This paper reviews research on learning from dynamic visual representations and presents principles for the design of animations and simulations that are educationally effective. Our review focuses on three design factors, visual design, interaction design, and pedagogical design, and presents existing research as well as questions for future inquiry.

The goal of this paper is to present principles for the design of animations and simulations that are educationally effective. Such visual environments are gaining increasing importance for educational use as well as for work-related tasks. We use visual representations of complex ideas to think and to communicate our thoughts to others. 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 animation (Lee, Plass, & Homer, 2006).

Imagine, for example, a student taking a chemistry 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 Figure 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 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 both 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 scaffolds would guide the learning process, and what kind of controls and navigation tools would be available to the learner.

Such decisions are fundamental to learning: There is mounting evidence that the educational efficacy of visualizations depends on how well its design reflects our understanding of human cognitive architecture. 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.

How does learning from animations compare to load in learning from other visual representations? Although much research comparing the effectiveness of non-interactive dynamic visualizations with static visualizations has failed to produce general advantages of dynamic visual representations, 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, suggesting that decorative animations many impose higher extraneous load. 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.

Media design research has begun to ask what particular design features are effective in reducing extraneous cognitive load and increasing germane cognitive load 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 at all, and begins to isolate design features
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. From a cognitive load perspective, dynamic visualizations that do not offer information or elicit mental activity beyond that in static visualizations are likely to increase extraneous cognitive load through the more complex interface they typically require. 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 describe the processes involved in perceiving and processing visual information. We will then discuss design principles for three different aspects of the design of visual learning materials, visual design, interaction design, and pedagogical design, and presents existing research as well as questions for future inquiry. We will conclude the paper with a discussion of how cognitive load theory can guide the design of effective dynamic visual materials, such as science simulations, and outline future research that is needed for a better understanding of visual learning.

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, only recently discovered but considered far more ancient in evolutionary terms, and much cruder in its visual capability, 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 & 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 & 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 (Grezes, Costes, & Decety, 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 & Koenig, 1992; Ungerleider & 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 & 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 (1) identifying the important features of a visual display, which is referred to as surface-level processing or external identification, (2) relating the
visual features to their meaning, i.e., semantic processing, and (3) constructing the communicated message, i.e., pragmatic processing (Bertin, 1983; also see Kosslyn, 1989; Schnotz, 2002; Shah & 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.

*Dual Coding Theory* 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 & Paivio, 1991; Mayer, 1989; Mayer & Gallini, 1990; Mayer & Moreno, 1998; Paivio & Csapo, 1973; Paivio, 1971, 1991; Plass, Chun, Mayer, & Leutner, 1998, 2003; Rieber, 1990; 1991).

*Cognitive Load Theory* describes how the processing of the information and construction of referential connections is executed under the constraints of limited working memory resources (Sweller, 1999). Cognitive load research has 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.

The *Cognitive Theory of Multimedia Learning* describes cognitive processes involved in learning from multimedia materials. Learners first select relevant visual and verbal information from the stimulus, organize that information into coherent verbal and visual mental representation, and 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, 2005).

The *Integrated Model of Text and Picture Comprehension* (Schnotz & Bannert, 2003) 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). Schnotz’s theory suggests that in processing symbolic or iconic representations, learners always construct multiple mental representations. 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 (Graesser, Millis, & Zwaan, 1997; Schnotz, 2005). Likewise, when processing iconic representations, learners also construct both forms of internal representations.

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

Much of the research investigating multimedia learning has focused on identifying effective ways of designing educational multimedia materials that include both visual and textual information. One of the generally accepted findings of research on multimedia learning is that comprehension and transfer are enhanced when text is accompanied by visuals compared to when text is presented alone, which is referred to as the multimedia principle (Mayer, 2001; Fletcher & Tobias, 2005). A review of 155 experiments on representational visuals by Levie and Lentz (1982) concluded that illustrations accompanying instructional texts functioned to aid in both comprehension as well as retention, as compared to processing the text without visual aids. More recently, Carney and Levin (2002) reviewed research from the last several decades and concluded that visuals are especially effective in support of building of useful mental models 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. Research on the modality principle found that when text and images are presented 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 (Brünken, Plass, & Leutner, 2004; Brünken, Steinbacher, Plass, & Leutner, 2002; Low &
Sweller, 2005; Moreno & Mayer, 1999; Mousavi, Low, & Sweller, 1995; Penney, 1989). Research on the *split-attention principle* showed that when two sources of visual information are presented together, learners experience higher cognitive load and reduced learning when the information is presented in separated rather than in integrated form (Ayres & Sweller, 2005; Mayer, Steinhoff, Bower, & Mars, 1995; Sweller, Chandler, Tierney, & Cooper, 1990; Tarmizi & Sweller, 1998). Other research has shown that for specific types of visual materials, such as maps, learning materials are more effective when maps are presented before accompanying text, which is referred to as the *conjoint retention hypothesis* (Kulhavy, Stock, & Kealy, 1993; Kulhavy, Stock, & Peterson, 1992).

Our review of research on learning with visualizations, i.e., primarily pictorial information, found that empirical studies mostly fall into one of two categories. The first category is concerned with the effectiveness of a ‘prototype’ of a visual representation for a particular learning goal. For the chemistry simulation in our example, this type of research would ask questions comparing the efficacy of different visual representations, e.g., *Are simulations more effective than animations or static images?* Studies in this category, which can typically be considered *media comparison research*, make the implicit assumption that the materials used for the research are well designed, and do not seek to empirically verify this assumption.

A second type of research on visual learning focuses on the improvement of the design of the visual information itself. 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 text or as graphic?* Below, we will review the literature on learning from dynamic visualizations, with a focus on media design research rather than media comparison research.

**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 & Moreno, 2003; Mayer, 2005a; Mayer, 2005b; Moreno, 2006; Moreno & Mayer, 2007). Dynamic Visualizations are a special form of multimedia learning materials that are characterized by their interactive nature and their extensive use of visual representations of information. Their effective design can therefore be described through principles for visual design and principles for interaction design. Because
dynamic visualizations place high processing demands on learners, we include an additional type of principle for effective pedagogical design considerations. In the following sections we will therefore present design principles for each of these three 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 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, 2005; Sweller, 2005), or the personalization principle, which recommends the use of a conversational rather than a formal style of communication with the learner (Mayer, 2005), see Table 1.

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Insert Table 1 here

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Below we will first review and briefly summarize visual design principles, interaction design principles, and pedagogical 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. These candidates for principles will be discussed in more detail since they have not been reported as well as the other 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 presented as a natural choice for conveying concepts that change over time (Hegarty, 2004; Tversky, Morrison, & Betrancourt, 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
Three design principles have been established that relate to the visual design of dynamic representations, the split-attention principle (Ayres & Sweller, 2005), the contiguity principle, and the cueing principle (Mayer, 2005).

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 & 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 split attention, designers can integrate the sources with one another, both in their physical arrangement as well as the timing of their presentation (Ayres & Sweller, 2005). For dynamic visualizations this involves placing of labels 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.

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, 2005a; Mayer & Moreno, in press). This 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

Cueing
Cueing refers to the addition of design elements that direct the learner’s attention to important aspects of the learning material. Cognitive load theory predicts that cueing, also referred to as
signaling (Mayer, 2005), can reduce cognitive load because it can reduce learners’ search for key information.

The effectiveness of cueing has been established primarily for text-based materials (Lorch, 1989) and for static visuals (Dwyer, 1978; Jeung, Chandler, & Sweller, 1997). A study by Mautone and Mayer (2001) did not find an effect of visual cueing for animations, which the authors interpreted as a result of the low complexity of the content of the animation and of the few distracting elements. Tabbers, Martens, and van Merriënboer (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. In addition to investigating the effect of spoken versus written text, they examined the effect of visual cues that relate to the most relevant elements of a diagram in a dynamic visual display. In their research, they presented 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. The authors explain that these weak effects, which differ from past research on cueing, may have resulted from the learner-paced nature of the dynamic visualization, in that the learners could 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.

In a related study, de Koning, Tabbers, Rikers, and Paas (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. These results indicate that 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. In sum, those 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 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 & Yantis, 2006). The cueing design recommendation is therefore that animations 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 & 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 appears to be particularly the case for materials in which learners have low prior knowledge (Lee et al., 2006; Plass et al., in press).

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 Figure 1.

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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 conducted 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. All participants received an even number of graphical and textual feedback responses while working with the simulation. 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 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 (in computer-game-like tasks), but only in some cases on tests of explicit learning (traditional text-based questions) (Rieber, 1996, Rieber et al., 1996). In a related study with the same simulation activity, Rieber, Tzeng, and Tribble (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, Chandler, & Sweller (2003) compared the relative effectiveness of written (symbolic) versus pictorial (iconic) instruction to build molecular models. The complexity of the molecules to be constructed was used to operationalize 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. Initial evidence that adding iconic representations to simulations may improve learning was obtained by Lee, Plass, and Homer, 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 Figure 1. The burners and weights are iconic representations that have a close association with the concept of temperature and pressure, respectively. In addition to adding icons, the method of reducing extraneous cognitive load of the simulation also included integrated the sliders controlling the simulation into the display rather than separating them, and displaying all results taken in the graph rather than showing only most recent simulation result.

Two hundred and fifty-seven middle school students (age 13-15) participated in this research as part of their regular classroom instruction. They were randomly assigned to the treatment conditions. Learning outcomes were measured using a 10-item comprehension test and a transfer test with 4 open-ended questions. The study found that the load-reducing methods employed (adding iconic representations, integrating sliders, and showing all data points on the chart) significantly improved comprehension and transfer.

A follow-up study was conducted in order to isolate the effect of adding iconic representations of key information to simulations (Plass, Homer, Milne, Jordan, Kim, & Barrientos, in press). The materials used for this research consisted of a simulation of the Kinetic Theory of Heat, which describes 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). An 8-item pre-test assessed prior knowledge of properties of gas and of kinetic theory of heat. The knowledge post-test assessed learning at two levels. A 10-item multiple-choice questionnaire measured comprehension, and 6-item, short-answer questionnaire measured higher-level transfer, asking learners to explain different phenomena and real-life applications of the kinetic theory. Participants in this research were 93 students from a public high school in Texas (age 16-18 years) who were randomly assigned to one of the two treatment conditions. The results showed a
main effect of representation type for comprehension, indicating that adding icons improved the overall understanding of the simulation. An interaction effect of prior knowledge and representation type indicated that this effect was especially strong for low-prior knowledge learners.

Integration of Multiple Dynamic Visual Representations

Another design feature of simulations that has been studied is how to best integrate multiple representations in interactive dynamic visualizations. 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, 2005), 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 & 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.

In simulation research, one aspect of multiple representations that has been empirically investigated is in the use of static visuals as pre-training for simulation activities (see Mayer & Moreno, in press). For example, Bodemer, Ploetzner, Feuerlein, and Spada (2004) conducted a study with 84 participants to test whether extraneous load could be decreased by introducing participants to static visuals of the material before they viewed the dynamic and interactive visuals, and whether germane load could be increased by encouraging participants to formulate and test hypotheses. Before using the simulations, participants were first presented with static visuals along with textual and algebraic information as an introduction to the material. The manner in which this material was presented varied as follows: in the non-integrated information group, the static visuals, textual, and algebraic information were in split-source format; in the integrated information group the three sources of information were integrated; in the active integration of information group, the participants were asked to complete a task in which they related the textual and algebraic information with that of the static visuals by a drag and drop operation. After completing a pretest and receiving a short explanation of the visuals they would be using, the participants viewed the static visuals and accompanying text and algebraic information. Learners then interacted with the visuals for about 45 minutes and completed a
Results from this study show that those participants that were in the active integration of information group outperformed participants who received split-source material or pre-integrated material. Those individuals in the non-integrated information and integrated information groups did not differ from one another at posttest. The authors concluded that learning from interactive dynamic representations is improved by encouraging the active integration of static visuals and symbolic material, which may decrease extraneous cognitive load. A follow-up study replicated the finding that dynamic visualizations that are preceded by integrative exercises improve learning (Bodemer, Ploetzner, Bruchmüller, & Häcker, 2005).

A second aspect 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 & Russel, 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 (S-NL), 2) a simulation containing separate dynamically-linked representations (S-DL), and 3) a simulation with physically integrated and dynamically-linked representations (I-DL). Seventy-two Dutch vocational students between the ages of 16 and 18 were randomly assigned to use one of these simulations. Paper-and-pencil pre- and posttests consisting of 38 multiple-choice items were administered. 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 I-DL condition scored significantly better than those in the S-NL condition, though there was no significant difference between the S-DL condition and the other conditions. These findings
suggest that while integrated dynamically linked simulations led to the highest posttest scores, dynamic linking alone was not responsible for the increase in learning outcomes. 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 (see Mayer & Moreno, in press).

Multiple external representations can have a variety of forms and functions (Ainsworth & van Labeke, 2004), and cognitive load implications have only been investigated for a small number of them. Initial research exists on two of these functions of multiple representations. First, providing learners with opportunities to actively integrate static visuals with symbolic information before engaging in interactive simulations has been found to support learning (Bodemer, et al., 2004; Bodemer et al., 2005). Similar findings have been reported as a pre-training effect, see Mayer & Moreno, in press. A second function, especially related to simulations, is the need to integrate and link multiple dynamic visual representations. Initial research has found that such representations best facilitate learning when they are dynamically linked and integrated with one another (van der Meij & de Jong, 2006). Cognitive Load Theory predicts that the integration of related visual representations reduces extraneous load that would have been expended to conduct a visual search for separated information, and that the dynamic linking of related visual representations reduces extraneous cognitive load that would have been required to integrate non-linked representations, which is consistent with the contiguity principle.

**Interaction Design Principles**

Interactive dynamic visual representations, often referred to as simulations, allow learners not only to control the pace of the dynamic representation, but also to manipulate its content and processes. Interactivity in multimedia learning environments can be defined on a cognitive and a functional level (Kennedy, 2004). Emerging typologies for the functional level distinguish among interactivity on a feedback level (which includes learner control), manipulation level, adaptation level, and communication level (e.g., Moreno & Mayer, 2007; Kalyuga, 2007). Simulations are characterized by allowing for high levels of manipulation-level interactivity that impact the content of the simulation through user actions such as the setting of parameters, and control of the representation of the information, such as by moving or rotating of objects.

Research in specialized disciplines has shown that a high degree of control over the representation of the information facilitates comprehension (Garg, Norman, & Sperotable, 2001; Harman, Humphrey, & Goodale, 1999; James, Humphrey, Vilis, Corrie, Baddour, & Goodale, 2002), and that manipulation of the content of visualizations may foster higher level thinking.
such as conceptual reasoning and hypothesis generating and testing (Stieff & Wilensky, 2003; Wu, Krajzic, & Soloway, 2001). Of interest here are the cognitive load implications imposed by interactivity in these materials.

**Established Principle**

**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 & Chandler, 2001; Mayer, Dow, & Mayer, 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. When the materials are broken into segments and allow control over the pacing of the segments, 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, 2005; Mayer & Moreno, in press).

**Additional Principles**

**Learner Control of Pacing**

A second design feature that was studied as a way to reduce cognitive load in dynamic visualizations is learner control. It is not clear whether learner control in general has a strong positive effect on learning (Niemiec, Sikorski, & Walberg, 1996; Swaak & de Jong, 2001). However, learner control over the pace of the presentation of visual materials has been shown to improve learning. 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 of non-interactive visualizations may be too fast for some learners. The 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 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). In a study of the effects of providing learners with control over the pace of a narrated animation, Mayer and Chandler (2001) compared 2 versions of instruction on how lightning works. Fifty-nine college students used either a continuous 140-s animation without user control or 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. One group of 15 students first received the continuous animation without control, and then the separated animation with the control button. While another group of 15 students received first the control version and then the no-control version (experiment 1). An additional group of 15 students received the no-control version twice, and a group of 14 students received the control version twice (experiment 2). Learning outcome measures included a retention test measuring comprehension of the content and a transfer test measuring deep learning. Learners’ perceived levels of cognitive load were measured using a 1-item instrument developed by Paas & van Merriënboer (1993, 1994). The results of this research showed no difference in comprehension between the treatments in either experiment. For transfer, results in experiment 2 showed that students receiving the treatments with learner control outperformed those who did not have any control over the pacing of the animations. Experiment 1 showed in addition 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 of providing these controls (Schwan & Riempp, 2004). Thirty-six 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 of 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 & 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, Kersten, and Sweller (2007) provided 72 students (aged 9–11 years) with animations that showed determinants of day and night on earth. One group received a system-paced continuous animation, one group a learner-paced simulation with discrete segments, and a third group received 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). Learning outcomes were assessed using two tests, one with 8 low-complexity questions (with lower element interactivity), and one with 5 high-complexity questions (with higher element interactivity). Cognitive load was assessed with a 1-item 9-point scale. Relative efficacy scores were computed as a result of cognitive load and performance measures (Paas & Van Merriënboer, 1993). Results found 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 contrast to these two studies on learner control of the pacing of the information, in which learner control was a feature that did not have a central educational function, Lowe (2004) 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, comprehension of information in dynamic representations is improved when learners are able to control the pacing of the presentation (Hasler et al., 2007; Mayer & Chandler, 2001; Schwan & Riempp, 2004; Swaak & de Jong, 2001; Tabbers et al., 2004). 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. Cognitive load theory predicts that by providing learners with these types of control over the pacing of animations and video, the high cognitive load of processing dynamic visual representations is reduced, and new information can be better integrated into existing knowledge structures (Betrancourt, 2005; Mayer & Chandler, 2001). 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 & Riempp, 2004), can
avoid a redundancy effect through learner control. Interactive dynamic displays may therefore reduce extraneous cognitive load by providing learner control over the pacing of the presentation, as information can be stored and processed at a rate that reflects the needs of the learner.

Exploration v. Worked-Out Examples
How does cognitive load in simulation learning compare to load in learning from other visual representations? Research has provided indications that interactive dynamic visualizations may increase germane load 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.

Rieber (1990) investigated using interactive animated graphics as compared with static graphics in science instruction with 10- and 11-year-old students. The computer simulation described and explained Newton’s laws of motion and subsequently allowed children 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.

A comparison of an interactive chemistry simulation with a worked-out example of the same material with 64 high school students (16-18 years old) revealed benefits of the simulations that can be attributed to increased germane load (Plass, Homer, Milne, Jordan, Kim, & Barrientos, 2007). Participants were randomly assigned to either the simulation or the worked-out example and were asked to learn everything they could about the topic, the Ideal Gas Law, which none of the students had studied before. The simulation treatment consisted of the simulation presented in figure 1. The worked-out example presented the content to the learner in a narrated step-by-step walk-through of screen shots from the simulation that was designed to assure that all of the important aspects of the content were covered. Students could control the advance from one segment to the next at their own pace. Results showed significantly higher comprehension scores for the group that received the simulations compared to the group receiving worked-out examples. 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 worked-out examples, where learners had control only over the pacing of the materials.

Findings from two studies by Schnottz, Böckheler, and Grzondziel (1999) shed additional light on the cognitive load implications of interactivity in the exploration of dynamic representations. The researchers compared the static “circle” diagram of the earth’s time zones described previously (Schnotz & Bannert, 2003) 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. In the second study in Schnotz et al. (1999), the authors added a 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. interpret 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.

Other studies have shown that depending on the learning task, germane cognitive load may be reduced by animating the simulation content (Schnotz & Rasch, 2005). In an extension of previous work, Schnotz and Rasch developed two interactive graphic versions of the “circle” diagram of the earth’s time zones, as described above. Students in the animated graphics group were presented with graphics that could be manipulated, such that the student defined the date and time in a city and the earth moved to match it, or simulated, such that the graphic simulated the earth’s rotation. These two types of interactive animated visuals were used together and compared to static visuals. Cognitive ability and prior knowledge, together considered by the authors as learning prerequisites of the undergraduate participants, were also taken into account. The findings indicate that while students with both high and low learning prerequisites answered time-difference questions significantly better after having used the simulations, the same was not the case with 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. Therefore, the computer simulations reduced the germane cognitive load associated with the mental activity of creating internal models. The authors suggest that while these simulations communicated factual information more effectively than static visuals, overall they increased extraneous load, due to the processing of redundant
information, and decreased germane cognitive load, as students did not engage in mental simulation building.

A final study of this type focused on intrinsic motivation in learning from a simulation of Newton’s laws of motion (Rieber, 1991). The study provided learners with an interactive computer simulation activity, paired with either an animation or static visuals. Seventy 10-year-olds first used the simulation and were then randomly assigned to either the animated graphic condition or the static graphic condition. Rieber’s (1991) results indicate that students who viewed the animated graphic performed significantly better than the static graphic group on incidental-learning outcomes. Measures of motivation suggested that working with an interactive simulation was more intrinsically motivating than answering questions or working on a word puzzle. The findings also suggest, however, that those students who viewed the animated visuals were more prone to misconceptions about gravitation than those who viewed the static visuals. In sum, while animated visuals, paired with multiple-choice and simulated graphic practice, increased incidental learning, they also predisposed students to erroneous conclusions concerning the subject matter. These results highlight 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.

**Content Manipulation**

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. In other words, the learner control findings are mainly based on research on learning with animations, and learner interactivity findings are based on research on learning with simulations. 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, Tabbers, & Paas, 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).

In summary, research on learning from interactive dynamic visual representations has found several possible effects of simulations on cognitive load. Simulations may reduce extraneous cognitive load as result of the control available to the learner that allows them to
process the information at a rate that reflects their needs (Cook, 2006; Hegarty, 2004; Tabbers et al., 2004). Simulations may also lead to increased germane load by increasing the degree of activity and engagement (Chandler, 2004; Hegarty, 2004; Plass et al., 2007; Rieber, 1990) and increasing intrinsic motivation (Rieber, 1991). However, simulations may also result in increased extraneous load when the information they provide is redundant because the simulation could be performed mentally by the learner (Schnotz & Rasch, 2005) or when the parts of the simulation that change substantially do not contain the most important information (Lowe, 2003). Finally, simulations might decrease germane load when the simulations does the cognitive processing for the learner even though the learners could have processed the information themselves (Schnotz et al., 1999). The empirically based findings on effective design features to optimize cognitive load in interactive dynamic representations will be summarized in the following section.

**Pedagogical Design Features**

While simulations and visualizations offer much promise in the way of instruction of dynamic content, there are several pedagogical design features that likely work to enhance these computer-based learning tools. The next section will address features of design that work to frame simulation-based learning. Visualizations are best designed with minimal extraneous information, be it visual, textual, or auditory, so that extraneous load is minimized (Mayer, 2005). Simulations provide an opportunity for pure discovery learning, though learning outcomes are greatly supported by guidance, be it in the form of domain specific explanations or explanatory feedback on learner performance (de Jong & van Jooligen, 1998). Providing the learner with explicit opportunities for reflection may also facilitate instruction through simulations. Two emerging pedagogical design features, worked-out examples and task-appropriateness, that are in need of more empirical support will also be discussed.

**Established Principles**

**Coherence**

The coherence principle is based on the idea that eliminating irrelevant information frees up cognitive resources so they can be used for essential processing (Harp & Mayer, 1997, 1998; Mayer, 2001, 2005; Mayer, Bove, Bryman, Mars, & Tapangco, 1996; Mayer, Heiser, & Lonn, 2001; Mayer & Moreno, 2003; Moreno & Mayer, 2000). Mayer and his colleagues have argued that added information that does not pertain the instructional goal, be it in the form of words or pictures, presents extraneous cognitive load that inhibits cognitive processing and transfer of knowledge. For example, when a multimedia message that is accompanied by words and pictures that are intended to make the instructional material more engaging may make the instructional
objective less concise and therefore more difficult to learn. One method of reducing the extraneous load and making visual materials easier to process involves excluding irrelevant visual information from the learning materials.

Much research has been conducted supporting the notion that coherent multimedia messages make for better instructional tools. For instance, the use of concise booklets, as compared to embellished booklets (with added textual details and illustrations), about lightning formation have been found to result in better student performance on transfer tests in several studies (Harp & Mayer, 1997, 1998; Mayer et al., 1996). In the context of computer-based learning, past research indicates that extraneous soundtracks, narrations, and visual video clips, result in decreased learning outcomes (Mayer, Heiser, & Lonn, 2001; Moreno & Mayer, 2000). More recently, Mayer, Deleeuw, and Ayres (2007) employed a concise and expanded version of a computer-based lesson explaining a hydraulic brake system and found that deeper learning occurred in those students who were given the concise lesson. In sum, there is empirical evidence for the coherence principle, supporting the notion that people learn better when extraneous material of any modality is excluded from multimedia instructional tools.

Guided-Discovery Principle

The guided-discovery principle states that individuals learn better when guidance is used in discovery based learning in multimedia contexts (Mayer, 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 & van Jooligen, 1998; Kirschner, Sweller, & Clark, 2006; Mayer, 2004). Guidance, be it 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 guidance can include any effort to direct the instruction of the simulation user, one example of guidance is a model progression design, in which the complexity of the simulation is gradually increased (Swaak de Jong, & van Jooligen, 2004). 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 & 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 & van Jooligen,
1998; Rieber, et al., 2004; Moreno & Durán, 2004; Moreno & Mayer, 2005; Zhang, Chen, Sun &
Reid, 2004). The effect of such explanations may be mediated by characteristics of the learners as
well as the nature of the simulated phenomenon. De Jong and van Jooligen (1998) conducted a
series of studies comparing different types of guidance, and found that explanations of domain
knowledge in the context of simulations increase learning outcomes. Model progression as a
guidance tool was found to be helpful only when the content of the simulation was very complex.
Moreno and Durán (2004) found that verbal explanations describing each step of their math
animation increased the learning of arithmetic procedures, particularly for those students who had
high levels of computer experience. Zhang et al. (2004) provided explanations about scientific
experimental design that were embedded in the introduction of simulation on floating and sinking
and found that only students with low reasoning ability benefited from the explanations. The
findings from these studies suggest that while guidance is most certainly needed in computer-
based discovery learning, the form of guidance that is most effective is dependent on the
individual characteristics of learners and the complexity of the domain.

Feedback given in the course of a computer simulation is another manner of guiding
discovery-based learning. Though feedback is at times discussed to as a distinct principle of
multimedia learning (Moreno & Mayer, 2007), the research investigating the efficacy of feedback
typically describes it as a guidance technique (Moreno, 2004; Moreno & Mayer, 2005). Feedback
is evaluative information that is provided responses to user performance, and has been found to
promote learning in computer-based instruction (Azevedo & Bernard, 1995). Recent research
conducted by Moreno and colleagues has focused on the efficacy of explanatory feedback as
compared to corrective feedback. Corrective feedback is when it is communicated to the learner
whether they are right or wrong, whereas with explanatory feedback, in addition to learning
whether or not they are correct, the learner is given a domain relevant explanation of why their
answer was correct or incorrect. In the context of computer simulations, these studies indicate that
guidance in the form of embedded explanatory feedback supports retention and transfer more
than corrective feedback alone, particularly for novice learners (Moreno, 2004; Moreno & Mayer,
2005). As described in a previous section, Rieber and his colleagues have investigated the use of
graphical versus textual feedback in computer simulation instruction. The results of these studies
suggest that knowledge gain was greater when participants received graphical compared to
textual embedded feedback (Rieber, 1996; Rieber et al., 1996; Rieber, Tzeng, & Tribble, 2004).
Overall, feedback that is rich in domain information and is easily interpreted seems to be effective in promoting learning from simulations.

**Reflection**

The *reflection principal* states that computer-based learning should provide many opportunities for students to reflect on the process of gaining knowledge (Moreno, 2005; Moreno & Mayer, 2005, 2007). For example, a simulation that prompts a learner to discuss why a particular answer they have provided is correct offers a moment for the learner to reflect on his or her own meaning making and cognitive process. As researched by Moreno and Mayer (2005), reflection can be in the form of elaborative interrogation, in which the learner is asked by a pedagogical agent to provide an explanation for an answer during a problem solving session. In a series of studies, Moreno and Mayer asked college students to explain their answers while using a plant-designing simulation. These results failed to provide uniform support for the notion that reflection, in the form of explanation of learner answers, increases learning outcomes in interactive simulations. A follow-up study suggests that reflection was only effective in increasing retention and transfer scores when students were asked to reflect on correct answers provided by the simulation, rather than on their own answers. A review of the literature failed to reveal additional empirical support for the reflection principle in multimedia learning contexts.

**Additional Principles**

*Worked-out Example Principle*

Another means of guiding learning in exploration-based simulations is through worked-out examples. The *worked-out example principle* states that when learners are asked to study worked-out examples rather than actually solving problems independently there test performance is improved (Kirschner et al., 2006; Renkl, 2005). Worked-out examples are thought to reduce cognitive load, as only the essential relationships, as outlined in the example, are stored in memory for future use (Kirschner et al., 2006). A step-by-step guide to a chemistry problem, with a clear indication of the solution, would be an example of a worked-out example.

Empirical support for the worked-out example effect in traditional pedagogical contexts was established over two decades ago (Sweller, 1987; Sweller & Cooper, 1985), though the evidence for the worked-example effect is less clear in research in multimedia instruction. Tarmizi and Sweller (1988) investigated the efficacy of worked-out examples in a multimedia mathematics exercise with high school students and found that, when worked-examples are tailored to the particular features of the verbal and visual information given, the examples promoted learning. Despite the empirical support for worked-out examples in traditional learning
environ (for a review, see Atkinson, Derry, Renkl, & Wortham, 2000), there is little research focusing on computer-based worked-out examples.

There is research to indicate that learning from simulations may be more effective than learning from computer-based worked-out examples. A comparison of an interactive chemistry simulation with a worked-out example of the same material with 64 high school students (16-18 years old) revealed benefits of the simulations that can be attributed to increased germane load (Plass, Homer, Milne, Jordan, Kim, & Barrientos, 2007). Participants were randomly assigned to either the simulation or the worked-out example and were asked to learn everything they could about the topic, the Ideal Gas Law, which none of the students had studied before. The simulation treatment consisted of the simulation presented in figure 1. The worked-out example presented the content to the learner in a narrated step-by-step walk-through of screen shots from the simulation that was designed to assure that all of the important aspects of the content were covered. Students could control the advance from one segment to the next at their own pace. Results showed significantly higher comprehension scores for the group that received the simulations compared to the group receiving worked-out examples. 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 worked-out examples, where learners had control only over the pacing of the materials.

Darabi, Nelson, and Palanki (2007) investigated worked-out examples embedded within a computer simulation of a chemical processing plant with 67 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 were randomly assigned to receive either process-oriented examples, in which a procedure for analyzing plant malfunctions is 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. It is clear that the role of worked-out examples in computer simulations has yet to be thoroughly investigated.
Task Appropriateness
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 & Bannert, 2003). This finding is consistent with earlier work on transfer-appropriate processing (Morris, Bransford, & Franks, 1977) – the effectiveness of visual representations has to be evaluated based on the performance for which they prepare the learner. Specific visualizations can either have a facilitating, enabling, or inhibiting effect on specific learning processes (Schnotz & Rasch, 2006). 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 & Rasch, 2006). 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, Anglin, & Carney, 1987; Plass, Hamilton, & Wallen, 2004). 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 & Levin, 2002).

The effectiveness of static visuals appears to depend on their relevance to the task presented. Schnotz and Bannert (2003) investigated whether different types of visuals accompanying text improved comprehension. They compared two distinct static visuals regarding time zones around the world. A “carpet” diagram presented the earth as a rectangle, with the left to right dimension representing earlier-later relations in time. A “circle” diagram presented the earth as a circle as seen from the North Pole, with the counter-clockwise rotation used to represent earlier-later relations in time. The assigned tasks focused on questions of either time-difference or circumnavigation. The authors proposed that while the two diagrams are informationally equivalent, each is better suited for one task than for the other. Sixty college students were randomly assigned to a text-only, “carpet” diagram plus text, or “circular” diagram plus text group. The results showed a significant interaction between the type of diagram used and performance on the different tasks. These findings suggest that the inclusion of a static visualization along with text in and of itself may not be sufficient for improved performance. Rather, visualizations need to be task-appropriate in order to improve learning outcomes. Schnotz and Bannert conclude that ill-suited visuals may interfere with the construction of efficient mental
models. From a cognitive load perspective, these results suggest that task-inappropriate visuals may increase extraneous cognitive load.

Research has shown that depending on the learning task, germane cognitive load may be reduced by animating the simulation content (Schnotz & Rasch, 2005). In an extension of previous work, Schnotz and Rasch developed two interactive graphic versions of the “circle” diagram of the earth’s time zones, as described above. Students in the animated graphics group were presented with graphics that could be manipulated, such that the student defined the date and time in a city and the earth moved to match it, or simulated, such that the graphic simulated the earth’s rotation. These two types of interactive animated visuals were used together and compared to static visuals. Cognitive ability and prior knowledge, together considered by the authors as learning prerequisites of the undergraduate participants, were also taken into account. The findings indicate that while students with both high and low learning prerequisites answered time-difference questions significantly better after having used the simulations, the same was not the case with 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. Therefore, the computer simulations reduced the germane cognitive load associated with the mental activity of creating internal models. The authors suggest that while these simulations communicated factual information more effectively than static visuals, overall they increased extraneous load, due to the processing of redundant information, and decreased germane cognitive load, as students did not engage in mental simulation building.

A review of research on functions of pictures in text comprehension suggested that illustrations can be categorized into five types: decorative, representative, organizing, interpreting, and transforming (Carney & Levin, 2002; Levin, Anglin, & Carney, 1987). In a study with 113 participants, we compared the effect of three types of visualizations, representative, organizing, and interpreting, on retention, comprehension, and transfer (Plass, Hamilton, & Wallen, 2004). Learners read a text on how cellular phones work. For one group, the text included visual annotations that were designed to support the selection of relevant information by representing individual concepts, e.g., a cell tower. A second group received visual annotations that were designed to support the organization of the concepts depicted into meaningful mental representations with a coherent structure, for instance, by visualizing relationships or spatial arrangements among different visual elements, e.g., how a cell phone communicates with the cell tower. A third group received visual annotations designed to support
the integration of information by connecting several concepts and ideas, e.g., the cell phone, cell tower, and mobile telephone switching office. Controls did not receive any annotations with the text. Results showed that different types of annotations supported different functions in cognitive processing: Visual annotations designed to represent information were more effective on tests of retention of facts than any other type of annotation. Visual annotations designed to organize or integrate ideas in the text resulted in better comprehension and transfer performance than representational visualizations. These results confirmed findings from a related study that had suggested that different types of annotations can support cognitive functions in the learning process (Wallen, Plass, & Brünken, 2005), and suggest that visuals with functions that are not matched to the learning goals may generate higher extraneous load.

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 fundamentals of cognitive load theory, and the other concerned with more applied questions of the design of animations and simulations for education.

Future Research on Fundamentals of Cognitive Load in Visual Learning

There are a number of lines of research that promise to further our understanding of cognitive load in visual learning. One of these areas is related to the role of visual attention. Neuroscience research has shown that objects compete for representation and processing even at a neuronal level (Desimone & 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 & 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 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 (Grezes, Costes, & Decety, 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 research. 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 visual learning 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 & Koenig, 1992; Ungerleider & 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 & 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. Schnott (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). Schnott 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., 2007). Descriptive, symbolic representations are informationally dense and require a larger amount of prior knowledge to interpret. However, once interpretation of symbolic representations becomes automatized, 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., 2007), 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, Daubman, & Nowicki, 1987; Isen & 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, Song, & Plass, 2007). More research is needed on the role of positive affect on cognitive load and learning.

The research reviewed in this paper point to a few additional issues that warrant future investigation. A pattern of findings has emerged that calls into question the additive nature of cognitive load induced by elements of a visual representation. For textual representations, adding more descriptive information has traditionally been associated with increased mental effort in processing the information. However, for visual representations, adding depictive information may in some cases reduce cognitive load by reducing the need to interpret the descriptive representations of text or making a visual representation easier to interpret. Further research is needed to identify the conditions in which adding visual materials (even redundant materials) results in a reduction of cognitive load. Another issue that emerges is the need for better grounding of cognitive load theory in basic research on brain functions. The concept of the “visual channel” is too vague, with recent neuroscience research on visual perception suggesting that visual cognitive load is more localized in specific functional areas (e.g., the “what” versus “where” pathways). Similarly, the overlap of visual and verbal processing needs further research. A related issue involves the influence of top-down processes on perception. If a learner’s prior knowledge affects how he or she actually perceives a situation, then this suggests that the well known “expertise reversal effect” may also be having an effect at a very basic perceptual level.

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.

Another issue that requires more systematic investigation is the impact of interactivity on cognitive load. Here, again, a typology of levels of interactivity would be helpful in order to conceptualize future research on learners’ control of the materials, manipulation of the educational content, and related system feedback. Although research has provided insights into the effect of different types of interactivity on learning outcomes, the cognitive load implications of different types and levels of interactivity need to be better understood.

A final issue warranting future research is concerned with the design of multiple simulations or animations. 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 & Joolingen, 1998; Rieber & Parmley, 1995; Rieber, 2005). This finding mirrors research by Renkl, Atkinson, Maier, & Staley (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.

In summary, our review of the literature presented in this paper indicates that research on cognitive load in visual learning needs more attention in two different directions, one connecting cognitive load research to neuroscience research to provide a stronger theoretical foundation, and the other connecting cognitive load research to design research that takes a more sophisticated view of the complexity, diversity, and types of animations and simulations, thus making it more practically applicable.

References


Figures

Figure 1. Simulation of the Ideal Gas Law (CREATE, 2006)