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Design factors for educationally effective animations and simulations

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Abstract This paper reviews research on learning from dynamic visual representations and offers principles for the design of animations and simulations that assure their educational effectiveness. In addition to established principles, new and revised design principle are presented that have been derived from recent research. Our review focuses on the visual design and interaction design of these visualizations and presents existing research as well as questions for future inquiry.

Keywords Simulation · Animation · Visualization · Design · Science · Learning · Cognition

How do animations and simulations have to be designed in order to be educationally effective? This paper will review research on learning from dynamic visualizations and present findings related to visual design and interaction design of animations and simulations. In the past we were limited to images that, once drawn, could not be altered; today we have tools allowing us to view animations, visualizations that play at a constant rate and rigid sequence that cannot be altered by the viewer, and even to manipulate simulations, visualizations that allow viewers to manipulate the rate of the animation, as well as view and review different parts of the display in any sequence (Hegarty 2004) or manipulate parameters of the model underlying the

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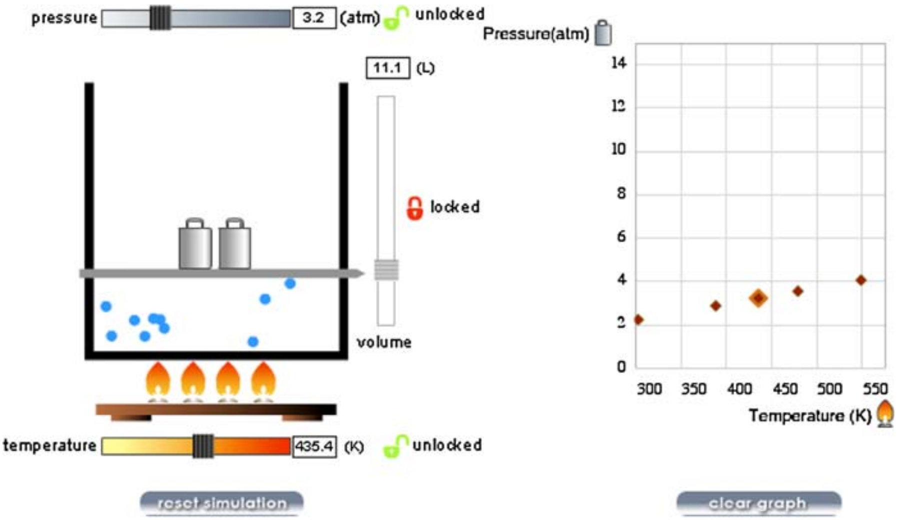
animation (Lee et al. 2006). Because these dynamic visual environments are gaining increasing importance for the representation of complex ideas and communication of our thoughts in higher education as well as in professional settings, we are interested in empirically validated design principles that assure their educational effectiveness.

Imagine, for example, a student taking a freshmen science class that covers the ideal gas law, which models the relationship among pressure, volume, and temperature of an ideal gas (i.e., a gas where all collisions between atoms or molecules are perfectly elastic and in which there are no attractive forces between molecules). The student uses a simulation of the ideal gas that visually represents the gas as molecules within a container. The simulation has sliders to adjust temperature, pressure, and volume, and icons representing temperature (as flames below the container) and pressure (as weights on top of the container), see Fig. 1.

After viewing a video clip showing overheated aerosol cans exploding, the student is interested in learning about the relation of temperature and pressure for a given volume. The student selects a volume and clicks the lock icon to indicate that this gas property should remain constant. As the student adjusts the slider in order to increase the temperature, the simulation shows how the pressure of the gas will change for the given volume. The 'measures' taken by the student are plotted in a chart that is presented to the right of the simulation. After concluding these observations, the student may chose to further investigate how temperature and volume relate for a given pressure, or how volume and pressure relate for a given temperature.

Although such visualizations are thought to have great potential to enhance learning, they often require learners to invest substantial mental effort to process them, and their educational effectiveness depends on a multitude of design



pressure 3.2 (atm) unlocked

11.1 (L) locked volume

temperature 435.4 (K) unlocked

Fig. 1 Simulation of the Ideal Gas Laws, with icons considerations that are involved in the development of effective visual materials for learning. In the simulation described above, designers had to consider the educational objectives, content, learner characteristics, educational settings, and plans for curricular integration in order to determine if information should be represented as static visualization (image), dynamic visualization (animation), or interactive dynamic visualization (simulation). The designer then had to make decisions on the information design, i.e., how to represent content and controls in the visual interface and the interaction design, i.e., how to implement tools and features enabling learning strategies, what kind of controls and navigation tools to make available to the learner, and what kind of scaffolds to provide to guide the learning process. Such design decisions fundamentally impact the ability of the visualizations to facilitate learning: There is mounting evidence that the educational efficacy of visualizations depends on how well its design reflects our understanding of human cognitive architecture (Mayer 2005a). In particular, the effectiveness of these materials depends on whether learners have sufficient cognitive resources to perceive and process the essential information in dynamic visualizations (Mayer 2005a; Sweller 1999).

In studies on the effectiveness of animations and simulations, researchers initially asked how these dynamic visualizations compared to learning from other visual representations, such as static images. Although such media comparison research has come under strong criticism (Clark 1983, 1994), a recent meta-analysis of 26 studies comparing dynamic and static visualizations conducted by Höffler and Leutner (2007) revealed a medium-sized overall advantage of dynamic over static visualizations. The analysis further revealed that dynamic visualizations are more effective than static visualizations only when they are of a representational rather than decorative nature. The analysis also showed a larger benefit of dynamic over static visualizations when the target knowledge was procedural motor knowledge rather than procedural or declarative knowledge.

In a change of focus of the inquiry from media comparisons to the design of effective visualizations, media design research has begun to ask what particular design features are effective in reducing unnecessary processing and increasing knowledge construction in dynamic visualizations. This area of research goes beyond the question of whether dynamic visuals are better learning tools than static visuals or no visuals, and begins to isolate design factors and evaluate their impact on learning. For example, Tversky et al. (2002) argued that dynamic visuals should be used to convey information that static pictures cannot, such as fine-grained actions changing over time. Tversky et al. also suggest using schematic rather than realistic visuals, to allow users to perceive subtle changes in relationships and fully grasp the sequence of events portrayed without superfluous visual information. However, many of these possible benefits of animations have not yet been sufficiently verified empirically.

In this paper we will therefore discuss how the design of dynamic visual representations affects learners' comprehension of animations and simulations. We will first briefly describe the processes involved in perceiving and processing visual information. We will then discuss design principles for two different aspects of the design of visual learning materials, visual design and interaction design, and present existing research as well as questions for future inquiry. We will conclude the paper by outlining future research that is needed for a better understanding of visual learning and the design of dynamic visual learning materials.

Visual perception and cognitive processing of visual information

Vision is a process in which our eyes constantly sample the information available in the ambient optical array (Gibson 1961). The resulting retinal image registers the invariants in this sampling, i.e., the attributes that do not change as the eye shifts its point of view. The retina transforms and reduces the optical information into electric impulses that convey this information to the brain. Two routes are involved in this low-level sensory processing. In one, sensory signals from the eye travel through the thalamus to the primary visual cortex of the occipital lobe, and then to the amygdala. This route leads to cognitive processing of the visual stimulus. A second route lets signals travel to the thalamus and then directly to the amygdala, allowing for pre-cognitive emotional and behavioral responses (Helmuth 2003; LeDoux 2003).

Because only a small amount of the visual information available to the retina can be processed, objects "compete" at a neuronal level for representation and processing (Desimone and Duncan 1995). Visual attention represents the outcome of this competition and determines which objects from the visual array are perceived and enter into awareness. Attention and perception are regulated by both automatic, "bottom-up" processes and voluntary, "top-down" processes. Bottom-up processes are based on perceptual properties of objects, such as contrast and visual uniqueness. For example, objects with high contrast are more visually salient and tend to be processed with enhanced signal strength (Serences and Yantis 2006). Top-down processes are intentional and based on the perceiver's knowledge, goals and expectations. For example, the specific neural pathways that become activated by observation of motion are determined in part by whether or not the perceiver has a specific goal (Grèzes et al. 1998). Together, these bottom-up and top-down processes create a coherent image of the visual environment.

The initial neural processing of visual stimuli takes place in the primary visual cortex, which specializes in processing information about static and moving objects and pattern recognition, analyzing objects' spatial frequency, direction, speed, orientation, and motion. The spatial component of the visual information is processed at later stages. After this initial processing, the sensory information is further processed in several areas that collectively are referred to as the secondary visual cortex, which specializes in the perception of motion, color, and form. Some of the visual information is selected for processing and sent to two different systems. The *ventral system* consists of areas of cortex located in the inferior temporal lobe and processes information related to object properties, such as the form and color of the signal. This is often referred to as the "what" pathway. The *dorsal system,* consisting of areas in the parietal lobe, processes information related to spatial properties, such as shape, size, and movement, and is also referred to as the "where" pathway (Kosslyn and Koenig 1992; Ungerleider and Mishkin 1982).

Although this dichotomy of the dorsal and ventral pathways might be an oversimplification, working memory research has indeed found that visual (visual-object) and spatial (visual-spatial) working memory comprise dissociable parts of working memory (Logie and Della Sala 2005; Oliveri et al. 2001). Visual stimuli that contain language are sent to areas that specialize in language processing (Wernicke's area and Broca's area), but are also processed in areas of the visual cortex responsible for object recognition (Mesulam 1998).

Even in the very early stages of vision, then, we do not hold 'true' images of the world around us in memory, but rather interpretations of the stimuli; visual mental representations of the world that are constructed based on prior knowledge, cultural conventions, and stimuli perceived through our other senses (Arnheim 1969; Barry 1997). In our example of the gas law simulation, a learner's interpretation of flames as representing heat and weights as representing pressure relies on cultural conventions of the use of these images.

The cognitive processes involved in comprehending a visual image can be described on various levels. At a minimum, they include (a) identifying the important features of a visual display, which is referred to as surface-level processing or external identification, (b) relating the visual features to their meaning, i.e., semantic processing, and (c) constructing the communicated message, i.e., pragmatic processing (Bertin 1983; also see Kosslyn 1989; Schnotz 2002; Shah and Hoeffner 2002). The specifics involved in visual processing on the cognitive level are described by several theories that have emerged over the past four decades. These cognitive theories are based on models of working memory that assume that visual information is processed in a visual working memory, while verbal information is decoded and processed in a verbal working memory. Space only permits us to briefly mention some of these theories.

Dual Coding Theory is a process theory that describes how related information that is concurrently processed in both systems (the verbal system for modality-specific verbal information, and the non-verbal system for modality-specific images) can enhance recall, compared to information processed in one system only (Clark and Paivio 1991; Mayer 1989; Mayer and Gallini 1990; Mayer and Moreno 1998; Paivio and Csapo 1973; Paivio 1971, 1991; Plass et al. 1998, 2003; Rieber 1990, 1991).

Cognitive Load Theory is a capacity theory that describes how the processing of the information and construction of knowledge is executed under the constraints of limited working memory resources (Sweller 1999) and describes three types of load. *Intrinsic* load is related to the inherent complexity of the information, *extraneous* load is related to the unnecessary processing of nonessential or even unrelated information, and *germane* load describes the mental effort invested by the learner to comprehend the material (Sweller 1999). Cognitive load research suggested several methods for optimizing visual displays and simulations. Such methods are especially important under conditions that impose high cognitive load, such as when the content of the material is of high complexity (high intrinsic load), when information is presented in a dynamic, time-based format, or when the control of a simulation requires a high amount of mental effort by the learner (Mayer 2005a).

The *Cognitive Theory of Multimedia Learning* is a process theory describes cognitive processes involved in learning from multimedia materials, suggesting that learners first select relevant visual and verbal information from the stimulus, organize that information into coherent verbal and visual mental representation, and then integrate these mental representations with one another and with prior knowledge (Mayer 2001). The theory also advances a series of principles that describe how the temporal and spatial arrangement of visual and verbal information, the modality used to represent the information, and the level of coherence or redundancy in the information affect learning (Mayer 2001, 2005a).

The *Integrated Model of Text and Picture Comprehension* (Schnotz and Bannert 2003), a process theory, also rests on the assumption that cognitive processing relies on multiple memory systems with limited capacity, as well as distinct channels for processing and storage of information from different modalities. Schnotz's theory distinguishes the processing of descriptive, textual input of symbolic information, and depictive, visual input of iconic information (Schnotz 2005). The processing results in the construction of mental models, i.e., depictive (iconic) internal representations that structurally correspond to the information they describe (Kosslyn 1994), and of propositional internal representations, i.e., descriptive representations that use symbols to describe the information (Schnotz 2005). When processing symbolic representations, learners use the presented text as well as their prior knowledge in order to construct a propositional model of the text as well as a mental model with related visualizations of the information. Likewise, when processing iconic representations, learners also construct both forms of internal representations (Graesser et al. 1997; Schnotz 2005). Based on the terminology from this theory, we will use the terms *depictive,* or *visualization,* for visual images, icons, and other non-textual displays, and the terms *descriptive*, or *textual*, for written or spoken text.

Early research on the cognitive processes involved in learning with visual information has produced empirical studies on the efficacy of visual representations for learning scientific concepts (Arnheim 1969; Levie et al. 1987; Winn 1994) and has investigated the comprehension of graphics and pictures (Schnotz and Kulhavy 1994; Willows and Houghton 1987) and how learning scientific information from diagrams, maps, and charts can be more effective than learning from text (Guthrie et al. 1993; Hegarty and Just 1993; Kosslyn 1989; Mandl and Levin 1989; Shah and Carpenter 1995; Winn et al. 1991). Much of the research in this area has also focused on specific materials, such as charts, graphs, and diagrams (Bertin 1983; Shah and Hoeffner 2002; Winn et al. 1991).

The focus of the more recent research on multimedia learning has been on identifying effective ways of designing educational multimedia materials that include both depictive (pictorial) and descriptive (textual) information. This work has found that comprehension and transfer are enhanced when text is accompanied by pictures compared to when text is presented alone, which is referred to as the *multimedia principle* (Mayer 2001; Fletcher and Tobias 2005). However, when presenting text and visualizations together, learners experience higher cognitive load and are less able to comprehend the material when the text information is presented visually, as on-screen text, as compared to presenting the text aurally, i.e., as narration, which is known as *modality principle* (Brünken et al. 2002, 2004; Low and Sweller 2005; Moreno and Mayer 1999; Mousavi et al. 1995; Penney 1989). Finally, research has shown that specific types of visualizations, such as maps, are more effective when they are presented before rather than after accompanying text, which is referred to as the *conjoint retention hypothesis* (Kulhavy et al. 1992, 1993).

Our review of research on learning with visualizations, i.e., primarily pictorial information, will be concerned with research on the improvement of the design of the visual information. Questions that are investigated by studies falling into this category include how visual information should be designed to support specific cognitive functions, e.g., *How should a simulation be designed to foster higher-level thinking?*, how the effectiveness of the visual is determined by the type of representation chosen to depict particular information, e.g., *Should temperature be depicted as icon or as text?*, or how the format of embedded information in the simulation affects learning, e.g., *Should embedded information in a science simulation be presented as video or as static images?*

Design principles for effective dynamic visualizations

Several general design principles for multimedia materials have been developed based on research on multimedia learning over the past decade (Mayer and Moreno 2003; Mayer 2005b, c; Moreno 2006; Moreno and Mayer 2007). Dynamic visualizations are a special form of multimedia learning materials that are characterized by their interactive nature and their extensive use of pictorial representations of information. Their effective design can therefore be described through principles for visual design and principles for interaction design. Theoretical heuristics for the design of animations were summarized by Weiss et al. (2002). In the following sections we will present design principles for each of these two areas that relate to the specific demands of dynamic visualizations. We will not discuss established principles that apply to the design of multimedia materials in general, such as *coherence principle*, which recommends the exclusion of extraneous materials from multimedia environments (Harp and Mayer 1997, 1998; Mayer 2001, 2005a; Mayer et al. 1996, 2001, 2007; Mayer and Moreno 2003; Moreno and Mayer 2000), the *redundancy principle*, which recommends the elimination of the need for learners to process information they already know and advises against the use of on-screen text that is identical to text already included in a narration (Mayer 2005a; Sweller 2005), or the *personalization principle*, which recommends the use of a conversational rather than a formal style of communication with the learner (Mayer 2005a).

Below we will first review and briefly summarize visual design principles and interaction design principles for effective dynamic visualizations that have been established previously and are discussed in detail elsewhere. We will then suggest some emerging principles that draw upon recent research. Emerging principles will be discussed in more depth since they have not been reported in as much detail as the previously established principles.

Visual design principles

In this section we will describe visual design principles that specifically apply for dynamic visual representations. Dynamic visualizations, or animations, are often viewed as a natural choice for conveying concepts that change over time (Hegarty 2004; Tversky et al. 2002). Dynamic visualizations can be categorized in many ways. Lowe (2003) identified three types of dynamic representations: transformations, in which physical properties of an object are altered, translations, in which objects are moved from one place to another, and transitions, in which objects appear or disappear. Ainsworth and VanLabeke (2004) distinguished three different types of dynamic representations: time-persistent, expressing the relation between at least one variable and time; time-implicit, showing a range of values with no specific time frame; and time-singular, displaying one or more variables at a single point in time. These different categorizations all share the notion that dynamic visualizations display the process of change over time, whether time is explicitly expressed or not.

Established principles

Two design principles have been established that relate to the visual design of dynamic representations, the split-attention principle (Ayres and Sweller 2005) and the contiguity principle (Mayer 2005a).

Split-attention principle

The split-attention principle states that comprehension of multimedia materials is hindered "when learners are required to split their attention between and mentally integrate several sources of physically or temporally disparate information, where each source of information is essential for understanding the material." (Ayres and Sweller 2005, p. 135). Examples for this effect are materials where a video is presented with subtitles, where animations presented with explanatory texts that change dynamically with the animation, or where a video and an animation are presented next to one another. A learner will only experience a split-attention effect if both sources of information are essential for comprehension and if the materials are of a relatively high level of difficulty for this learner. In order to avoid slit attention, designers can integrate the sources with one another, both in their physical arrangement as well as the timing of their presentation (Ayres and Sweller 2005). For dynamic visualizations this principle involves the placing of labels, instructions, and explanations next to the object to which they refer, placing related objects near one another, and avoiding the presentation of two dynamic sources of information (e.g., video and animation) at the same time (Mayer et al. 1995; Sweller et al. 1990; Tarmizi and Sweller 1988).

Spatial and temporal contiguity principle

The *contiguity principle* describes how presenting related sources of information close to one another, rather than separated, enhances learning by reducing extraneous visual search tasks (Mayer 2005b; Mayer and Moreno, in press). This principle has been established for the spatial arrangement of the information (spatial contiguity principle) and for the timing of the presentation of the information (temporal contiguity principle). Examples for this effect are narrations that are presented after the corresponding visual information was shown (temporal contiguity), or labels that are not integrated with the corresponding visualizations (spatial contiguity). Designers can avoid comprehension problems due to spatial contiguity by placing related objects next to another rather than far from each other, and problems due to temporal contiguity by presenting related information at the same time rather in succession.

Additional principles

Additional principles for information design of simulations and animations that can be derived from the literature include the cueing principle, which has previously been established (Mayer 2005a), and is presented in a revised form, the representation type principle, the color coding principle, and the integration of multiple dynamic visual representations principle.

Cueing

Cueing refers to the addition of design elements that direct the learner's attention to important aspects of the learning material. Cueing, also referred to as signaling, can enhance learning because it can reduce the need for the processing of extraneous information, such as required during the search for key information (Mayer 2005a).

The effectiveness of cueing has been established primarily for text-based materials (Lorch 1989) and for static visuals (Dwyer 1978; Jeung et al. 1997). A study by Mautone and Mayer (2001) did not find an effect of visual cueing for animations, which the authors attributed to the low complexity of the content of the animation and of the few distracting elements. Tabbers et al. (2004) therefore hypothesized that the visual cueing of critical information of a dynamic visualization will help to counter the issues of complexity and pacing evident in dynamic representations. They examined the effect of visual cues that relate to the most relevant elements of a diagram in a dynamic visual display, presenting university students with a dynamic representation of an instructional design model accompanied by visual text or audio text, either with or without visual cues. The results showed an effect for visual cues; students who viewed the dynamic display with the cues achieved significantly higher retention scores than those who did not view cues. However, the effect for visual cues was weak and was not evident on the transfer measure. Tabbers et al. argued that these weak effects, which differ from past research on cueing, may have resulted from the learner-paced nature of the dynamic visualization, which allowed the learners to scroll through textual or audio explanations at their own pace. According to this interpretation, stronger effects for cueing, as well as effects for audio text, would have been evident for dynamic visuals with system-set pacing. Nonetheless, the results suggest that visual cueing may have reduced cognitive load by requiring fewer cognitive resources to be expended on searching for the relevant visual information. A follow-up study by de Koning et al. (2007) provided undergraduate students with an animation of the cardiovascular system. One group received the animation with visual cues for key functional processes; the other received the animation without these cues. Results indicated that the group receiving the cued animation outperformed the uncued group on comprehension and transfer tests related to both cued and uncued content. In other words, cueing supported not only the learning of cued content but also of the content of the uncued animation, a finding which the authors attribute to the effect of cues on overt attentional allocation.

Another study showed that dynamically represented content itself can serve as cues. This research compared interactive dynamic graphics to static graphics, using weather maps as the instructional content (Lowe 2003). Undergraduate students were asked to either learn from an animation or static graphics. The animation group received a computer-based instructional simulation of a series of weather maps, whereas the static group received paper maps. The simulation provided direct control of the rate at which the information was displayed. The findings indicate that those students who received the animated version of the weather maps tended to remember earlier and more readily those features that were persistent and contrasted with the visual context of the overall pattern of the map. The students in the animated graphics group neglected those components of the display with low perceptual salience, regardless of their importance to the meteorological system portrayed. In other words, these students paid attention to components that changed substantially more or less than their surroundings, regardless of their importance overall in the system. Students in the interactive animation group were less sensitive to subtle dynamic aspects of the display, despite their ability to control the rate of the information presented. Students seemed to focus narrowly on those perceptual features of the most salient components, which indicates that these salient changes in animations can act as powerful cues.

In summary, research on learning from animations suggests a modification to the existing cueing principle. Learners focus their attention relatively narrowly on the visually most salient components of an animation (Lowe 2003). This result corresponds to findings in neuroscience research that showed that salient perceptual properties of objects, such as contrast and visual uniqueness, determine very early in visual perception what information gets processed (Serences and Yantis 2006). The emerging *cueing design recommendation* therefore amends the cueing principle by stating that cueing may be most important for animations without learner control, and that designers should either make the educationally most important aspects of the animation the visually most salient ones, or should use cueing to direct learners' attention to critical information (de Koning et al. 2007; Tabbers et al. 2004).

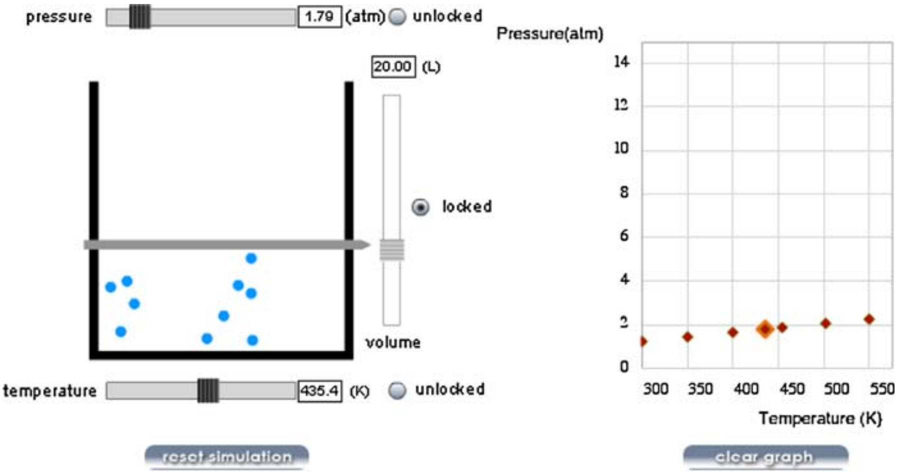
Representation type of information

One of the critical considerations in the visualization of information is the type of representation a designer will choose for key information. The *Integrated Model of Text and Picture Comprehension* (Schnotz 2005; Schnotz and Bannert 2003), based on a typology of signs developed in semiotics (Peirce 1955), distinguishes among depictive presentations, such as icons or images, and descriptive representations, such as written or spoken language. An emerging design principle for dynamic visualizations is that learning is enhanced when key information is represented in iconic (pictorial) form rather than only in symbolic (textual) form. This finding appears to apply in particular for materials that induce high cognitive load, and for learners who have low prior knowledge in the subject matter taught (Lee et al. 2006; Plass et al. 2009).

Imagine, for example, a learner who is studying the *ideal gas laws* with a computer simulation. This learner would benefit from the addition of icons that represent temperature as burners and pressure as weights, both of which are key information for understanding the gas laws, see Fig. 1 for simulation with icons and Fig. 2 for the variant without icons.

The effect of the representation type of the information can be explained by cognitive load theory, which predicts that processing depictive information requires less mental effort than processing descriptive information as depictive information (i.e., icons and pictures) by definition relate directly to their referent, whereas descriptive information (i.e., symbols and words) need to be interpreted before they can be integrated with other information.

Several studies have been conduced that support this emerging principle. For example, Rieber et al. (1996) investigated the use of graphical versus textual feedback in using a computer simulation of Newton's laws of motion. Graphical feedback consisted of an animated graphic of an object, whereas textual feedback consisted of a numeric readout of the same information. Overall, all participants' formal understanding of Newton's laws of motion increased as result of working with the simulations. Scores on the computer game increased significantly when participants received graphical as opposed to textual feedback, though overall interactivity decreased significantly with graphical feedback. Qualitative inquiry



pressure 1.79 (atm) ○ unlocked

20.00 (L) ● locked volume

temperature 435.4 (K) ○ unlocked

Fig. 2 Simulation of the Ideal Gas Laws, without icons found that virtually all participants strongly preferred graphical feedback to textual feedback. Rieber's findings suggest that graphical feedback led to higher performance than textual feedback on tests of implicit learning through in computer-game-like tasks, but only in some cases on tests of explicit learning through traditional text-based questions (Rieber 1996; Rieber et al. 1996). In a related study with the same simulation activity, Rieber et al. (2004) found that comprehension was significantly higher for those participants who received graphical feedback than participants who received textual feedback.

A related study by Carlson et al. (2003) compared the relative effectiveness of written (symbolic) versus pictorial (iconic) instruction to build molecular models. The high vs. low complexity of the molecules included in the study was used to operationalize high vs. low intrinsic cognitive load. The study found that written and pictorial instructions were equally effective for building simple molecular models. However, for building complex molecules the pictorial (iconic) directions were more effective for students than the written (symbolic) directions. These results indicate that pictorial (iconic) representations reduced extraneous load compared to the written (symbolic) information, freeing cognitive resources and allowing students to solve complex tasks. The conclusions were supported by a second study involving the naming of carbon-containing molecules.

Other research on representation of information in simulations investigated the effects of adding iconic information to the visual display of computer-based chemistry simulations as described in the example above. Initial evidence that adding iconic representations to simulations may improve learning was obtained by Lee et al. (2006). Materials in this study represented key information only symbolically, as temperature (T) and pressure (p), or by using both symbolic and iconic representations, adding depictions of burners (for temperature) and weights (for pressure), see Fig. 1. The burners and weights are iconic representations that have a close association with the concept of temperature and pressure, respectively. The study found that learners' comprehension and transfer was significantly improved in the simulations with adding iconic representations.

A follow-up study was conducted in order to isolate the effect of adding iconic representations of key information to simulations (Plass et al. 2007). The materials used for this research consisted of a simulation of the *Kinetic Theory of Heat*, which described the effect of temperature and number of particles on the internal pressure of a gas. Two versions of the simulations were developed that varied in their representational format (symbolic versus iconic). In the symbolic version of the simulation, essential information was presented in symbolic format (e.g., numbers were given to indicate temperature), while in the iconic version, iconic representations were added to represent the same information in visual form (e.g., different numbers of burners represented different temperatures). The results showed a main effect of representation type for comprehension, indicating that adding icons improved the overall understanding of the simulation under high but not under low cognitive load conditions. An interaction effect of prior knowledge and representation type indicated that this effect was especially strong for low-prior knowledge learners (Plass et al. 2009).

Color coding

The emerging color coding principle states that instructional materials in which color is used to highlight important features and attributes of visual displays results in enhanced learning (Dwyer and Moore 1991; Keller et al. 2006).

Prior research has investigated design issues such as color in instructional visualizations (Dwyer 1972, 1978). Color can be used in dynamic visualizations and simulations to emphasize key design features and draw connections between multiple sources of information across media. Color coding may facilitate reductions in working memory and search demands in simulations (Kalyuga et al. 1999; Keller et al. 2006). Color-coded knowledge maps have been found to be more effective instructional tools than knowledge maps without color (Hall and Sidio-Hall 1994a), an effect that is further enhanced when students themselves generate the color-coding system (Hall and Sidio-Hall 1994b).

Kalyuga et al. (1999) conducted an experiment in which color coding was manipulated as a means of integrating text with a diagram, in a computer-based instructional program. Sixteen individuals were randomly assigned to one of two groups. In the conventional separate-diagram-and-text group, participants viewed a basic interactive diagram of an electrical circuit with a textual explanation below. In the color-coded-diagram-text group, the diagram and the text were identical, except that by clicking on the paragraph of text, the learner could see the electrical elements described in the text highlighted in the same colors in the diagram and the text. The results revealed a significant difference favoring the color coding group in subjective rating scales, where color-coded users found the task easier, and multiple choice scores, where color-coded users performed higher. The authors concluded that the color-coding technique for integrating multimedia information may work to eliminate problems with the split-attention effect. In addition, the colors likely supported learners search strategies when studying the diagram (Keller et al. 2006). It is important that colors employed for this purpose be distinct, as perceived similarity of colors may inhibit efficient visual search (Reijnen et al. 2007). This emerging principle can be considered a subset of the cueing principle, with a special focus on the use of color as cue for important information.

Integration of multiple dynamic visual representations

The emerging principle of the integration of multiple dynamic visual representations in simulations suggest that learning is facilitated best when multiple representations in interactive visualizations are dynamically linked and integrated with one another (van der Meij and de Jong 2006).

Most instances of multimedia learning involve multiple representations of information that have to be integrated by the learner, and although important foundational research on learning from multiple representations has been conducted (Mayer 2005a), many questions regarding cognitive processes and cognitive load involved in the integration of multiple representations and resulting design features for these representation remain (Ainsworth 2006; Goldman 2003; Seufert and Brünken 2006). For example, Ainsworth and Van Labeke (2004) suggest that multiple dynamic representations facilitate learning when these representations provide complementary processes or information, when one representation better defines (constrains) the information in the other representation, or when learners are engaged in comparing or contrasting multiple representations to construct understanding. Yet, only very limited empirical data is available that describes the educational effectiveness and cognitive load implications of these functions of multiple representations for simulations and animations.

A challenge of integrating multiple representations in interactive dynamic visualizations is the need to integrate multiple representations that are changing dynamically. In the example of our gas law simulation, information on gas properties is presented in the representation of the gas container as well as in the chart, both of which change when the learner manipulates a gas property. These visualizations are representations of the same phenomenon on different conceptual levels, and the integration of different types of representations of chemistry has been found to be challenging for novices, while they are frequently and successfully used by experts (Kozma and Russell 1997). Van der Meij and de Jong (2006) explored the effect of physically integrating multiple representations as well as the effect of dynamically linking multiple representations such that actions performed by the user on one representation are automatically shown on all other representations. Dynamic linking is therefore related to Rieber's (1991) notion of graphical feedback, in that the state of the simulation in one representation determines the visual information presented in another representation. However, in this case, multiple representations are viewed simultaneously rather than consecutively. Van der Meij and de Jong developed three versions of a computer simulation involving multiple representations addressing the physics topic of 'moments': (1) a simulation containing separate, non-linked representations, (2) a simulation containing separate dynamically-linked representations, and (3) a simulation with physically integrated and dynamically-linked representations. Overall, posttest scores were significantly better than pretest scores, suggesting that all participants learned from the simulations. A significant difference was found between the three conditions, such that participants receiving the integrated and dynamically linked condition scored significantly better than those in the separate, non-linked condition, though there was no significant difference between the separate dynamically-linked condition and the other conditions. These findings suggest that while integrated dynamically linked simulations led to the highest posttest scores, the increase in learning outcomes also depended on the integration of the materials. The authors conclude that in order to maximize learning, simulations should be designed such that multiple representations are both physically integrated and dynamically linked, a finding that is in line with the contiguity principle and applies it to the specifics of learning from visualizations (see Mayer and Moreno, in press).

Interaction design principles

Interactive dynamic visualizations, often referred to as simulations, allow learners not only to control the pacing and sequencing of the dynamic representation, but also to manipulate its content and determine the way it is represented. From an activity or control perspective, we can therefore distinguish three levels of interactivity, the control of the information delivery (e.g., clicking the pause button), manipulation of the content (e.g., setting parameters in a simulation), and control of the representation (e.g., moving or rotating an object on the screen) (Kalyuga 2007). From a learning perspective, we can distinguish functional interactivity, i.e., learners' behavior and actions, and cognitive interactivity, i.e., learners' information processing and knowledge construction (Kennedy 2004). Research in specialized disciplines has shown that a high degree of control over the representation of the information facilitates comprehension (Garg et al. 2001; Harman et al. 1999; James et al. 2002), and that manipulation of the content of visualizations may foster higher level thinking such as conceptual reasoning and hypothesis generating and testing (Stieff and Wilensky 2003; Wu et al. 2001).

Established principles

Two design principles have been established that relate to the interaction design of dynamic representations, the segmenting principle (Mayer 2005a) and the guided discovery principle (de Jong 2005).

Learner control–segmenting

The *segmenting principle* describes how learners' comprehension of materials is better when they can control the advance of the presentation from one segment to the next rather than viewing a continuous presentation (Mayer and Chandler 2001; Mayer et al. 2003; Moreno 2007). The segmenting effect is believed to apply in situations where the intrinsic load of the materials is so high that learners do not have enough cognitive resources for the essential processing of the content. For example, a simulation of the *Ideal Gas Laws,* which involves three interacting gas properties (pressure, volume, and temperature) could be segmented into two separate screens with only two interacting variables, one for Charles' Law (volume and temperature) and one for Boyle's Law (volume and pressure), see Lee et al. (2006). When the materials are broken into segments and allow control over when to advance to the next segment, learners may be able to effectively distribute this load over the amount of time they need to process the materials (Lee et al. 2006; Mayer 2005a; Mayer and Moreno, in press).

Guided-discovery principle

The *guided-discovery principle* states that individuals learn better when guidance is used in discovery-based learning in multimedia contexts (de Jong 2005). While computer simulations offer a unique context for discovery learning, novice learners often struggle with exploratory learning when there are no supports to guide their efforts (de Jong and van Joolingen 1998; Kirschner et al. 2006; Mayer 2004). Guidance, either in the form of domain specific explanations, direct advice on when to perform certain actions, explanations of domain information, or monitoring tools that aid in storing information, facilitates effective discovery learning (de Jong 2005). In multimedia and simulation-based contexts, guided learning is preferable to pure discovery learning as guidance decreases the extraneous cognitive load demands on the learner by supporting the learner's abilities to organize and integrate new information (Moreno 2004). While any effort to direct the instruction of the simulation user can be considered guidance, one example of guidance is a model progression design, in which the complexity of the simulation is gradually increased (Swaak et al. 2004; White and Fredriksen 1990). Another example of guidance in a science-oriented simulation is the availability of a "hypothesis scratchpad," which offers a designated space alongside the simulation for learners to make notes about testable hypotheses using a predefined set of variables and conditions (van der Meij and de Jong 2004). With the use of this guidance tool, learners may be more likely to focus on the formation of hypotheses while interacting with the simulation.

One thoroughly researched type of guidance is explanations of domain specific information, which are often embedded in simulations or computer programs. The effectiveness of these embedded explanations has been demonstrated repeatedly (de Jong and van Joolingen 1998; Rieber et al. 2004; Moreno and Durán 2004; Moreno and Mayer 2005; Zhang et al. 2004). The effect of such explanations may be mediated by characteristics of the learners as well as the nature of the simulated phenomenon.

Feedback given in the course of a computer simulation is another manner of guiding discovery-based learning. Though feedback is at times discussed as a distinct principle of multimedia learning (Moreno and Mayer 2007), the research investigating the efficacy of feedback typically describes it as a guidance technique (Moreno 2004; Moreno and Mayer 2005; Morrison et al. 1995). Feedback is evaluative information that is provided responses to user performance, and has been found to promote learning in computer-based instruction (Azevedo and Bernard 1995). Research with computer simulations found that corrective feedback, where it is communicated to the learner whether they are right or wrong, supported retention and transfer less than explanatory feedback, where learners in addition to being told whether or not they are correct, are also given a domain relevant explanation of why their answer was correct or incorrect, and found that this effect applied particularly to novice learners (Moreno 2004; Moreno and Mayer 2005). Overall, feedback that is rich in domain information and is easily interpreted seems to be effective in promoting learning from simulations.

Additional principles

Additional principles for the interaction design of simulations and animations that can be derived from the literature include the learner control of pacing principle, the task appropriateness principle, and the manipulation of content principle.

Learner control–pacing

The emerging learner control of pacing principle states that learning is improved when learners are given control over the pacing of information through features such as start/pause/stop buttons. Learner control involves many different facets, and it is not clear whether learner control in general has a strong positive effect on learning (Niemiec et al. 1996; Swaak and de Jong 2001). Such an effect has been found, however, for learner control over the pace of the presentation of visual materials. Tabbers et al. (2004) suggest that the issue of pacing is of considerable importance in evaluating the learning impact of dynamic representations from a cognitive load perspective. The quick pacing and rigidity of the sequence of non-interactive dynamic representations places heavy demands on working memory, as information presented at earlier stages in the animation must be stored and then integrated with information presented at later stages (Hegarty 2004). This finding differs from static displays, which are available for re-inspection. Interactive dynamic visualizations enable learners to pace their learning from the visual materials, and may reduce the working memory load of visually presented material by eliminating the need for simultaneous processing of all visual information presented (Cook 2006).

Research support for this effect has been found in several studies. For example, Mayer and Chandler (2001) compared a continuous 140-s animation without user control to a version of the same animation that was divided into 16 parts, with a “continue” button, which allowed users to advance the presentation from one part to the next. The results showed that students with learner control outperformed those who did not have any control over the pacing of the animations, and that transfer test performance was higher, and cognitive load reduced, when learners first received the version of the animation with learner control and then the version without control, as compared to the reverse order.

A study of the effect of learner control over the pace and direction of video instruction found strong effects for providing these controls (Schwan and Riempp 2004). Participants received either a non-interactive continuous video on how to tie nautical knots of varying difficulty, or the same video with controls allowing them to pause, change the speed, and reverse the direction of the video. Students were asked to study each of four knots until mastery. Results show a significant decrease in the overall time required to master the knots for the group that had video controls. Closer analysis showed that the time spent watching the videos did not differ significantly, but the practice time for learners who had received the controls was significantly lower than for learners who did not receive controls. Learners used the controls more frequently for the more difficult knots compared to the less difficult ones (Schwan and Riempp 2004). The authors noted that controls allowed learners to skip over easier parts and focus on more difficult parts of the video, which can be interpreted as avoiding the processing of redundant information, i.e., lowering extraneous cognitive load.

Another study of learner control of pacing by Hasler et al. (2007) provided middle school students with animations that showed determinants of day and night on earth. The study compared a system-paced continuous animation, a learner-paced simulation with discrete segments, and learner-paced animations with a start/stop buttons that allowed them to control the pacing of the simulation. A narration-only group served as control. The researchers predicted that the system-paced conditions (continuous and narration-only) would induce higher cognitive load than the learner-paced conditions (segments and stop/play). Results showed no differences among the groups for low-complexity questions. However, for high-complexity questions, the groups that were provided with the pacing control performed better than the groups that did not receive such controls. Interestingly, this effect was present for the start/stop group despite the fact that most learners in this group did not use this feature—its mere presence was sufficient to affect learning. This research suggests that even the feeling of being in control over one's learning can improve comprehension of the animation.

In summary, learning from dynamic representations is improved when learners are able to control the pacing of the presentation because new information can be integrated into existing knowledge structures at a rate that reflects the capabilities and needs of the learner (Betrancourt 2005; Hasler et al. 2007; Mayer and Chandler 2001; Swaak and de Jong 2001; Tabbers et al. 2004). In addition, allowing a learner to speed through or skip parts of a presentation that he or she perceives as easy, and to focus on the more difficult parts (Schwan and Riempp 2004), can avoid a redundancy effect through learner control. In contrast to the segmenting principle, which applies to the control of advancing from one segment to the next, the benefits of learner control of pacing refer to the finer level of granularity of control that is possible in continuous dynamic media, such as animation and video, for which learners are provided with functionality to start, pause, and stop the dynamically presented content, and to change the speed and direction of the presentation.

Task appropriateness

The emerging task appropriateness principle states that the efficacy of a simulation depends on the degree to which it is in line with learning objectives. Research suggests that visualizations must be task-appropriate in order to improve learning outcomes, i.e., they need to prepare learners for future tasks to be performed (Levin 1989; Schnotz and Bannert 2003). This finding is consistent with earlier work on transfer-appropriate processing (Morris et al. 1977)—the effectiveness of visual representations has to be evaluated based on the performance for which they prepare the learner. Specific visualizations were found to have a facilitating, enabling, or inhibiting effect on specific learning processes (Schnotz and Rasch 2005). Simulations may enable the learner to perform tasks they otherwise would not be able to perform by reducing the cognitive load of the task. Simulations may reduce cognitive load in tasks that requires high mental effort, i.e., they may facilitate processing. However, simulations may also inhibit processing by providing unnecessary support, i.e., performing a task the learner could have performed him- or herself, and therefore reduce learning (Schnotz and Rasch 2005). Visualizations can have specific functions in either supporting the retention of factual knowledge, the comprehension of materials, or the application of the presented information to new situations (Levin et al. 1987; Plass et al. 2004). It has similarly been suggested that animations can have a cosmetic, decorative function, attention gaining function, motivation function, presentation function, or clarification function (Rieber 1989, quoted in Weiss et al. 2002). In general, visualizations appear to be most effective when they are interpretational in nature, i.e., when they aid in explaining a difficult text or describe a complex cause-and-effect system or process (Carney and Levin 2002).

This principle is supported by several studies on learning from animations and simulations. For example, two studies by Schnotz et al. (1999) compared a static "circle" diagram of the earth's time zones with a simulation based on the same material. The first study in Schnotz et al. (1999) showed that simulations are more suited for knowledge acquisition than static pictures, but that for simulation tasks requiring the learner to mentally execute the simulation, static pictures are more suited than simulations. Other studies have shown that depending on the learning task, germane cognitive load may be reduced by animating the simulation content (Schnotz and Rasch 2005). This research compared two interactive graphic versions of the "circle" diagram of the earth's time zones. College students were either presented with visualizations that could be manipulated, such that the student defined the date and time in a city and the earth moved to match it, or that were simulated, such that the graphic simulated the earth's rotation. The findings indicate that while students with both high and low prior knowledge and cognitive abilities answered time-difference questions significantly better when they received the simulations, no such difference was found for the circumnavigation questions. The authors argue that the time-difference questions require factual knowledge, while circumnavigation questions require mental simulations. They conclude that the simulations presented were redundant, as students of this age are able to make their own mental simulations. The authors suggested that while these simulations communicated factual information more effectively than static visuals, they increased extraneous cognitive load, due to the processing of redundant information, and decreased germane load, as students did not engage in mental simulation building.

Manipulation of content

The emerging principle of manipulation of content suggests that learning from visualizations is improved when learners are able to manipulate the content of a dynamic visualization compared to when they are not able to do so.

An example of content manipulation is the chemistry simulation shown in Fig. 1, where learners are able to manipulate the properties of the gas, such as temperature, volume, or pressure. Other simulations may allow learners to set the voltage in an electric circuit or the speed of a car.

Research has provided indications that interactivity in visualizations may increase learners invested mental effort by heightening the degree of activity and engagement in the learning process (Hegarty 2004) and the construction of mental schemas (Chandler 2004). Hegarty (2004) suggests that dynamic displays that require no interaction may lead to passive viewing on the part of the learner. From a cognitive load perspective, non-interactive dynamic visuals may fail to elicit the mental activity associated with desirable increases in germane cognitive load that would result in increased learning. Bodemer et al. (2004) found in a study on pre-training for dynamic and interactive visuals that participants who were asked to actively integrate the pre-training information group outperformed participants who received pre-integrated material and concluded that learning from interactive dynamic representations is improved by encouraging the active integration of static visuals and symbolic material. A follow-up study replicated these findings (Bodemer et al. 2005). Other research suggests that the ability to manipulate the content in a simulation is increases intrinsic motivating (Rieber 1991).

Research in support of this principle has been conducted for several decades. For example, Rieber (1990) used a computer simulation of Newton's laws of motion to investigate the effect of interactive animated graphics as compared with static graphics in science instruction with middle school students. The simulation allowed participants to manipulate forces of motion through representations of a foot and a ball to be kicked. Results showed a significant main effect for type of visual presentation, such that children who were presented with the simulation scored significantly higher than those who used the static graphics or no graphics, though some concerns were raised about the informational equivalency of the static and animated graphics (Tversky et al. 2002). Rieber concluded that interactive simulations can be used effectively for material that requires the visualization of motion and trajectory. Rieber's (1991) follow-up study highlighted not only the potential of interactive dynamic visuals as motivating and appealing instructional tools that increase germane cognitive load, but also the importance of investigating effective design features that prevent misconceptions in learning from these materials.

A comparison of a chemistry simulation that allowed for content manipulation with a version of the same material that only allowed for control of pacing revealed higher learning outcomes from the content manipulation simulation (Plass et al. 2007). Participants were randomly assigned to either the simulation or animation with control of pacing functionality and were asked to learn everything they could about the topic, the *Ideal Gas Law*. The simulation treatment consisted of the simulation presented in Fig. 1. Results showed significantly higher comprehension scores for the group that were able to manipulate the content of the simulation compared to the group that could only control the pacing. Because the difference between the two treatments was primarily the type of interaction with the materials available to the learner, this study suggests that the manipulation-level interactivity provided by simulations increased learners' germane cognitive load compared to materials where learners had control only over the pacing of the materials.

Darabi et al. (2007) investigated worked-out examples embedded within a computer simulation of a chemical processing plant with college students in a laboratory setting. The simulation asked participants to manage the upkeep of the plant by diagnosing and repairing the plant's malfunctions as they arose. Participants received either process-oriented examples, in which a procedure for analyzing plant malfunctions was explained, product oriented examples, in which five steps for solving the malfunctions were given, or conventional problem solving, which guided troubleshooting for the various malfunctions. Their learning of how to address unfamiliar chemical plant malfunctions was assessed using a transfer performance test. The findings demonstrated that traditional problem solving strategies, as opposed to worked-out examples, led to superior transfer scores. This was particularly true for students less experienced in chemical engineering. The two types of worked-out examples did not differ in their support of learning outcomes. The researchers concluded that worked-out examples that are embedded in simulations should be accompanied by traditional problem-solving practice exercises.

Schnotz et al. (1999) conducted a study on interactivity in which they added collaborative tasks to the treatment in which pairs of learners were allowed to discuss the materials during learning. Results showed that under these conditions, simulations were less effective for knowledge acquisition as well as for simulation tasks. Schnotz et al. interpreted the results by pointing to the higher extraneous cognitive load caused by the need to coordinate the learning activities of the group in the collaborative simulation treatment.

However, some possible problems with content manipulation were revealed in a study by Lowe (2004), who provided learners with animated weather maps and asked them to interrogate the features of these maps and their changes. Here, the video-like controls of the animation became a central exploration feature. In his analysis of the exploration patterns of the 12 participants, Lowe found that learners had limited exploration strategies, focusing on low-level exploration of isolated aspects of the animation. Lowe suggests that the cognitive load requirements of using these exploratory strategies were too high for learners and recommends the inclusion of scaffolds to guide learners (Lowe 2004).

In summary, unlike user control over the pacing of dynamic visualizations, which does not affect the learning content, learner interactivity allows users to manipulate the content of the visualization. Providing learners with such content-manipulating interactivity beyond the control of the pacing of the presentation was found to result in improved learning compared to materials without interactivity (Plass et al. 2007). This effect is likely due to the increased cognitive engagement, i.e., the increased germane load (Chandler 2004; Hegarty 2004; Rieber 1990; Wouters et al. 2007), and increased intrinsic motivation (Rieber 1991). Cognitive Load Theory predicts an increased germane load due to this increased intrinsic motivation resulting from the learners' ability to manipulate aspects of the environment. However, when additional tasks are required that increase extraneous load, caused, for example, by the need to coordinate the interaction with a collaborator, the benefit of interactivity disappears (Schnotz et al. 1999).

Suggestions for future research

As the review of research on learning with visual representations has shown, there are several areas that require further investigation. In this section, we will outline two types of possible research questions, one focusing on more theoretical issues of learning from dynamic visualizations, and the other concerned with more applied questions of the design of animations and simulations for education.

Future research on the design of animations and simulations for education

A striking impression from the review of research on cognitive load in learning from animations and simulations was that researchers seemed to treat all dynamic representations as if they were alike. Yet there are many different types and categories of animations and simulations, and it has become clear that future research on the effectiveness of these materials should move on from asking questions about animations and simulations in general to basing these questions on an appropriate typology of dynamic visual representations. These typologies could be based on the type of representation used (e.g., graphs, maps, networks, diagrams, etc.), the level of abstraction (e.g., line drawing, schematic cartoon, photo-realistic, etc.) and the type of content that is represented.

It has also become quite apparent that a more systematic approach for empirical research is needed for information design as well as for interaction design. Much of the current research on simulations and animations comes from different theoretical contexts and cannot easily be compared and synthesized because it has as its primary focus the further development of these theories rather than the question of how to better design dynamic visual representations. It would be beneficial to conduct more research with a focus on the different aspects of animation/simulation learning, such as undertaken by Rieber and de Jong.

One aspect of such research with a focus on dynamic visual representations is the interaction design. This research would require a more detailed typology of levels of interactivity in order to conceptualize future research on learners' control of the delivery of the materials, manipulation of the educational content, and control of the representation format. Although research has provided insights into the effect of different types of interactivity on learning outcomes, the implications of different types and levels of interactivity for learning need to be better understood.

Another aspect of future research on simulations and animations concerns the design of multiple simulations or animations that are to be studied in sequence. Initial research indicates that learning is facilitated when simulations become progressively more difficult and complex, and students progressively more knowledgeable about the simulation content (De Jong and van Joolingen 1998; Rieber and Parmley 1995; Rieber 2005). This finding mirrors research by Renkl et al. (2002) on fading from completely worked-out examples to problem-based learning, which showed that learners' increasing expertise was able to compensate for the increased demands of problem solving on learners' cognitive capacity (Renkl 2005). Future research should investigate cognitive-load related questions of visual aspects of model progression, e.g., focusing on the development of a visual language for the representation of science content in computer simulations.

A final topic for future research is related to information design. Although multimedia learning research has provided important insights into learning from multiple representations, research needs to more systematically investigate features of effective design of visual learning materials and integrate cognitive, cultural, as well as neuroscience approaches, as described in the following section.

Future research on fundamentals of learning from visualizations

In order to better understand how to improve the information design of dynamic visualizations, we need to better integrate results from the fields of visual perception and visual cognition. One aspect of this research that is highly related to learning from simulations and animations concerns visual attention. Neuroscience research has shown that objects compete for representation and processing even at a neuronal level (Desimone and Duncan 1995), and more research is needed to better understand how bottom-up and top-down processes can be used to guide learners' attention to the essential parts of the visual information. Automatic bottom-up processes, for example, which guide perception based on salient properties of perceived objects, can be influenced by visual features such as high contrast and visual uniqueness (Serences and Yantis 2006). Designers currently do take advantage of the processes that affect visual salience, but additional research is needed to create a more thorough and comprehensive set of guidelines of what makes objects visually salient. On the other hand, top-down processes, which are based on a perceiver's knowledge, goals and expectations, have been found to influence what visual information is actually perceived, particularly in high load situation (Grèzes et al. 1998; Lavie 2005). This means that two learners with different goals observing the same material or process can have different perceptual experiences. The educational implications of this phenomenon warrant further investigation. For example, perhaps one objective of an advance organizer should be to shape the visual attention of learners by affecting their knowledge, goals and expectation. More research is needed to determine how best to take advantage of the "bottom-up" and "top-down" processes that guide visual attention, as higher attention allows more cognitive resources to be available for visual learning.

Another finding from neuroscience that has promising implications for learning from dynamic visualizations involves the distinct *object* and *location* perceptual systems (i.e., the "what" versus "where" systems). These two visual systems process unique information via distinct neuronal pathways (Kosslyn and Koenig 1992; Ungerleider and Mishkin 1982). Whereas object properties, such as form and color, are processed via the "what" pathway (involving areas of cortex located in the inferior temporal lobe), spatial properties, such as shape, size, and movement, involve the "where" pathway (involving areas of the parietal lobe). There is evidence that information processed via the "what" and "where" systems rely on dissociable parts of working memory (Logie and Della Sala 2005; Oliveri et al. 2001). Future research should explore whether carefully designed visual learning materials could "offload" visual cognitive load between these two perceptual systems.

More research is also needed to determine how the type of representations used in visual learning materials can affect cognitive load and learning. Schnotz (2005), drawing upon Peirce's (1931–1958) semiotics, distinguishes between *depictive* and *descriptive* representations. Depictive representations correspond to Peirce's *icons* and include photographs, drawings, models and graphs. In these visual representations, meaning is derived by physical or structural commonalities between the representation and its referent. Descriptive representations correspond to Peirce's *symbols* and include words and numbers. With these types of representations, meaning is derived through social convention with an arbitrary relation between the representation and its referent (i.e., no visually similarity). Schnotz argues that descriptive and depictive representations are ideally suited for different functions: descriptive representations are best for expressing abstract knowledge, and depictive representations are best for drawing inferences because they are informationally complete. Any choice of representations in visual learning materials must take into account not only the function of the representation, but also the prior knowledge of the learners who will be using the materials. There is evidence that the cognitive load associated with depictive, iconic representations versus descriptive, symbolic representations depends in part on the prior knowledge of the learner (Lee et al. 2006; Plass et al. 2009). Descriptive, symbolic representations are informationally dense and require a larger amount of prior knowledge to interpret. However, once interpretation of symbolic representations becomes automated, then a great deal of information can be conveyed in a very economical fashion. Depictive, iconic representations convey less information, but rely far less on prior knowledge for interpretation, making them more transparent. This suggests that depictive representations are best suited for novice or low-prior knowledge learners. Our ongoing research supports this claim (Plass et al. 2009), but further research is needed.

Another growing area that needs additional research involves the link between visual representations and emotions in learning. The amygdala plays a central role in both emotion and memory (LeDoux 2003), and it has been suggested that positive emotions facilitate working memory processes such as are required for creative problem solving, and help long-term memory and retrieval as well (Isen et al. 1987; Isen and Patrick 1983). Though previous research on affect in learning has found that removing interesting but irrelevant materials increases learning (Mayer 2001), recent research suggests that visual materials can be designed to induce a positive affect in learners and improve learning outcomes (Norman 2003; Um et al. 2007). More research is needed on the role of positive affect on cognitive load and learning.

Conclusion

In this paper we have presented a number of design principles for the visual design and the interaction design of dynamic visualizations such as animations and simulations. In addition to existing principles, we have described emerging principles for these two areas. In particular, for information design, we described an expanded cueing principle, a representation type of information principle, a color coding principle, and an integration of multiple dynamic visual representations principle. For interaction design, we proposed in addition a learner control of pacing principle, a task appropriateness principle, and a manipulation of content principle.

This research has important theoretical and educational design implications. On the theoretical side, our review provides a summary of existing research that shows a strong need for additional theoretical and empirical work, especially connecting the study of learning from dynamic visualizations with work in the area of neuroscience and cognition. On the educational design side, this paper presents existing and emerging design guidelines specifically for the design of dynamic visualizations. Although still limited in scope, the application of these empirically validated guidelines for information design and interaction design should result in the development of animations and simulations that are educationally more effective and result in a stronger educational impact of dynamic visualizations.

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References

Ainsworth, S. (2006). DeFT: A conceptual framework for considering learning with multiple representations. *Learning and Instruction, 16*(3), 183–198.

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

Arnheim, R. (1969). *Art and visual perception: A psychology of the creative eye*. Berkeley: University of California Press.

Ayres, P., & Sweller, J. (2005). The split-attention principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning*. New York: Cambridge.

Azevedo, R., & Bernard, R. M. (1995). A meta-analysis of the effects of feedback in computer-based instruction. *Journal of Educational Computing Research, 13*(2), 111–127.

Barry, A. M. (1997). *Visual intelligence: Perception, image, and manipulation in visual communication*. Albany, NY: SUNY Press.

Bertin, J. (1983). *Semiology of graphics: Diagrams, networks, maps*. Madison, WI: University of Wisconsin Press.

Betrancourt, M. (2005). The animation and interactivity principles in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning*. New York: Cambridge.

Bodemer, D., Ploetzner, R., Bruchmüller, K., & Häcker, S. (2005). Supporting learning with interactive multimedia through active integration of representations. *Instructional Science, 33*, 73–95.

Bodemer, D., Ploetzner, R., Feuerlein, I., & Spada, H. (2004). The active integration of information during learning with dynamic and interactive visualizations. *Learning and Instruction, 14*, 325–341.

Brünken, R., Plass, J. L., & Leutner, D. (2004). Assessment of cognitive load in multimedia learning with dual-task methodology: Auditory load and modality effects. *Instructional Science, 32*(1), 115–132.

Brünken, R., Steinbacher, S., Plass, J. L., & Leutner, D. (2002). Assessment of cognitive load in multimedia learning using dual-task methodology. *Experimental psychology, 49*(2), 109–119.

Carlson, R., Chandler, P., & Sweller, J. (2003). Learning and understanding science instructional material. *Journal of educational psychology, 95*(3), 629–640.

Carney, R. N., & Levin, J. R. (2002). Pictorial illustrations still improve students' learning from text. *Educational Psychology Review, 14*(1), 5–26.

Chandler, P. (2004). The crucial role of cognitive processes in the design of dynamic visualizations. *Learning and Instruction, 14*, 353–357.

Clark, R. E. (1983). Reconsidering research on learning from media. *Review of Educational Research, 53*(4), 445–459.

Clark, R. E. (1994). Media will never influence learning. *Educational Technology Research and Development, 42*(2), 21–29.

Clark, J. M., & Paivio, A. (1991). Dual coding theory and education. *Educational Psychology Review, 3*(3), 149–210.

Cook, M. P. (2006). Visual representations in science education: The influence of prior knowledge and cognitive load theory on instructional design principles. *Science Education, 90*(6), 1073–1091.

Darabi, A. A., Nelson, D. W., & Palanki, S. (2007). Acquisition of troubleshooting skills in a computer simulation: Worked example vs. conventional problem solving instructional strategies. *Computers in Human Behavior, 23*(4), 1809–1819.

de Jong, T. (2005). The guided discovery principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 215–228). New York: Cambridge.

de Jong, T., & van Joolingen, W. R. (1998). Scientific discovery learning with computer simulations of conceptual domains. *Review of Educational Research, 68*(2), 179–201.

de Koning, B., Tabbers, H., Rikers, R., & Paas, F. (2007). Attention cueing as a means to enhance learning from an animation. *Applied Cognitive Psychology, 21*, 731–746.

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience, 18*, 193–222.

Dwyer, F. M. (1972). *A guide for improving visualized instruction*. State College, PA: Learning Services.

Dwyer, F. M. (1978). *Strategies for improving visual learning*. State College, PA: Learning Services.

Dwyer, F. M., & Moore, D. M. (1991). Effect of color coding on visually oriented tests with students of different cognitive styles. *Journal of Psychology: Interdisciplinary and Applied, 125*(6), 677–680.

Fletcher, J. D., & Tobias, S. (2005). *The multimedia principle*. New York, NY: Cambridge University Press.

Garg, A. X., Norman, G., & Sperotable, L. (2001). How medical students learn spatial anatomy. *The Lancet, 357*, 363–364.

Gibson, J. J. (1961). Ecological optics. *Vision Research, 1*(3–4), 253–262.

Goldman, S. R. (2003). Learning in complex domains: When and why do multiple representations help? *Learning and Instruction, 13*, 239–244.

Graesser, A. C., Millis, K. K., & Zwaan, R. A. (1997). Discourse comprehension. *Annual Review of Psychology, 48*, 163–189.

Grèzes, J., Costes, N., & Decety, J. (1998). Top-down effect of strategy on the perception of human biological motion: A PET investigation. *Cognitive Neuropsychology. Special Issue: Perception and action: Recent Advances in Cognitive Neuropsychology, 15*(6), 553–582.

Guthrie, J. T., Weber, S., & Kimmerly, N. (1993). Searching documents: Cognitive processes and deficits in understanding graphs, tables, and illustrations. *Contemporary Educational Psychology, 18*(2), 186–221.

Hall, R. H., & Sidio-Hall, M. A. (1994a). The effect of color enhancement on knowledge map processing. *Journal of Experimental Education, 62*(3), 209–217.

Hall, R. H., & Sidio-Hall, M. A. (1994b). The effect of student color coding of knowledge maps and test anxiety on student learning. *Journal of Experimental Education, 62*(4), 291–302.

Harman, K. L., Humphrey, G. K., & Goodale, M. A. (1999). Active manual control of object views facilitates visual recognition. *Current Biology, 9*, 1315–1318.

Harp, S. F., & Mayer, R. E. (1997). The role of interest in learning from scientific text and illustrations: On the distinction between emotional interest and cognitive interest. *Journal of Educational Psychology, 89*(1), 92–102.

Harp, S. F., & Mayer, R. E. (1998). How seductive details do their damage: A theory of cognitive interest in science learning. *Journal of Educational Psychology, 90*(3), 414–434.

Hasler, B. S., Kersten, B., & Sweller, J. (2007). Learner control, cognitive load and instructional animation. *Applied Cognitive Psychology, 21*, 713–729.

Hegarty, M. (2004). Dynamic visualizations and learning: Getting to the difficult questions. *Learning and Instruction, 14*(3), 343–351.

Hegarty, M., & Just, M. A. (1993). Constructing mental models of machines from text and diagrams. *Journal of Memory and Language, 32*(6), 717–742.

Helmuth, L. (2003). Cognitive neuroscience. Fear and trembling in the amygdala. *Science, 300*(5619), 568–569.

Höffler, T., & Leutner, D. (2007). Instructional animation versus static pictures: A meta-analysis. *Learning and Instruction, 17*, 722–738.

Isen, A. M., Daubman, K. A., & Nowicki, G. P. (1987). Positive affect facilitates creative problem solving. *Journal of Personality and Social Psychology, 56*, 1122–1131.

Isen, A. M., & Patrick, R. (1983). The effect of positive feelings on risk-taking: When the chips are down. *Organizational Behavior and Human Performance, 31*, 194–202.

James, K. H., Humphrey, G. K., Vilis, T., Corrie, B., Baddour, R., & Goodale, M. A. (2002). "Active" and "passive" learning of three-dimensional object structure within an immersive virtual reality environment. *Behavior Research Methods, Instruments, & Computers, 34*, 383–390.

Jeung, H., Chandler, P., & Sweller, J. (1997). The role of visual indicators in dual sensory mode instruction. *Educational Psychology, 17*, 329–343.

Kalyuga, S. (2007). Enhancing instructional efficiency of interactive e-learning environments: A cognitive load perspective. *Educational Psychology Review, 19*(3), 387–399.

Kalyuga, S., Chandler, P., & Sweller, J. (1999). Managing split-attention and redundancy in multimedia instruction. *Applied Cognitive Psychology, 13*(4), 351–371.

Keller, T., Gerjets, P., Scheiter, K., & Garsoffky, B. (2006). Information visualizations for knowledge acquisition: The impact of dimensionality and color coding. *Computers in Human Behavior, 22*(1), 43–65.

Kennedy, G. E. (2004). Promoting cognition in multimedia interactivity research. *Journal of Interactive Learning Research, 15*(1), 43–61.

Kirschner, P. A., Sweller, J., & Clark, R. E. (2006). Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. *Educational Psychologist, 41*(2), 75–86.

Kosslyn, S. M. (1989). Understanding charts and graphs. *Applied Cognitive Psychology, 3*(3), 185–225.

Kosslyn, S. M. (1994). *Image and brain: The resolution of the imagery debate*. Cambridge, MA: The MIT Press.

Kosslyn, S. M., & Koenig, O. (1992). *Wet mind: The new cognitive neuroscience* (p. 548). New York: Free Press.

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*, 949–968.

Kulhavy, R. W., Stock, W. A., & Kealy, W. A. (1993). How geographic maps increase recall of instructional text. *Educational Technology Research and Development, 41*(4), 47–62.

Kulhavy, R. W., Stock, W. A., & Peterson, S. E. (1992). Using maps to retrieve text: A test of conjoint retention. *Contemporary Educational Psychology, 17*, 56–70.

Lavie, N. (2005). Distracted and confused? Selective attention under load. *Trends in Cognitive Sciences, 9*(2), 75–82.

LeDoux, J. (2003). The emotional brain, fear, and the amygdala. *Cellular and molecular neurobiology, 23*, 727–738.

Lee, H., Plass, J. L., & Homer, B. D. (2006). Optimizing cognitive load for learning from computer-based science simulations. *Journal of Educational Psychology, 98*, 902–913.

Levie, W. H., Houghton, H. A., & Willows, D. M. (1987). Research on pictures: A guide to the literature. In D. M. Willows & H. A. Houghton (Eds.), *The psychology of illustration: Vol. I. Basic research* (pp. 1–50). New York: Springer-Verlag.

Levin, J. R. (1989). A transfer-appropriate-processing perspective of pictures in prose. In H. Mandl & J. R. Levin (Eds.), *Knowledge acquisition from text and pictures* (p. 58). Amsterdam: Elsevier Science Publishers.

Levin, J. R., Anglin, G. J., & Carney, R. R. (1987). On empirically validating functions of pictures in prose. In D. M. Willows & H. A. Houghton (Eds.), *The psychology of illustration: Vol. I. Basic research* (pp. 51–85). New York: Springer.

Logie, R. H., & Della Sala, S. (2005). Disorders of visuospatial working memory. In P. Shah & A. Miyake (Eds.), *Cambridge handbook of visuospatial thinking* (pp. 81–120). New York: Cambridge.

Lorch, R. F., Jr. (1989). Text signaling devices and their effects on reading and memory processes. *Educational Psychology Review, 1*, 209–234.

Low, R., & Sweller, J. (2005). The modality principle in multimedia learning. In R. E. Mayer (Ed.), *Cambridge handbook of multimedia learning* (pp. 147–158). New York: Cambridge.

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

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

Mandl, H., & Levin, J. R. (1989). *Knowledge acquisition from text and pictures*. New York: North-Holland.

Mautone, P. D., & Mayer, R. E. (2001). Signaling as a cognitive guide in multimedia learning. *Journal of Educational Psychology, 93*(2), 377–389.

Mayer, R. E. (1989). Models for understanding. *Review of Educational Research, 59*(1), 43–64.

Mayer, R. E. (2001). *Multimedia learning*. New York: Cambridge.

Mayer, R. E. (2004). Should there be a three-strikes rule against pure discovery learning? *American Psychologist, 59*(1), 14–19.

Mayer, R. E. (Ed.). (2005a). *Cambridge handbook of multimedia learning*. New York: Cambridge.

Mayer, R. E. (2005b). Principles for managing essential processing in multimedia learning: Segmenting, pretraining, and modality principles. In R. E. Mayer (Ed.), *Cambridge handbook of multimedia learning* (pp. 169–182). New York: Cambridge.

Mayer, R. E. (2005c). Principles for reducing extraneous processing in multimedia learning: Coherence, signaling, redundancy, spatial contiguity and temporal contiguity principles. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 183–200). New York: Cambridge.

Mayer, R. E., Bove, W., Bryman, A., Mars, R., & Tapangco, L. (1996). When less is more: Meaningful learning from visual and verbal summaries of science textbook lessons. *Journal of Educational Psychology, 88*(1), 64–73.

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., Deleeuw, K. E., & Ayres, P. (2007). Creating retroactive and proactive interference in multimedia learning. *Applied Cognitive Psychology. Special Issue: A Cognitive Load Approach to the Learning Effectiveness of Instructional Animation, 21*(6), 795–809.

Mayer, R. E., Dow, G. T., & Mayer, S. (2003). Multimedia learning in an interactive self-explaining environment: What works in the design of agent-based microworlds? *Journal of Educational Psychology, 95*(4), 806–812.

Mayer, R. E., & Gallini, J. K. (1990). When is an illustration worth ten thousand words? *Journal of Educational Psychology, 82*(4), 715–726.

Mayer, R. E., Heiser, J., & Lonn, S. (2001). Cognitive constraints on multimedia learning: When presenting more material results in less understanding. *Journal of Educational Psychology, 93*(1), 187–198.

Mayer, R. E., & Moreno, R. (1998). A split-attention effect in multimedia learning: Evidence for dual processing systems in working memory. *Journal of Educational Psychology, 90*(2), 312–320.

Mayer, R. E., & Moreno, R. (2003). Nine ways to reduce cognitive load in multimedia learning. *Educational Psychologist, 38*(1), 43–52.

Mayer, R., & Moreno, R. E. (in press). Techniques that reduce extraneous cognitive load and manage intrinsic cognitive load during multimedia learning. In J. L. Plass, R. Moreno, & R. Brünken (Eds.), *Cognitive load: Theory and application*. New York: Cambridge University Press.

Mayer, R. E., Steinhoff, K., Bower, G., & Mars, R. (1995). A generative theory of textbook design: Using annotated illustrations to foster meaningful learning of science text. *Educational Technology Research and Development, 43*(1), 31–43.

Mesulam, M. M. (1998). From sensation to cognition. *Brain, 121*, 1013–1052.

Moreno, R. (2004). Decreasing cognitive load for novice students: Effects of explanatory versus corrective feedback in discovery-based multimedia. *Instructional Science, 32*(1–2), 99–113.

Moreno, R. (2006). Learning in high-tech and multimedia environments. *Current Directions in Psychological Science, 15*(2), 63–67.

Moreno, R. (2007). Optimising learning from animations by minimising cognitive load: Cognitive and affective consequences of signaling and segmentation methods. *Applied Cognitive Psychology, 21*, 765–781.

Moreno, R., & Durán, R. (2004). Do multiple representations need explanations? The role of verbal guidance and individual differences in multimedia mathematics learning. *Journal of Educational Psychology, 96*(3), 492–503.

Moreno, R., & Mayer, R. E. (1999). Cognitive principles of multimedia learning: The role of modality and contiguity. *Journal of Educational Psychology, 91*(2), 358–368.

Moreno, R., & Mayer, R. E. (2000). A coherence effect in multimedia learning: The case for minimizing irrelevant sounds in the design of multimedia instructional messages. *Journal of Educational Psychology, 92*(1), 117–125.

Moreno, R., & Mayer, R. E. (2005). Role of guidance, reflection, and interactivity in an agent-based multimedia game. *Journal of Educational Psychology, 97*(1), 117–128.

Moreno, R., & Mayer, R. (2007). Interactive multimodal learning environments: Special issue on interactive learning environments: Contemporary issues and trends. *Educational Psychology Review. Special Issue: Interactive Learning Environments: Contemporary Issues and Trends, 19*(3), 309–326.

Morris, C. D., Bransford, J. D., & Franks, J. J. (1977). Levels of processing versus transfer appropriate processing. *Journal of Verbal Learning and Verbal Behavior, 16*, 519–533.

Morrison, G. R., Ross, S. M., Gopalakrishnan, M., & Casey, J. (1995). The effects of feedback and incentives in achievement in computer-based instruction. *Contemporary Educational Psychology, 20*, 32–50.

Mousavi, S. Y., Low, R., & Sweller, J. (1995). Reducing cognitive load by mixing auditory and visual presentation modes. *Journal of Educational Psychology, 87*(2), 319–334.

Niemiec, R., Sikorski, C., & Walberg, H. J. (1996). Learner-control effects: A review of reviews and a meta-analysis. *Journal of Educational Computing Research, 15*(2), 157–174.

Norman, D. (2003). *Emotional design: Why we love (or hate) everyday things*. New York: Basic Books.

Oliveri, M., Turriziani, P., Carlesimo, G. A., Koch, G., Tomaiuolo, F., Panella, M., et al. (2001). Parieto-frontal interactions in visual-object and visual-spatial working memory: Evidence from transcranial magnetic stimulation. *Cerebral Cortex, 11*(7), 606–618.

Paivio, A. (1971). *Imagery and verbal processes* (p. 596). Oxford, England: Holt, Rinehart & Winston.

Paivio, A. (1991). *Images in mind: The evolution of a theory*. New York: Harvester Wheatsheaf.

Paivio, A., & Csapo, K. (1973). Picture superiority in free recall: Imagery or dual coding? *Cognitive psychology, 5*(2), 176–206.

Peirce, C. S. (1955). Logic as semiotic: The theory of signs. In J. Buchler (Ed.), *The philosophical writings of Peirce* (pp. 98–110). New York: Dover Books.

Penney, C. G. (1989). Modality effects and the structure of short-term verbal memory. *Memory & Cognition, 17*(4), 398–422.

Plass, J. L., Chun, D. M., Mayer, R. E., & Leutner, D. (1998). Supporting visual and verbal learning preferences in a second-language multimedia learning environment. *Journal of Educational Psychology, 90*(1), 25–36.

Plass, J. L., Chun, D. M., Mayer, R. E., & Leutner, D. (2003). Cognitive load in reading a foreign language text with multimedia aids and the influence of verbal and spatial abilities. *Computers in Human Behavior, 19*(2), 221–243.

Plass, J. L., Hamilton, H., & Wallen, E. (2004, April). *The effects of three types of multimedia aids on three cognitive learning outcomes in the comprehension of scientific texts*. Paper presented at the Annual Meeting of the American Educational Research Association (AERA) in San Diego, CA.

Plass, J. L., Homer, B. D., Milne, C., Jordan, T., Kalyuga, S., Kim, M., et al. (2009). Design factors for effective science simulations: Representation of information. *International Journal of Gaming and Computer-Mediated Simulations, 1*(1), 16–35.

Plass, J. L., Homer, B. D., Milne, C., Jordan, T., Kim, M., & Barrientos, J. (2007). *Representational mode and cognitive load: Optimizing the instructional design of science simulations*. Featured Research Paper presented at the annual convention of the Association for Educational Communication and Technology (AECT) in October, 2007 in Anaheim, CA.

Reijnen, E., Wallach, D., Stöcklin, M., Kassuba, T., & Opwis, K. (2007). Color similarity in visual search. *Swiss Journal of Psychology, 66*(4), 191–199.

Renkl, A. (2005). The worked-out examples principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 229–245). New York: Cambridge.

Renkl, A., Atkinson, R., Maier, U., & Staley, R. (2002). From example study to problem solving: Smooth transitions help learning. *Journal of Experimental Education, 70*, 293–315.

Rieber, L. P. (1989). A review of animation research in CBI. In *Proceedings of selected research papers presented at the Annual Meeting of the Association for Educational Communication and Technology* (pp. 370–389). Dallas, TX.

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

Rieber, L. P. (1991). Effects of visual grouping strategies of computer-animated presentations on selective attention in science. *Educational Technology Research and Development, 39*, 5–15.

Rieber, L. P. (1996). Animation as feedback in a computer-based simulation: Representation matters. *Educational Technology Research and Development, 44*, 5–22.

Rieber, L. P. (2005). Multimedia learning in games, simulations, and microworlds. In R. E. Mayer (Ed.), *Cambridge handbook of multimedia learning*. New York: Cambridge.

Rieber, L. P., & Parmley, M. W. (1995). To teach or not to teach? Comparing the use of computer-based simulations in deductive versus inductive approaches to learning with adults in science. *Journal of Educational Computing Research, 13*(4), 359–374.

Rieber, L. P., Smith, M., Al-Ghafry, S., Strickland, B., Chu, G., & Spahi, F. (1996). The role of meaning in interpreting graphic textual feedback during a computer-based simulation. *Computers Education, 27*(1), 45–58.

Rieber, L. P., Tzeng, S., & Tribble, K. (2004). Discovery learning, representation, and explanation within a computer-based simulation: Finding the right mix. *Learning and Instruction, 14*, 307–323.

Schnotz, W. (2002). Commentary: Towards an integrated view of learning from text and visual displays. *Educational Psychology Review, 14*(1), 101–120.

Schnotz, W. (2005). An integrated model of text and picture comprehension. In R. E. Mayer (Ed.), *Cambridge handbook of multimedia learning* (pp. 49–70). New York: Cambridge.

Schnotz, W., & Bannert, M. (2003). Construction and interference in learning from multiple representation. *Learning and Instruction, 13*, 141–156.

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

Schnotz, W., & Kulhavy, R. W. (1994). *Comprehension of graphics*. Amsterdam, Netherlands: North-Holland/Elsevier Science Publishers.

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. Special Issue: Research on Cognitive Load Theory and Its Design Implications for E-Learning, 53*(3), 47–58.

Schwan, S., & Riempp, R. (2004). The cognitive benefits of interactive videos: Learning to tie nautical knots. *Learning and Instruction, 14*, 293–305.

Serences, J. T., & Yantis, S. (2006). Selective visual attention and perceptual coherence. *Trends in Cognitive Sciences, 10*(1), 38–45.

Seufert, T., & Brünken, R. (2006). Cognitive load and the format of instructional aids for coherence formation. *Applied Cognitive Psychology, 20*(3), 321–331.

Shah, P., & Carpenter, P. A. (1995). Conceptual limitations in comprehending line graphs. *Journal of Experimental Psychology: General, 124*(1), 43–61.

Shah, P., & Hoeffner, J. (2002). Review of graph comprehension research: Implications for instruction. *Educational Psychology Review, 14*(1), 47–69.

Stieff, M., & Wilensky, U. (2003). Connected chemistry: Incorporating interactive simulations into the chemistry curriculum. *Journal of Science Education and Technology, 12*, 285–302.

Swaak, J., & de Jong, T. (2001). Learner vs. system control in using online support for simulation-based discovery learning. *Learning Environments Research, 4*, 217–241.

Swaak, J., de Jong, T., & van Joolingen, W. R. (2004). The effects of discovery learning and expository instruction on the acquisition of definitional and intuitive knowledge. *Journal of Computer Assisted Learning, 20*(4), 225–234.

Sweller, J. (1999). *Instructional design*. Camberwell, Vic: ACER Press.

Sweller, J. (2005). Implications of cognitive load theory for multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 19–30). New York: Cambridge.

Sweller, J., Chandler, P., Tierney, P., & Cooper, M. (1990). Cognitive load as a factor in the structuring of technical material. *Journal of Experimental Psychology: General, 119*(2), 176–192.

Tabbers, H., Martens, R., & van Merriënboer, J. J. G. (2004). Multimedia instructions and cognitive load theory: Effects of modality and cueing. *British Journal of Educational Psychology, 74*, 71–81.

Tarmizi, R. A., & Sweller, J. (1988). Guidance during mathematical problem solving. *Journal of Educational Psychology, 80*(4), 424–436.

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

Um, E., Song, H., & Plass, J. L. (2007). *The effect of positive emotions on multimedia learning*. Paper presented at the World Conference on Educational Multimedia, Hypermedia & Telecommunications (ED-MEDIA 2007) in Vancouver, Canada, June 25–29, 2007.

Ungerleider, L. G., & Mishkin, M. (1982). Two cortical visual systems. In D. G. Ingle, M. A. Goodale, & R. J. Q. Mansfield (Eds.), *Analysis of visual behavior* (pp. 549–586). Cambridge, MA: MIT Press.

van der Meij, J., & de Jong, T. (2004). *Learning with multiple representations.* Paper presented at the 2004 Annual Meeting of the American Educational Research Association, San Diego, CA.

van der Meij, J., & de Jong, T. (2006). Supporting students' learning with multiple representations in a dynamic simulation-based learning environment. *Learning and Instruction, 16*, 199–212.

Weiss, R. E., Knowlton, D. S., & Morrison, G. R. (2002). Principles for using animation in computer-based instruction: Theoretical heuristics for effective design. *Computers in Human Behavior, 18*, 465–477.

White, B. Y., & Fredriksen, J. R. (1990). Causal model progression as a foundation for intelligent learning environments. *Artificial Intelligence, 42*, 99–157.

Willows, D. M., & Houghton, H. A. (Eds.). (1987). *The psychology of illustration—Vol. I. Basic research*. New York: Springer-Verlag.

Winn, W. (1994). *Contributions of perceptual and cognitive processes to the comprehension of graphics*. Amsterdam, Netherlands: North-Holland/Elsevier Science Publishers.

Winn, W., Li, T.-Z., & Schill, D. (1991). Diagrams as aids to problem solving: Their role in facilitating search and computation. *Educational Technology Research and Development, 39*(1), 17–29.

Wouters, P., Tabbers, H. K., & Paas, F. (2007). Interactivity in video-based models. *Educational Psychology Review, 19*(3), 327–342.

Wu, H., Krajcik, J. S., & Soloway, E. (2001). Promoting understanding of chemical representations: Students' use of a visualization tool in the classroom. *Journal of Research in Science Teaching, 38*, 821–842.

Zhang, J., Chen, Q., Sun, Y., & Reid, D. J. (2004). Triple scheme of learning support design for scientific discovery learning based on computer simulation: Experimental research. *Journal of Computer Assisted Learning, 20*(4), 269–282.

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