# Chapter 6
# The Efficacy of Visuohaptic Simulations in Teaching Concepts of Thermal Energy, Pressure, and Random Motion

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## 6.1 Introduction

The abstract topics of heat and pressure have been shown to be difficult to teach and learn and are often embedded in naïve conceptions (Harrison et al. 1999; Clough and Driver 1985; Erickson 1979; Erickson and Tiberghien 1985; Tiberghien 1985). Students often mix ideas of heat and temperature and struggle with concepts of heat gain and loss as well as how heat relates to phase changes (Harrison and Treagust 1996; Lee et al. 1993). Other studies have shown that students have difficulty understanding atomic and molecular particles, particle motion, and the relationship of particle motion to heat and pressure (Kesidou and Duit 1993). Like heat, pressure is also a poorly understood topic that students struggle to understand (Shepardson and Moje 1994). Furthermore, students have difficulty conceptualizing the relationship between pressure and thermal motion and how particle motion relates the two (Shepardson and Moje 1994).

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Inherent in understanding applications of particle motion such as diffusion, Brownian motion, phase changes, and molecular self-assembly is the idea of random movement (Garvin-Doxas and Klymkosky 2008). Randomness is a particularly difficult concept to teach and appears to conflict with our innate desire to find order in our world (Batanero et al. 1998; Sun and Wang 2010). Children and adults often believe that there are nearly always drivers or blueprints that control and direct events that have been identified as random such as a coin toss or a lottery (Garvin-Doxas and Klymkosky 2008; Paparistodemou and Noss 2004). Pratt (1998) has termed these as "unreliable intuitions" (p. 2). Even though understanding randomness is difficult for students, it is essential if students are to gain accurate and fundamental concepts of atomic and molecular motion and associated applications in biological and physical systems. In this study we examine the impact of visuohaptic technology as a tool to teach students about thermal energy, pressure, and random motion. Haptic technology creates a sense of touch for the student using forces and vibrations that allow the user to interact with a virtual world through a stylus or joystick. The term visuohaptics is used in this paper to denote instructional tools that utilize vision and haptic perceptual information.

## 6.2 Theoretical Framework: Touch and Embodied Cognition

Interest in the relationships of perceptual/motor experiences (such as touch) and cognition has grown in recent years as new technologies have emerged. This area of research, known as embodied cognition, rests on a theoretical framework that argues that mental constructs are built from and on sensory motor experiences. This idea that our experiences moving through and manipulating the physical world contribute to our understandings of our environment makes sense. But taken further, the argument maintains that our cognitive architecture rests on these sensory motor experiences. Wilson (2002) suggested that:

> (t)here is a growing commitment to the idea that the mind must be understood in the context of its relationship to a physical body that interacts with the world. It is argued that we have evolved from creatures whose neural resources were devoted primarily to perceptual and motoric processing, and whose cognitive activity consisted largely of immediate, on-line interaction with the environment. Hence human cognition, rather than being centralized, abstract, and sharply distinct from peripheral input and output modules, may instead have deep roots in sensorimotor processing (p. 625).

According to the theory of embodied cognition, higher-order and meaningful thought is a product of neural circuits that are representative of sensory motor activity and characterize embodied experience (Anderson 2007; Lakoff 2012). Wilson (2002) maintains that mental structures that were originally developed in response to physical action are decoupled from the original use, are co-opted, and are used for thinking and knowing.

### *6.2.1 Haptics: Embodied Technology for Science Instruction*

Haptic technology researchers have long maintained that touch is a primary sensory channel and as such is an effective tool for learning an array of topics. Haptic joysticks and other force feedback tools extend the sensory motor perception beyond the hand into the environment. This extension of hand to tool is viewed as a way of connecting the environment, the sensory motor activity, and the mind. For example, Merleau-Ponty (1962/1945) pointed out that even a simple haptic tool like the cane used by an individual with visual impairment serves as an extension of the hand allowing for the perception of textures and objects at the end of the cane. The person with the cane feels objects not in the hand but instead in the cane as an extension of the body (Anderson 2007). Haptic technologies replicate this hand-tool perceptual relationship with virtual and simulated environments by allowing users to touch and feel objects in virtual worlds.

Although research has verified that interactive simulations can be engaging and may promote the learning of science concepts (e.g., de Jong and Njoo 1992; Finkelstein et al. 2005; Hsu and Thomas 2002; Huppert and Lazarowitz 2002; Stull et al. 2011; Tao and Gunstone 1999; Zacharia 2003, 2005; Zacharia and Anderson 2003), there are limited educational studies available to inform educators about the best uses and most appropriate contexts for haptic simulations. There is an almost intuitive belief that in educational settings being able to touch and manipulate objects results in better understandings of concepts and phenomena. Hands-on science experiences are often described as being powerful ways to engage students in learning. However, when the meaning of hands-on is unpacked, it is not immediately clear which elements of the experience are essential to promote learning. Is it the tactile and embodied information that makes hands-on experiences meaningful (de Koning and Tabbers 2011)? Or, is the process of active investigation paired with hands-on experiences makes touch so effective (Loomis and Lederman 1986; Lederman and Klatzky 1987)?

At a fundamental level we know humans explore the world around them with touch and develop concepts of properties through tactile feedback from infancy (Piaget and Inhelder 1967). Furthermore, individuals use tactile sensations to learn about shape, volume, temperature, hardness, texture, weight, and contour (Lederman and Klatzky 1987). These are all critical properties of materials and are used in exploring and investigating science. But is it necessary to touch materials, or is it enough to use vision when learning about properties of materials? There is evidence that vision dominates our senses as the primary mode of learning (Sathian et al. 1997). But it isn't clear how, or if, haptic feedback provided in addition to visual perceptual information enhances learning. Klatzky et al. (1991) have argued that perhaps vision alone will suffice if the task can be accomplished with only visual feedback.

Of the few studies that exist that compare visual and haptic feedback, there are mixed results on whether the addition of haptic feedback to simulations makes a difference in learning. Studies by Jones et al. (2006) and Minogue and Jones (2009) reported that groups that received visuohaptic treatments scored significantly higher on post-assessments than visual-only groups for using haptic technology to learn about viruses. The results of the study by Jones et al. (2006) found that the attitudes of students using the software program with a haptic device were significantly higher than students that just solely used the computer software with visual images but no haptic feedback.

The link between embodied cognition (such as haptic experiences) and positive affect has been reported as a fundamental component of learning (Lee and Schwarz 2012). Evidence of this embodied experience and affect can be found in metaphorical language such as interactions that make your "blood boil," or "something smelling fishy," or being "numb" after a frightening experience (Lakoff and Johnson 1999: Lee and Schwarz 2012). Although physical reactions to emotional experiences have been well documented, research on the role of embodied thought as a cognitive tool with associated emotional components has been less well developed.

The study by Minogue and Jones (2009) suggested that "haptic augmentation of computer-based science instruction may lead to a deeper level of processing" (p. 1359). Other researchers have also reported that haptic feedback can improve learning. Schönborn et al. (2011) conducted a study of biomolecular binding and reported that the visual-haptic group was able to produce tighter fits between molecules during a simulation and had higher learning gains. Schönborn et al. stated, "[students] experiencing a coordinated visual and tactile representation of biomolecular binding could have a potentially deep-seated influence on students' construction of knowledge concerning submicroscopic phenomena" (Schönborn et al. 2011, p. 2096).

Not all research has found that haptic investigations make a meaningful difference in learning. Minogue et al. (2006) investigated the use of haptic feedback on middle school students' concepts of cell morphology and reported that the visuohaptic feedback group was not statistically different in learning gains than the visual feedback group. Harris et al. (2009) examined the impact of haptic feedback on postsecondary students' understandings of protein structure and function and found that there were no significant differences in the haptic- and visual-only groups. Wiebe et al. (2009) took a different approach to examining visuohaptic technology and measured both learning gains and eye tracking with a group of middle school students learning about virtual levers. These researchers found the visuohaptic group did not outperform the visual-only group on post-instruction assessments. Furthermore, Wiebe et al. reported that the visuohaptic group had a longer fixation time on the software (calculated by using eye tracker data) than the visual group.

It is not clear from these studies if the additional sensory feedback gained through haptic technology contributes to cognitive overload such that the additional information that might be gained from the tactile modality is overridden by the limitations of memory storage. Sweller's (1994) cognitive load theory suggests that individuals need to reduce cognitive load in order for effective processing and learning to occur. The study noted above by Wiebe et al. (2009), which found visuohaptic feedback resulted in a longer fixation time with eye tracker data, argues for a closer look at these issues of cognitive load.

One interpretation of the mixed results that have been found in previous studies is that the learning context drives the benefits gained from adding haptic feedback. As discussed above, if the learning task can be accomplished with vision alone, then haptic feedback may not enhance the learning gain (Klatzky et al. 1991). In the studies described above, the learning contexts included studies of levers, cell morphology, and protein structure. It is possible that these are topics that can be learned predominately through visual feedback, and as a result tactile feedback does not add significant information for the learner. But what happens when the learning context is not visually based such as learning about pressure and heat and the requisite forces involved? Would haptic feedback make a significant difference in the effectiveness of the learning experience? This study explores this very question in an effort to better understand the efficacy of visuohaptic technology as a tool for learning science. The recent developments of new forms of haptic devices and force feedback gaming applications continue to raise questions about the role of haptics and the potential new uses of haptics in learning.

## 6.3 Materials and Methods

### 6.3.1 Research Questions

This study was designed to investigate the following research questions:

*Is visuohaptic feedback more effective than visual-only feedback for learning concepts of thermal energy, pressure, and random motion?*

*Does receiving visuohaptic feedback result in greater retention of concepts of thermal energy, pressure, and random motion, as measured by a delayed post-test than receiving visual-only feedback?*

### 6.3.2 Study Context and Instruction

The study was designed to investigate the role of haptic feedback in learning about thermal energy, pressure, and random motion. The study was conducted in a naturalistic setting that included grade-appropriate science instruction given as part of normal instruction in classrooms. The topic for the lesson was molecular motion and the role of random motion in thermal energy and pressure. The lessons were part of the state's science curriculum for sixth-grade students. Four classes (all taught by the same teacher) participated in the study (participants are described further below). Half of the students were randomly assigned to instruction that included a simulation that provided only visual feedback ($n = 35$), and half of the students were assigned to use the simulation both visual and haptic feedback ($n = 43$). Prior to beginning of the study, students were trained on how to use the computer technology, and students were allowed to continue with the training until all were comfortable navigating in the virtual simulation.

The study began with a pre-test given several days prior to instruction. Following the initial lesson about heat and pressure (described below), students in both groups (visual and visuohaptic) completed the simulation (about 50 min). Two days later students were post-tested, and 2 months later students completed a delayed post-test.

The instruction began with a task for students to make macroscopic observations of colored dye diffusing in a cup of water. Students were asked to describe the movement and make predictions about future movement of the dye. The next part of the lesson asked students to reflect on particle motion in hot and cold water and to define temperature. This was followed by instruction that described the relationship of pressure to the number of particles contained in a given space. After this introduction to thermal motion and pressure, students were introduced to the simulation designed to allow the students to explore molecular motion with or without haptic feedback.

Students worked through series of tasks that involved making manipulations with the simulation. The instructional program began by showing students a closed three-dimensional system (a virtual box) filled with moving particles (virtual water vapor molecules). Students who had visual-only feedback could observe particles colliding and moving throughout the box. Students with visuohaptic feedback could see the movement of the particles but could also feel the impact of particle collision with a Novint Falcon® haptic device from Novint Technologies, Inc. A grip bubble on the Falcon is connected to a computer that permits a user to manipulate objects in a computer simulation which in turn provides tactile feedback to the user. The instructional program allowed participants to maneuver and control an object (a pollen grain) that was constantly subjected to the random motion of surrounding particles in a closed system. The program allowed users to manipulate the temperature (from *zero temperature* to *high temperature*) and pressure (*high pressure* to *low pressure*) in the closed system. When operating the haptic device along with the computer simulation, participants were able to “feel” the numerous particles that randomly bombard the object they were guiding in the simulation. The intensity of the force feedback depends upon the temperature and pressure settings in the simulation.

Students were given a laboratory guide that led them through a range of explorations with guiding questions designed to focus their attention on the movement of the particles with each variable. At each stage of the simulation, students were asked to make predictions, alter conditions, make observations, and then record their observations. For example, students were asked to predict what would happen to the movement of particles when they changed the temperature setting to high or low. They were also asked to predict molecular movement at different temperatures and to predict a specific direction of movement for a selected molecule. Next, students were given a macroscale model of a virus capsid (plastic capsid pieces in a plastic container) and were asked to model different thermal energy levels (by shaking the container) and to observe what happened during the capsid self-assembly at different levels of thermal energy. The final component of the instruction asked the student to reflect on what they had experienced with the dye and the water, the simulation, and the virus capsid and respond to questions that asked them to compare and contrast the motion of particles in the simulation with virus capsid particles to the molecules of dye in the water.

### 6.3.3 Participants

Participants were drawn from a public middle school located in a rural-suburban community in the southeastern region of the United States. Participants were volunteers and included 78 students (24 males and 45 females; 73 % Caucasian; 15 % African American; 6 % Hispanic; 3 % Asian; and 3 % other). The mean age of the students was 13.5 years of age (range 13–15).

### 6.3.4 Assessments

Students completed alternate forms of the 30-item multiple choice test that was designed for this study and included a pre- and parallel post-assessment. The items were designed after consulting with the state's science curriculum and national curricular standards. The assessments included questions related to thermal energy, temperature, pressure, and random motion. There were knowledge-level questions (such identifying the term for the measure of the average particle speed of a substance), interpretation questions (reasoning that a cold environment may be needed to do precise experiments at the nanoscale), and prediction questions (what happens to the pressure of a gas when the temperature of a gas increases while the volume remains constant). Participants were also asked three open-ended questions about their interest in the simulation, whether they would recommend the simulation for other students and whether they felt like they understood the lesson. Those in the visuohaptic simulation were asked to describe what they thought they would have missed learning if they had not been able to feel the particles and had only been able to see the particles.

Assessment items were piloted using a think-aloud protocol with two middle school students. Items were revised after the pilot assessment and were validated by a team of four science educators, two physicists, one chemist, a middle school science teacher, and an engineer. Cronbach's alpha was calculated with the study sample to establish reliability with a value of .80 for the pre-assessment, .67 for the post-assessment, and .83 for the delayed post-assessment (low but acceptable reliability for newly developed scales with limited numbers of items, e.g., Nunnally 1988).

The pre- and post-assessments were given 2 days before and after the treatment. The delayed post-assessment was given 2 months after the treatment and included 64 students who had completed all three assessments and the treatment. Students were given unlimited time to complete the assessment. The assessment items were designed to match the concepts taught in the simulation and included thermal motion, pressure, random motion, and novel applications of particle motion such as diffusion, self-assembly, and chemical bonding.

### 6.3.5 Analyses

Pre- and post-assessment items were scored as correct or incorrect, and a score of 3.33 points was given to each correct item (100 point scale). Means and standard deviations were calculated for the pre- and post-assessment scores. Responses to the affective items were recorded and the frequencies of responses were determined.

T-tests were conducted to compare scores for the two groups (haptic and visuohaptic) and the pre to post changes. A repeated measure analysis of variance was run to examine the interactions between groups (visual and visuohaptic) and assessment scores (pre- and post-assessments). Post-instruction assessment scores were analyzed to determine if there were differences by type of assessment item. Questions were classified into the following categories: pressure, temperature, diffusion, randomness, particle movement, and applications. Independent t-tests determined that there were no differences between the groups' post-test scores by individual items or by item category. Subsequent analyses were conducted with all items.

## 6.4 Results

### 6.4.1 Knowledge Results

The results of the analyses are shown in Tables 6.1 and 6.2. Equivalence between the two groups was established by comparison of the pre-tests for the two treatment groups. There were no significant differences in the pre-assessment scores for the visual and visuohaptic groups ($t(67) = .255$, $p < .79$).

The analysis of variance results showed that there were significant differences for assessment scores (pre-, post-, delayed post-assessments) but no significant differences for the students' scores for the visuohaptic and visual-only groups.

**Table 6.1** Repeated measures analysis of variance for assessment scores and group

| Effect | *MS* | *df* | *F* | *p* |
|---|---|---|---|---|
| Assessment scores (pre, post, delayed post) | 3883.87 | 2 | 33.31 | 0.000 |
| Assessment scores X group (visual and visuohaptic) | 935.47 | 2 | 3.44 | 0.068 |
| Error | 122.13 | 124 | | |

Note: There was no significant main effect for group (visual and visuohaptic) $F(1,62) = .044$, p < .835

**Table 6.2** Post hoc comparison of assessment scores between the visual and visuohaptic groups

| | Visual | Visuohaptic | | |
|---|---|---|---|---|
| Assessment | *Mean* (*SD*) | *Mean* (*SD*) | *t* value | *p* value |
| Pre-assessment | 55.23 (15.97) | 55.63 (15.11) | 0.105 | 0.917 |
| Post-assessment | 68.09 (16.63) | 72.42 (15.31) | 1.196 | 0.235 |
| Delayed post-assessment | 70.52 (17.30) | 65.23 (19.23) | 1.132 | 0.262 |

Post hoc paired t-tests showed that both groups experienced significant growth from pre- to post-assessment (visual group $t(67)=6.00, p<.00$; visuohaptic group $t(67)=7.58, p<.00$). When the pre-assessment scores were compared to the delayed post-assessment scores, there were also significant differences (visual group ($t(29)=5.511, p<.000$ and the visuohaptic group ($t(35)=2.771, p<.009$).

Table 6.2 shows the means and post hoc t-tests by treatment group. There were no significant differences for assessments by treatment group (pre-, post-, or delayed post-assessment).

## 6.4.2 Affective Results

Almost all of the students in both groups recommended that the simulation be used in the future to teach these concepts and reported understanding the simulation. However, there were statistically significant differences in the ratings by participants for the question that asked them how interesting the lesson was to them. The item asked participants to rate how interesting the lesson was on a scale of 1 (not at all interesting) to 5 (very interesting). Both groups found the lesson to be interesting, but the visuohaptic group found the lesson to be significantly more interesting (visuohaptic group $M=4.8$ ($SD=0.51$) and the visual group $M=4.3$ ($SD=0.36$) $t(62)=2.91, p<0.004$).

All the students in the visuohaptic group reported that the touch feedback helped them learn about particle motion. When asked, "what did you learn by being able to feel the particles that you would not have learned if you were only able to see the particles," the responses primarily related to understanding how the particles moved (73 %). In addition, 31 % of the visuohaptic participants discussed how the particles felt. For example, responses included "being able to feel the shape, size, movement, and speed" and "the texture and the force in which they collide with each other." Similarly to this last student that reported learning about force, a number of other students discussed the how the haptic technology allowed them to detect force. For example, students noted, "you could feel how they were forcing back against you plus you saw how they moved," "how vigorous and violent [the particles were]," "the feel of the particles and the power," and "the force and speed of the actual particles."

Several students reported that the haptic technology enabled their visualization of the particle movement. Students wrote comments such as "I could visualize the process going on" and "it helps you think in three dimensions." One student reported that the haptic simulation contributed to a sense of presence in the virtual environment. This student said, "I felt like I was there and could actually feel the particles rather than being told."

## 6.5 Discussion

Advocates of an embodied cognition view of learning argue that the goal of instruction is to create learning tasks that facilitate learning through building on prior experiences and the existing mental frameworks that arise from sensory motor learning. The results of this study suggest that the simulation was effective in teaching students about thermal motion, pressure, and random motion regardless of whether the students had access to haptic feedback. One interpretation of these results is that the visualization that comprised the software was sufficiently powerful to allow students to determine how increases and decreases in thermal energy would impact particle motion, how increases and decreases in the number of particles would change the pressure, as well as how pressure and thermal motion were related. As noted previously, it is possible that haptic feedback is most effective when there are no other effective avenues for students to perceive the targeted concept (i.e., vision is not available). An example of a haptic-only context would be the tactile feedback from a hand drill that an oral surgeon uses to determine when the root of a tooth has been fully extracted. The surgeon cannot see the root canal of the tooth and depends on the feedback from the drill inserted into the tooth. In the context of the present study, students with visuohaptic feedback could both see and feel the particle motion. There is some evidence that haptic feedback may be processed in the brain in the visual cortex (Sathian et al. 1997), and one interpretation of the results reported here is that haptic feedback is combined with the visual feedback as a visual image, and as a result the haptic information may not be adding to the conceptual learning.

Although the topic of this study was about forces and molecular motion (that are not easily perceived visually), the animations included visual simulations, and students could manipulate variables and see how the particle movement would change as thermal motion or pressure changed. We hypothesized that visuohaptic students would have a better understanding of random motion and the rapid movement of particles that result from thermal energy, but the results of the pre- and post-assessments did not support our hypothesis. It is possible that although we made every effort to assess haptic effects, the assessments we used (verbally based written forms of assessment) may not have fully measured the encoded information gained from the haptic simulation and may have inadvertently favored visual information.

It is possible that the tactile sensations detected as students changed the temperature and pressure may have distracted students from focusing on molecular motion. For example, one student noted that the simulation allowed her to feel "how (the particles) were forcing back against you plus you saw how they moved," "how vigorous and violent [the particles were], "the feel of the particles and the power," and "the force and speed of the actual particles." The force feedback of the falcon may have shifted the students' attention away from understanding the concepts of particle motion under different conditions to a focus on the falcon stylus. Or, as de Koning and Tabbers (2011) have suggested, the physical action used during the visuohaptic simulation may not have mapped on to the more abstract cognitive representational system.

Students reported that the haptic feedback helped them visualize the particle motion. They also reported that the haptic feedback helped them learn about the concepts, but the assessments did not measure a difference in the pre- and post-learning gains for the two treatment groups. Another interpretation of these results is that the haptic feedback information was ignored as students used the simulation in order to limit cognitive load.

Although one might expect that multimodal simulations would strengthen conceptual understanding, there may be a point where the additional information distracts from rather than enhances student learning. This study does not completely resolve the debate of whether or not haptic feedback enhances learning, but it does address the question (in this context) of whether visuohaptic instruction for nonvisually based phenomena such as forces is more effective. Here we found that both the visuohaptic and the visual simulations resulted in significant gains from pre- to post-instruction. Depending on the context, having the opportunity to manipulate and feel materials may not make a difference in learning.

From an embodied cognitive view, physical responses and movement are both built by, and contribute to, cognitive structures that have roots in evolutionary history. Some researchers have argued that embodied cognition developed as humans responded to evolutionary pressures (Wilson 2002). It is believed that over time the direct link to physical experiences was not required and humans were able to co-opt these mental structures in the formation of abstract concepts. What is not yet clear is that which types of learning tasks (if any) build on this sensory mother architectural mental framework and which do not? Most applications of haptic instructional tools have used haptic feedback to teach about microscopic and atomic scale phenomena such as cell organelles or protein folding (e.g., Jones et al. 2006). These studies have found limited advantages to having haptic feedback. Could it be that an evolutionary-based cognitive system built on tactile perceptual information works best for the types of learning that one might encounter on a human scale (the scale that involves actions in the natural environment)? Perhaps this system contributes little to the development of more abstract concepts at the micro- or nanoscale where processes such as particle motion and thermal energy exert effects.

## 6.6 Conclusions and Implications

It appears that even though the haptic feedback used in the present study was not more effective than visual-only feedback, it did not result in reduced learning. If the findings of this study are replicated, the results suggest that teachers and curriculum developers can use new and evolving touch technologies with confidence that visuohaptic simulations do not detract from learning. Furthermore, students find visuohaptic technological applications highly interesting, and they report that haptic feedback contributes to their visualization of science processes. The costs of new virtual and haptic technologies have fallen considerably in recent years, and whole schools are beginning to adopt virtual reality technology for school-wide use. Additional studies are needed to determine whether the increased student attitudes toward the learning task continue with extended use of visuohaptic and virtual reality tools. Over time one would expect that enhanced interest in the learning task would translate into learning gains. The studies of embodied cognition and haptic learning technologies are rapidly evolving, and although this study investigated one context of haptic learning, the relationships of embodied cognition, interactive haptic technologies, and science learning have not yet been fully explored.

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