When can animation improve learning? Some implications for human computer interaction and learning

John Black
Columbia University

When can animation improve learning? Some implications for human computer interaction and learning

Margaret S. Chan **John B. Black**

Department of Human Development
Teachers College, Columbia University
chan@tc.columbia.edu black@tc.columbia.edu

Abstract

For decades, research comparing the effectiveness of text and static illustrations with animation and narration to enhance learning has been inconclusive (Tversky et al., 2002). We argue that the failure to ascertain the benefits of animation in learning may relate to the way it is constructed, perceived, and conceptualized. Based on cognitive science and human learning theories, this paper proposes a *format-support hypothesis* of learning with various presentation formats. To validate this hypothesis, we implemented a special form of animation, direct-manipulation animation. An empirical study was conducted to evaluate the efficacy of static visuals and dynamic animation on comprehension and transfer. Results corroborated our hypothesis; the direct-manipulation animation group significantly outperformed the system-controlled animation group on written recall and system drawing. The static-visual group outperformed its counterparts on system drawing. From these findings, we recommend some design principles of computer-based animation to enhance HCI and foster effective learning.

Introduction

For decades, research comparing the effectiveness of text and static illustrations with animation and narration to enhance learning about systems and dynamic processes has been inconclusive (ChanLin, 1998; Hays, 1996; Mayer & Anderson, 1991; Pane et al., 1996; Park, 1998; Park & Gittelman, 1992; Rieber, 1989; Rieber & Hannafin, 1998). Interestingly, Tversky et al. (2002) pointed out that while some studies found that animation appeared superior to static visuals in enhancing learning and transfer, a careful examination of these studies revealed a lack of equivalence between animated and static graphics in content as well as differences in experimental procedures. In addition to methodological complications and information non-equivalence, we argue that the failure to ascertain the benefits of animation in learning may also relate to the way it is constructed, perceived, and conceptualized.

Drawing from research on human information-processing and working memory (Baddeley, 1986; Chandler & Sweller, 1996; Mayer, 2001; Miller, 1956; Simon, 1974), we propose a *format-support hypothesis* of learning with various presentation formats. Anchored in the literature of mental model construction and human-computer interaction (HCI) (Carroll, 2003; de Kleer & Brown, 1983; Gentner & Steven, 1983; Kieras et al., 2001; Shneiderman, 2004), our research implemented a special form of animation, *direct-manipulation animation* (DMA), to validate the hypothesis. Specifically, the format-support hypothesis posits that comprehension and learning will be enhanced if the presentation format supports what the learners need to construct a dynamic mental model of the referent phenomenon. Further, we conducted an empirical study with 32 seventh-graders on their learning of a fundamental physics concept−energy conversion−to evaluate the efficacy of static visuals, system-controlled animation, and direct-manipulation animation on comprehension, memory recall, and transfer. Finally, based on the findings of this study, we present some implications for learning and human-computer interaction, particularly regarding the integration of computer-based animation to foster effective learning.

Educational potentials and affective appeal of animation

According to Betrancourt and Tversky (2000), animation refers to "any application which generates a series of frames, so that each frame appears as an alteration of the previous one, and where the sequence of frames is determined by the designer or the user" (p. 312). One advantage of this presentation format over text and static visuals is its ability to represent change in time and to present information about change over time (Rieber, 1990; Tversky et al., 2002). A pervasive assumption appears to be that animation benefits learning. Furthermore, a series of empirical studies demonstrated that animation provides several instructional roles: attracting and directing attention; representing domain knowledge about movement; and explaining complex knowledge phenomena (Park, 1998; Park & Gittelman, 1992; Rieber, 1990).

Problems with animation

Despite the abovementioned promising benefits of animation on learning, a considerable number of studies revealed that there was no statistically significant difference between animation and static illustrations in promoting conceptual understanding (ChanLin, 1998; Pane et al., 1996; Rieber, 1989; Rieber & Hannafin, 1998). Limited working memory capacity and learners' prior domain-specific knowledge may account for such findings. Information to be learned has to be processed first through working memory, which is a cognitive structure that is very limited in both its capacity and duration (Baddeley, 1986; Miller, 1956; Simon, 1974). Although animation uses motion to depict motion and temporal changes, it may be too complex or fast to be perceived accurately. In fact, Sweller and colleagues (1996) pointed out that if a high level of interactivity among the entities is depicted in instructional materials (static and dynamic), the learners' working memory may be overloaded; consequently, they may have difficulty perceiving and understanding the learning content.

Moreover, learners' prior domain-specific knowledge may influence the effectiveness of animation in comprehension and learning. In a series of experiments with novices interpreting dynamic weather maps, Lowe (2003) found that learners who dealt with unfamiliar material tended to selectively attend to perceptually attractive changes in the animated display rather than to changes that were crucial to understanding the content.

The limitation of animation in promoting effective learning may relate not only to how animation is perceived and conceptualized, but also to how it is constructed. Kaiser et al. (1992) asserted that although animation may be explicit, "our perceptual appreciations do not spontaneously form the basis of our conceptual understanding of dynamics" (p. 686). In summary, to develop effective animation that promotes learning, we need to consider individuals' internal visualization processes and their mental model development; i.e., the learners' limited working memory capacity; the perceptual and cognitive demands that animation may impose on them, especially novices; and the support learners may need to perceive and understand the visible as well as the "hidden" functional relationships among components within complex systems.

Format-support hypothesis and direct-manipulation animation

Based on our understanding of the capacity limitations of the human working memory, as well as the processes involved in the way individuals comprehend information (static and animated), we propose a *format-support hypothesi*s of learning with various presentation formats. At the core of the hypothesis lies the constructivist nature of understanding. Specifically, the hypothesis posits that a good match between presentation format and what learners need to construct a dynamic conceptual understanding of the target phenomenon will promote comprehension and learning. The closer the match between presentation format (e.g., direct-manipulation animation, as presented in this paper) and the key features of the phenomenon (e.g., the fundamental functional relations in a dynamic system), the better the format will assist learners in developing robust mental models of the subject matter. In other words, the effectiveness of a presentation format is related to the extent to which it complements the learners' cognitive and comprehension processes. The format-support hypothesis applies to both static graphics and animated depictions.

Furthermore, as Mayer (2001) asserted, meaningful multimedia learning requires learners' active processing of the instructional material; merely showing animation to learners may not be sufficient to aid their learning. Moreover, the dynamic and temporal aspects of multiple elements in system-controlled animation may impose additional perceptual and cognitive processing demands on learners as they attempt to perceive and comprehend the animated content (Lowe, 2003). To overcome or mitigate the perceptual and cognitive demands that animation imposes on learners, we developed a special form of animation, which we call *direct-manipulation animation (DMA).* DMA allows learners to directly interact with navigation controls (i.e., buttons and sliders), freely determine their viewing direction (Chan & Black, 2005). With direct-manipulation animation, learners' interactions with the interface are rapid, incremental, and reversible, with results being immediately visible.

In the present empirical study, the learners freely navigated the journey of a roller coaster ride and simultaneously visualized the dynamic interchange between potential energy, kinetic energy, and total energy during the thrill ride by clicking on buttons or dragging sliders on the screen. In constructing this study, we envisioned that the learners might construct their reasoning process and develop an understanding of energy conversion by actively navigating the coaster ride forward and backward, e.g., the coaster cars' potential energy builds to its maximum as the cars climb up the first hill, which is a crucial process to insure that sufficient total energy is generated for the cars to complete the entire journey. Another advantage of reversible actions is that they encourage exploration because they diminish the fear of making a mistake. In fact, direct-manipulation interfaces are thought to minimize the "gulf of evaluation" in which the user must interpret the display, and the "gulf of execution" in which the user must determine how to act on the system (Norman, 1988). The learners can easily understand the system state revealed on the display and determine how to act on the system to achieve the desired results.

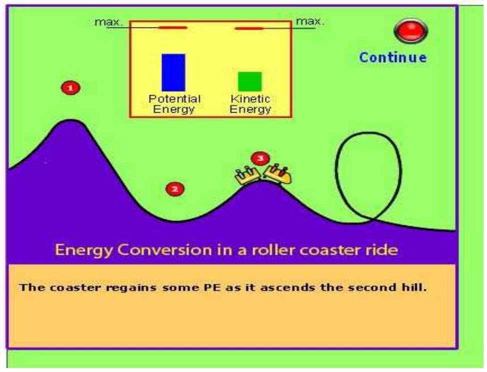

Figure 1. Screen shot of the direct-manipulation animation – "Energy in Action"

Major research questions

According to the mental animation theory (Hegarty, Kriz, & Cate, 2003), students provided with a series of still frames need to mentally animate the changes that occur from frame to frame to understand how a mechanical system works. Their mental animation thus leads to deeper processing and better learning. The format-support hypothesis builds on the mental animation theory and posits that comprehension and learning will be enhanced if a good match is made between the presentational format (static and dynamic) and what the learners need to construct a dynamic mental model of the system. Animation uses motion to convey motion and change in processes; thus, it appears to be an appropriate medium to illustrate the functional relations of dynamic systems (i.e., vividly animate the effect of a change in a parameter on the state of other parameters and their interactions). Further, direct-manipulation animation affords users to interact actively with the animated display; thus, it may serve as a good support to help learners construct dynamic mental models of interactive physical processes (e.g., how energy conversion works). The format-support hypothesis predicts that the presentation format (in this case, direct-manipulation animation compared to static visuals and system-controlled animation) that best matches learners' cognitive and comprehension processes during learning will lead to better comprehension, more robust mental model construction, and possibly improved transfer.

The two major research questions were:

- What are the effects of static visuals and dynamic animation in fostering students' learning of dynamic physical processes?
- What are the effects of system-controlled animation and direct-manipulation animation on students' comprehension of dynamic physical processes?

Empirical studies

Method

Thirty-two seventh-grade students from a science class at one urban public school in New York City volunteered to participate in the study. Using a three-group experimental post-test design, the study was a between-subjects comparison. The presentation format (static visuals, system-controlled animation, and direct-manipulation animation) was the independent variable. "Energy conversion and the law of conservation of energy" was selected as the research topic because the invisible and dynamic phenomena which comprise the law pose considerable barriers to understanding (Feltovich et al., 1992). Three dependent measures (written recall, system drawing, and problem-solving tasks) were used to assess how the participants learned about this dynamic physical system (energy conversion in a roller coaster ride).

Procedures

First, all participants individually completed surveys on their knowledge of the topic. Second, all participants were given 15 minutes to read a 600-word summary describing how energy is transferred during a roller coaster ride. Third, participants were randomly assigned to one of three treatment conditions: static visuals (SV; control), system-controlled animation (SCA), and direct-manipulation animation (DMA). The time allowed for all participants to view the visuals or interact with the animation was 5 minutes. Each participant in the SV group viewed a sequence of seven static snapshots representing the critical steps in energy conversion during a roller coaster ride. Each participant in the two animation groups was seated at an IBM ThinkPad, on which they viewed or interacted with a computer animation depicting how energy is converted during a roller coaster ride. Each participant in the SCA group viewed the animation, which illustrated the energy conversion processes in continuous motion. And each participant in the DMA group used a direct-manipulation version of the animation to explore the topic. Finally, all participants were asked to write a summary of energy conversion during a roller coaster ride (Written Recall – 5 minutes). Then, they drew diagrams to illustrate the energy conversion processes (System Drawing – 5 minutes). Finally, they were given three problem-solving tasks on flawed roller coaster designs (problem-solving – 6 minutes).

Results and Findings

The written recall was scored by tallying the number of correct idea units. The system drawing was scored by counting the number of pertinent phases of energy conversion depicted. The problem-solving tasks were scored by tallying the number of correct answers across the three problem-solving tasks. Two graduate students rated the results independently, and an inter-rater reliability score of .878 was achieved.

Table 1 shows the mean scores and standard deviations of the written-recall, system-drawing, and problem-solving tasks for each group. Based on independent *t-tests*, the direct-manipulation animation group significantly outperformed the system-controlled animation group on written-recall ($t(30)=2.05$, $p < .05$) and system-drawing ($t(30)=1.76$, $p < .05$). The static visuals group (M=6.07, SD=1.16) significantly outperformed the system-controlled animation (M=3.30, SD=1.15) and direct-manipulation group (M=4.63, SD=1.89) on system drawing, $F(1, 38) =1.561$, MSE=4.230, p =.045. Overall, the effect sizes − favoring the static visuals and direct-manipulation groups − were .38, .11, .58, respectively.

Table 1: Mean scores and standard deviations for each group on the written recall, system drawing, and problem-solving tasks

Group	Written recall		System drawing		Problem solving	
	M	SD	M	SD	M	SD
Static visuals	6.84	2.08	6.07**	1.16	4.33	1.88
System-controlled animation	4.32	2.00	3.30	1.15	3.85	2.13
Direct-manipulation animation	7.40*	2.06	4.63*	1.89	4.51	1.36

* The direct-manipulation group scored significantly better than the system-controlled animation group at p < .05, based on a t-test.
** The static visuals group scored significantly better than the system-controlled animation and the directed-manipulation groups at p <.05, based on an ANOVA.

The findings corroborated the format-support hypothesis and point to the potential of direct-manipulation animation in supporting learners in their efforts to develop dynamic mental models of the target phenomenon. The participants in the static visuals and direct-manipulation animation groups were able to recall more pertinent idea units and depict more relevant phases in their drawings than those in the system-controlled animation groups. This suggests the importance of allocating sufficient time for learners to process the information and parsing salient thematic information for comprehension and mental model construction. Furthermore, the performance of the static visuals group converges with the mental animation theory (Hegarty et al., 2003) in showing that learners who mentally animated the dynamic processes achieved a solid understanding of the content material. Regarding possible transfer, the results pointed to the expected direction; participants in the direct-manipulation animation group performed better than their counterparts. However, the three groups did not demonstrate any significant difference in their performance on problem-solving tasks. A possible explanation for this result is that the tasks might have been too easy for the participants. A follow-up study is planned to further investigate the effect of various presentation formats on transfer.

Implications for education and HCI design

Designing educationally effective presentations (static and animated) is a challenging task. Based on the findings of the empirical study, we recommend the following design principles of computer-based animation to foster effective learning and enhance human computer interaction.

Direct-manipulation offers a competitive edge to effective animation design. The consistently better performance of the participants in the direct-manipulation animation (DMA) group, compared with those in the system-controlled animation (SCA) group in memory recall, system drawing, and problem-solving, suggested that allowing learners to freely navigate the roller coaster ride forward and backward gave them an opportunity to connect the animated visual representation with the system dynamics. DMA supports the learners in actively controlling their viewing sequence in micro-steps so they can visualize how a change in a parameter affects other parameters in dynamic systems, e.g., by dragging the sliders to move the coaster cars back and forth, the learners may construct a conceptual understanding of the interrelationships between gravity and energy exchange, specifically while the cars are ascending and descending the loop-the-loop. In summary, the findings suggest that the effect of computer-based animation on learning could be improved or optimized if careful consideration is given to providing the support that learners may need to construct a robust conceptual understanding of the dynamics of target systems.

Decisions about using static graphics or animated displays to aid the learning process should be based on pedagogical rationales rather than technological possibilities or competence. Interestingly, in our study, the static visuals (SV) group outperformed its counterparts in the system drawing task. A plausible explanation for the result is the consistency between the information encoding format and this drawing task for the SV group. Specifically, the participants in the SV group used a series of static visuals to understand the energy conversion process, and one dependent measure was drawing diagram(s) to illustrate how the system works. Hence, not surprisingly, the participants in the SV group outperformed those in other groups on this task. This finding may serve as yet another indicator of the format-support hypothesis of learning − the static visual aspect. Undoubtedly, each presentation format has its strength in promoting comprehension. Creating animation can be time-consuming and labor-intensive. Thus, before enthusiastically launching into full-scale implementation, educators and instructional designers may find it both rewarding and helpful to ask, “Which presentation format, static or animated, will best support learners to comprehend the subject matter?”

Compared to the other two conditions, the SCA group performed poorly in memory recall, system drawing, and problem-solving. The perceptual and cognitive processing demands that system-controlled animation imposes on learners may account for such an inferior performance. Furthermore, the differential performance between the DMA and SCA groups suggests that while the animation does increase perceptually available information and possibly reduce cognitive processing, it may not automatically facilitate conceptual understanding. The importance of cognitive effort in learning should not be underestimated. In summary, for effective learning to occur with animation, learners need to have sufficient time and mental resources to perceive and comprehend the functional relationships among various components in the systems.

Finally, user-centered design could play a conducive role in constructing effective instructional animation. For instance, the location of buttons, switches, and sliders should be consistent to minimize unnecessary perceptual and cognitive demands on learners. Moreover, it would be desirable to provide alternative interaction methods in animation to accommodate different navigation styles or learning preferences (Chan et al., 2002; Shneiderman, 2004). For example, in the direct-manipulation animation used in the study, users navigated the content freely by dragging the slider forward and backward, or by clicking on the arrows at both ends of the sliders to advance the path incrementally. They can also accomplish the same task by using the keyboard’s arrow keys.

In conclusion, animation is an instructional tool. As with any tool, its appropriate use leads to desirable results. Our empirical study showed that direct-manipulation animation is more effective than static visuals and system-controlled animation in enabling learners to connect visual representation with system dynamics in their process of apprehending the functional relations of a dynamic system. This appropriate match between the presentation format and the assistance given to the learners in their knowledge construction process works to foster learning and mental model construction (i.e., the format-support hypothesis of learning).

References

Baddeley, A. D. (1986). *Working memory.* Oxford, England: Oxford University Press.

Black, J. B. (1992). *Types of Knowledge Representation* (CCT Report No. 92-3). New York: Teachers College, Columbia University.

Black, J. B. (2002). Cognitive design of educational technology. New York: Teachers College, Columbia University.

Carroll, J. (Eds.) (2003). HCI Models, Theories, and Frameworks: Toward a Multidisciplinary Science. San Francisco, CA: Morgan Kaufmann

Chan, M., Podlaseck, M., Alvarado, N., Schonberg, E., Hoch, R., Sprargen, S., & Riechen, D. (2002) A personalized navigation tool for online listening and free browsing: The Glass Engine, *World Conference on Educational Multimedia, Hypermedia and Telecommunications*, Vol. 2002, Issue. 1, 2002, 263-264

Chan, M. & Black, B. J. (2005) Effect of presentation mode and visualization type on understanding dynamic physical processes, Paper presented at *American Educational Research Association annual meeting*, Montreal, Canada, April 2005.

Chandler, P. & Sweller, J. (1996). Cognitive load while learning to use a computer program. *Applied Cognitive Psychology,* 10, 151-170.

ChanLin, L. J. (1998). Animation to teach students of different knowledge levels. *Journal of Instructional Psychology,* 25, 166-175.

de Kleer, J., & Brown, J. S. (1984). A qualitative physics based on confluences. *Artificial Intelligence*, *24*, 7-83.

Feltovich, P. J., Coulson, R. L., Spiro, R. J., & Dawson-Saunders, B. K. (1992). Knowledge application and transfer for complex tasks in ill-structured domains: Implications for instruction and testing in biomedicine. In D. Evans & V. Patel (Eds.), *Advanced models of cognition for medical training and practice*, (pp. 213-244). Berlin: Springer-Verlag.

Gentner, D., & Steven, A. (Eds.) (1983). Mental models. Hillsdale, NJ: Lawrence Erlbaum Associates.

Hegarty, M. (1992). Mental animation: inferring motion from static diagrams of mechanical systems. *Journal of Experimental Psychology: Learning, Memory & Cognition,* 18, 1084-1102.

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

Kieras, D., Meyer, D. & Ballas, J. (2001) Towards demystification of Direct manipulation: cognitive modeling charts the gulf of execution. SIGCHI' 01, ACM, Seattle.

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

Lowe, R. K. (1993). Constructing a mental representation from an abstract technical diagram. *Learning and Instruction,* 3, 157-179.

Mayer, R. E. (1989). Systematic thinking fostered by illustrations in scientific text. *Journal of Educational Psychology,* 81, 240-246.

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

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

Mayer, R. E., & Anderson, R. B. (1992). The instructive animation: Helping students build connections between words and pictures in multimedia learning. *Journal of Educational Psychology,* 84, 444-452.

Miller, G. A. (1956). The magical number seven plus or minus two: Some limits on our capacity for processing information. *Psychological Review,* 63, 81-97.

Morrison , J. B., Tversky, B., & Betrancourt, M. (2000). *Animation: Does it facilitate learning?* In Smart Graphics: Papers from the 2000 AAAI Symposium, pp. 53-60.

Norman, D. A. (1988). *The Design of Everyday Things***.** New York: Basic Books, Inc.

Pane, J. F., Corbett, A. T., & John, B. E. (1996). *Assessing dynamics in computer-based instruction.* In M. J. Tauber (Ed.), Proceedings of the ACM Conference on Human Factors in Computing Systems (pp. 797-804), Vancouver: ACM.

Park, O. (1998). Visual Displays and Contextual Presentations in Computer Based Instruction. *Educational Technology Research & Development,* 46 (3), pp. 18-32.

Park, O. C., & Gittelman, S. S. (1992). Selective use of animation and feedback in computer-based instruction. *Educational Technology, Research, and Development,* 40 (4), 27-38.

Rieber, L. P. (1989). The effects of computer animated elaboration strategies and practice on factual and application learning in an elementary science lesson. *Journal of Educational Computing Research*, 5 (4), 431-444.

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

Rieber, L. P. & Hannafin, M. J. (1988). Effects of textual and animated orienting activities and practice on learning from computer-based instruction. *Computers in the Schools*, 5, 77-89.

Shneiderman, B. (2003) *Designing the user interface: strategies for effective human computer interaction*. 4th ed. Reading, Massachusetts: Addison-Wesley Publishing Company, Inc.

Simon, H. (1974). How big is a chunk? *Science,* 183, 482-488.

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