences obviously suggests the need for an emphasis on such features during learning situations. Simply put, providing learners with perceptually salient experiences that align with sensory-based modalities should increase the likelihood that, all other things being equal (e.g., motivation and interest, arousal level), students will retain what they study.

Of course, the implications of these ideas are hardly new, particularly in science classrooms. Well-worn teaching methodologies including activity-based learning, problem-based assessment, role-playing assignments, and hands-on laboratory activities have historically played an important role in science learning. Each of these methodologies relies on the notion that students will more effectively learn when they actively engage with course material in a direct way. However, these methodologies should also work, as suggested in this review, as a function of aligning with perceptual experiences. Chemistry labs, botany field trips, and in-class physics experiments embody the underlying concepts being taught in their respective classes. For each of these cases, students can build representations as a function of their direct, perceptual experiences with the course content. So a relatively novel expectation for these activities is that building and retrieving memories that are directly linked to our actual perceptual experiences can lead to performance benefits.

Consider some of the existing empirical evidence with respect to this view. When learning how to use a compass, novice students were more successful if presented with instructions to use the compass along with a video depicting a hand operating the compass, as compared to when students simply listened to and read a text on the topic (Glenberg & Robertson, 1999). That is, participants could utilize the perceptual information provided by the video to build an understanding of the object rather than working only with written instructions. The benefits of actually working with material are not limited to the use of specific tools. Second graders' comprehension of narrative events also appears to benefit from physically manipulating objects (Glenberg, Gutierrez, Levin, Japuntich, & Kaschak, 2004). Children demonstrate better memory for narratives and a better understanding of the spatial relationships described in them after acting out story scenarios using toys, or even just imagining using the toys to act out the scenarios, than if they simply read and re-read the stories. Presumably the perceptual information afforded through physical action with the toys, and through mental simulation with those toys, helped the children form conceptually grounded mental models of the events. As another example, even abstract concepts may benefit from scaffolding to well known perceptual activities. Valenzeno, Alibali, and Klatzky (2003) showed that teachers' gestures facilitated children's learning of concepts (e.g., symmetry) when physical movements were used to point out structural differences between objects that exemplified those concepts (also see Alibali, 2005).

To show the benefits of perceptually-relevant activities, we now focus on one particular study from our own labs. This specific line of research focuses on the utility of 'visualizations' for fostering comprehension of topics and procedures in the Earth Sciences. In one of our projects, we have investigated whether enhancing the perceptual features of 'visualizations' can help students develop comprehension-based skills that traditionally require significant study time to acquire. Consider that in most Earth Science classrooms, instructors must spend a significant portion of class time teaching students how to read graphs and maps. These training periods are both critical and necessary, as they set the foundation for understanding the more content-driven topics to be covered as the semester unfolds. Because training on these topics, for novices, is often necessarily extensive, and because failure to acquire these skills is so detrimental to performance in later sections of courses, it is important to determine how to effectively and efficiently help students acquire these skills. Topographic maps are an excellent case example, as they are requisite for studying advanced topics in the Earth Sciences, and because they often present clear difficulty for novices to use. Thus, we examined the degree to which novel visualizations of topographic maps might help students work more effectively with the maps (Rapp, Culpepper, Kirkby, & Morin, in press).

In our experiments, novice Earth Science students studied topographic maps that were presented as traditional flat maps, maps with shading to provide some indication of height, maps printed in 3-D (and viewed as such using polarized spectacles) that more directly embodied the notion of height differences along topographic lines, or maps that contained both 3-D and shading cues. These latter three conditions are relatively novel 'visualizations' for topographic map training coursework. After studying their maps, participants were asked to answer perspective-based questions about the map content, with their studied map visible during the task. These questions asked students to determine whether a person standing at a particular location would be able to see objects at other locations. These types of tasks tap into some of the skills, and exemplify some of the activities, indicative of successful map use (e.g., Eley, 1991; Pick et al., 1995). Results showed that the 3-D map led to the best performance. In fact, the combination of shading and 3-D did not lead to additional benefits beyond those obtained for the 3-D maps alone. Because the 3-D maps contained salient, perceptual cues as to height, depth, and the topography of the map terrain, they presumably helped students more directly envision the relationships between particular map regions than traditional topographic maps or maps that included shading cues. Current studies are investigating the limits of these visualization benefits by assessing topographic map comprehension as a function of other performance measures (e.g., hypothesis testing, predictive inferences), as well as individual differences between map users (e.g., prior knowledge, spatial ability, gender).

An important issue that studies like these will need to assess is whether any learning benefits also result in transfer benefits; that is, whether the skills or knowledge acquired through these perceptually-driven interventions enhance performance on other similar and relatively dissimilar tasks. While some studies have suggested that perceptual experiences may be less effective at fostering transfer than more abstract ones (Sloutsky, Kaminski, & Heckler, 2005), there are also projects that have demonstrated effective transfer across perceptually similar domains of moderate conceptual similarity (Taylor, Renshaw, & Choi, 2004). The relationships between abstract or perceptual symbols to the particular learning domain, the method by which those symbols are directly or indirectly integrated into the learning activity, and the importance of the information conveyed by those symbols to the knowledge or skill being acquired are but a few factors to consider in terms of both acquisition and transfer (e.g., Goldstone & Sakamoto, 2003). Future work should examine the retention and likelihood of knowledge transfer following tasks that embody the perceptual remnants of mental representations.

Implications for Educational Methodologies

Given our introductory presentation on internal and external representations, it should be apparent that educational methodologies, and in particular 'visualizations', might benefit from a consideration of the nature of memory. One way to formalize this is to suggest that the internal representations we wish individuals to acquire should be directly guided by the external presentations we offer our students. For example, 'visualizations' that seek to describe a particular domain should include presentations and activities that engender, and indeed foster, the performance criteria expected from the task. If we wish our students to understand how to read topographic maps, and we understand some of the difficulties those students have with such activities, we can (a) design activities that directly address those difficulties and (b) require performance that aligns with what we desire students to accomplish with those maps. If the mental representations that students build are a direct function of their learning experiences, we should then create learning environments that exemplify what we hope students will be able to do. Some of these activities might rely on perceptual features, while others might focus more on motor activities or deductive reasoning.

In addition, one of the major benefits of 'visualizations' is that they can present information in novel ways. These novel presentations often rely directly on substantially innovative organizations of perceptual features (e.g., 3-dimensional simulations of earthquakes within the Earth's surface; color-coded clusters of geographical regions as a function of underlying mineral compositions; schematic, linear animations of developing weather systems), and thus they might reasonably take advantage of the nature of memory mechanisms and subsystems. As research on memory has suggested, care must be taken to avoid overloading any particular subsystem. In that sense, both 'visualizations' and the classroom or homework activities linked to those visualizations should allow students to allocate resources to multiple memory subsystems. This might involve presentations that carefully utilize both text and images (see Mayer, 2001, for discussion of effective design), to help students to build both visual and verbal representations.

Third, and perhaps most importantly, what we learn from any task, including one that involves 'visualizations', is clearly not restricted to the particular learning methodology itself. Rather, what we learn from a 'visualization' is a function of our prior knowledge, the task, our individual goals (which may or may not be derived directly from the task), the interface, the content of the 'visualizations', the design of the 'visualization', and so forth. Indeed our mental representations are built not just from what we see and hear but from what we already have stored in memory. Careful thought must be put into the design of a complete visualization experience, and not just the visual portion of that experience (Rapp, 2005; Rapp & Uttal, 2006). To ensure students will learn from what they are doing, a preliminary task analysis designed to assess precisely what the instructor wants the student to know, and why (as well as how) the 'visualization' might be a useful tool for doing this, is most beneficial. Careful preparation can provide useful guidance for thinking about and implementing effective educational design.

If 'visualizations' are designed in relation to how we actually process that information in the real world, we can engender internal representations that can be used in the future to solve real world problems. For example, the earlier mentioned research by Glenberg et al. (2004) demonstrated that teaching students an internal visualization procedure (imagery) can foster success for later comprehension experiences. This shows that internal visualizations may be quite useful for dealing with novel situations. By designing 'visualizations' that better match how humans represent the world, we may be able to facilitate a student's ability to mentally manipulate that information (e.g., via imagery). This, then, may enhance a student's ability to recognize when the concept learned during the visualization process is relevant to other situations.

These implications, derived from our general understanding of mental representations, may not necessarily be surprising. But time and again 'visualizations' are designed predominantly as a function of technological availability or designer interest in a topic, rather than as a function of technological validity or designer-informed goals for a particular learning experience. By taking into account what we know about the conditions that foster learning, the mechanisms that underlie such learning, and the degree to which we can align particular methodologies with those research literatures, we can better address instructional challenges. 'Visualizations' on their own are not a panacea, but we contend that by coupling what we know about 'visualization' design with research on how students learn, we can improve the likelihood of students acquiring core competencies in their science coursework.

Conclusion

In this chapter we have described the underlying nature of memory. We have focused specifically on what remains after learning by considering some perspectives from cognitive science on the perceptual attributes of knowledge. Internal representations, those memories we hope to engender in our students, are directly influenced by the external stimuli they experience. 'Visualizations', as an educational methodology, are one type of experience that might be useful for teaching complex scientific concepts. By designing 'visualizations' in ways that align with the nature of memory, it may be possible to more effectively help students understand those challenging concepts. In addition to finding better ways for students to learn complex concepts, 'visualizations' may also aid students in dealing with unfamiliar, but potentially related, problem solving situations.

Research evidence is really only beginning to show the utility of such alignments. We hope that researchers will continue to make connections with basic research on learning pedagogy in their examinations of the effectiveness of science 'visualizations'. Such connections can be useful for developing implications that improve the effectiveness of visualizations as tools in science classrooms, as well as explaining the nature, and mechanisms, of any potential learning benefits (Rapp, 2006).

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