Computers & Education 53 (2009) 667–676

Contents lists available at ScienceDirect

Computers & Education

journal homepage: www.elsevier.com/locate/compedu

Haptic feedback and students' learning about levers: Unraveling the effect of simulated touch

Eric. N. Wiebe [a,*], James Minogue [b], M. Gail Jones [a], Jennifer Cowley [c], Denise Krebs [a]

[a] Department of Mathematics, Science and Technology Education, North Carolina State University, Box 7801 – Poe 510M Raleigh, NC, USA
[b] Department of Elementary Education, North Carolina State University, Raleigh, NC, USA
[c] Department of Psychology, North Carolina State University, Raleigh, NC, USA

ARTICLE INFO

Article history:
Received 12 September 2008
Received in revised form 28 March 2009
Accepted 5 April 2009

Keywords:
Elementary education
Human-computer interface
Interactive learning environments
Multimedia/hypermedia systems
Virtual reality

ABSTRACT

While there has been extensive experimental research on haptics, less has been conducted on cross-modal interactions between visual and haptic perception and even less still on cross-modal applications in instructional settings. This study looks at a simulation on the principles of levers using both visual and haptic feedback: one group received visual and haptic feedback while the other just visual feedback. Using the triangulation of learning scores, eye tracking data, and video analysis of interaction with the levers, the efficacy of haptic feedback to improve learning was explored. The results indicate that while the total fixation time on the levers and numeric readout was greater for the visual and haptic group, very similar patterns of visual attention were seen between groups. Perhaps surprisingly, the visual only group scored higher on an embedded assessment. Explanations for these results are synthesized from theories of cross-modal perception and cognitive architecture.

1. Introduction

Despite ever increasing interest in the creation and use of computer-based instructional programs (e.g. interactive simulations, virtual labs, digital learning environments) for the teaching of school science concepts (Hennessy et al., 2007), the extent to which these technologies impact students' understandings is still unclear. While numerous studies (e.g. Bransford, Brown, & Cocking, 2000; Doerr, 1997; Linn, 2003; Winn, 2002; Zacharia, 2003) point to potentially positive impacts, other work (e.g. Bayraktar, 2002; de Jong & van Joolingen, 1998; Hsu & Thomas, 2002; Steinberg, 2000) suggests a rather tenuous link between the use of these technologies and learning gains.

Proponents of computer-based simulations note that these virtual environments allow students to make comparisons between elements of a system and witness the outcomes much as you would with their physical counterparts (Linn, 2004). In addition, students may also be able to explore relationships in simulations not feasible in the physical realm because of limits of time, space, cost, or safety. It is likely that the efficacy of this experience will be determined in part by how effectively key information about the phenomena can be communicated to the student, mediated by the computer-based system. Improvements in computer-based graphics have meant that very rich, high-resolution color graphics can be communicated visually to the student through most computer systems. Similarly, improvement in audio technology now means that most auditory-based information can also be communicated at high fidelity. While these two modalities cover much of the sensory information instructional designers might want to communicate to learners, it does not cover the full sensory range of what could be communicated nor does it address the general limitations in how learners communicate back to the simulation environment.

Along these lines, evolving technologies now make it possible to extend students' interactions with these computer-based learning environments beyond the audio and visual realm to include haptic (i.e., simulated touch) feedback (Burdea, 1996; Kátai, Juhász, & Adorjáni, 2008; Revesz, 1950; Robles-De-La-Torre, 2006). Haptic feedback devices provide a whole new modality of experience that can be tied directly to user input devices, more tightly binding the user experience directly to the simulated environment. Haptically augmented multimodal interfaces can be programmed to provide realistic force feedback (e.g. simulating object compliance, weight, and inertia) and/or tactile feedback (e.g. simulating surface contact geometry, smoothness, slippage, and temperature) by employing physical receptors in

* Corresponding author. Tel.: +1 919 515 1753; fax: +1 919 515 6892.
E-mail address: eric_wiebe@ncsu.edu (E.N. Wiebe).

0360-1315/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compedu.2009.04.004

the hand and arm that gather sensory information as users ''feel'' and manipulate two and three-dimensional virtual objects and events (Jacobson, Kitchen & Golledge, 2002; Jones, Minogue, Tretter, Negishi, & Taylor, 2006; Minogue, & Jones, 2006).

With haptic devices, such as the one seen in Fig. 1, not only can the simulation communicate haptic information about the phenomenal response to the learner, but also provide a more robust feedback mechanism as the learner interacts with the system. This point-probe device tracks the *x*, *y*, and *z* coordinates, as well as the pitch, roll, and yaw of the virtual point-probe that the user moves about a 3D workspace. Actuators (motors within the device) communicate preprogrammed forces back to the user's fingertips and arm as it detects collisions with the virtual objects on the screen, simulating the sense of touch. While potentially a breakthrough technology for instructional simulation environments, there is a paucity of research to guide instructional designers. This paper will explore the efficacy of a haptically augmented simulation environment for use in middle school science education, capitalizing on eye tracking data to help unravel the influence of simulated touch on student cognition.

2. Impetus for the study

An appropriate area of science education to employ haptic interfaces may be simulations that require the learner to both apply and respond to force feedback from a system. In upper elementary and middle school science, the study of levers is a common topic where students typically interact with constructed lever systems via the direct application of force with their hands and similarly receive feedback through the same pathway. It would, therefore, seem logical that the inclusion of haptic feedback in a computer-based lever simulation would enhance its positive impact as a learning tool. But despite the surface logic of the positive benefits of this application of haptics technology in science education, existing research literature does not provide a clear answer to its efficacy.

2.1. Haptics in science education

Despite a voluminous and relatively robust literature base from the fields of developmental and cognitive psychology regarding underlying principles and processes of the haptic perception and cognition (e.g. Heller, 1991; Klatzky & Lederman, 2002; Loomis & Lederman, 1986) very little is actually known about the educational impact of haptic technology. This is due largely in part to the fact there are only a handful of studies (e.g., Florence, Gentaz, Pascale, & Sprenger-Charolles, 2004; Jones, Andre, Superfine, & Taylor, 2003; Jones et al., 2006; Minogue, & Jones, 2006; Reiner, 1999; Williams, Chen, & Seaton, 2003) that have examined the use of haptic interfaces within the context of teaching and learning science concepts. One such study examined the influence of haptic feedback on middle and high school students' concepts of small objects such as viruses (Jones et al., 2003). In this exploratory study, students used a *nanoManipulator* (which combines an atomic force microscope (AFM) with software, a desktop computer, and a haptic desktop device) and received tactile and kinesthetic feedback from 3-D AFM images of viruses. Using this interface, students were able to push, cut and poke an actual virus and feel the interaction between this virus and the probing tip of an AFM. The results of the study showed a positive affective impact in that students who received haptic feedback reported being more interested in and feeling as if they could participate more fully in the experience.

Building on this, additional work (Jones et al., 2006) was done to investigate the impact of different types of feedback devices (a sophisticated haptic desktop device, a haptic gaming joystick, and a mouse with no haptic feedback) combined with computer visualizations viruses and nanoscale science influenced middle and high school students' experiences. Results suggested that the addition of haptic feedback from the haptic-gaming joystick and the PHANToM (SensAble Technologies, n.d.) (Fig. 1) provided a more immersive learning environment that not only made the instruction more engaging but may also influence the way in which the students construct their understandings about abstract science concepts as evidenced by an increased number of spontaneously generated analogies that appeared during student discourse.

Reiner (1999) examined the role of tactile perception in the conceptual construction of forces and fields by employing a modified trackball that transferred a simulated force applied by a field to the learner's hand. Through the qualitative analysis of graduate student drawings she presented ''embodied experiences'' as a way to explain the positive educational impact of haptics. That is to say, this learning environment stirs up tacit embodied knowledge, previously unexploited non-propositional knowledge. This type of knowledge is in immediate (without the mediation of symbols and concepts) relation to objects and bodily acts. She goes on to suggest that haptic devices are interfaces that promote the use of bodily non-propositional knowledge in the building of more accurate mental models and representations.

Additionally, researchers have developed and pilot-tested a series of haptically augmented software programs for teaching elementary school students simple-machine concepts (Williams et al., 2003). Although the researchers noted that the findings of this study are not the

Fig. 1. The PHANToM® Omni ™ desktop device from SensAble Technologies, Inc.