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Haptics in Education: Exploring an Untapped Sensory Modality

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As human beings, we can interact with our environment through the sense of touch, which helps us to build an understanding of objects and events. The implications of touch for cognition are recognized by many educators who advocate the use of "hands-on" instruction. But is it possible to know something more completely by touching it? Does touch promote the construction of more connected and meaningful understandings? Current technology makes the addition of touch to computer-generated environments possible, but the educational implications of this innovation are still largely unknown. This article is a baseline review that examines the role of touch in cognition and learning and explores the research investigating the efficacy of the haptic augmentation of instruction.

KEYWORDS: cognition, educational technology, haptics, learning, multimodality.

The human sense of touch is an active, informative, and useful perceptual system (Klatzky & Lederman, 2002). From our earliest days, we use touch to discover the world around us. Information gained through touch lays the foundation for the development of a wide range of concepts. The critical role of touch permeates the language that we use to describe learning. We often talk about "grasping" an idea, "getting a handle on" a problem, or being "touched" by a reading. Many educators believe that "hands-on" experiences—those that actively involve students in the manipulation of objects—are powerful teaching tools.

An emphasis on actively involving students in learning has influenced American schools throughout their history. McMurray wrote in 1921, "It is a truism of our educational creed that sensory impressions based on object lessons and motor response form the primary basis of thought in dealing with the later materials of knowledge" (p. 3). Elementary school teachers have long been interested in the use of manipulatives in their lessons. The manipulatives are designed to be touched and handled by students, helping them develop their muscular, perceptual, and psychomotor skills and providing concrete experiences with intangible concepts and ideas (Ross & Kurtz, 1993).

But is it possible to know something more completely by touching it? Does involving the sense of touch enable one to construct a more connected and meaningful understanding? Can augmenting existing instruction with touch exploit experiential, embodied, and tactile knowledge that might not otherwise be called

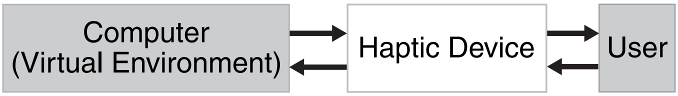

FIGURE 1. *An illustration of the bidirectional information exchange unique to haptic interfaces. Adapted from Okamura, Richard, & Cutkosky, 2002 (p. 346), with permission. Copyright 2002 by the American Society for Engineering Education.*

upon? Does the unique bi-directional exchange of information between a user and a haptic device (simulating the sense of touch) somehow enhance the learning experience? Questions such as these lie at the core of this review of literature.

What Is Haptics?

Revesz first introduced the term "haptics" in 1931. The origins of the word can be traced back to the Greek words *haptikos,* meaning "able to touch," and *haptesthai,* meaning "able to lay hold of" (Revesz, 1950; Katz, 1989). Today the term, in its broadest sense, encompasses the study of touch and the human interaction with the external environment through touch. The field of haptics, inherently multidisciplinary, involves research from engineering, robotics, developmental and experimental psychology, cognitive science, computer science, and, to a much lesser extent, educational technology.

The study of haptics has grown dramatically with the advent of touch in computing, as many researchers are involved in the development, testing, and refinement of tactile and force feedback devices (simulating object hardness, weight, and inertia), along with supporting software, that allow users to sense ("feel") and manipulate three-dimensional virtual objects (McLaughlin, Hespanha, & Sukhatme, 2002). Haptic devices can provide force feedback and/or tactile feedback (simulating surface contact geometry, smoothness, slippage, and temperature) by employing physical receptors (tactile and kinesthetic) that gather information for the haptic system, which then attempts to draw conclusions about a local object or environment (Jacobson, Kitchen, & Golledge, 2002). All haptic interface devices share the unparalleled ability to provide for simultaneous information exchange between a user and a machine, as depicted in Figure 1. For a more complete description of the currently available haptic devices and user interfaces, see Hayward, Oliver, Cruz-Hernandez, Grant, and Robles-De-La-Torre (2004).

Everyday Importance

Although as human beings we interact with our surroundings through five sensory channels—sight, sound, taste, smell, and touch—it is only our sense of touch that enables us to modify and manipulate the world around us (McLaughlin, Hespanha, & Sukhatme, 2002). Imagine living in the world without the sense of touch: Notwithstanding the known physical and social implications, formerly simple everyday tasks would become extremely difficult. Finding the doorknob in a darkened room would require the use of a flashlight, and locating your car keys in a purse would necessitate a visual check of its entire contents.

Moreover, consider the numerous professions or jobs that rely heavily on the sense of touch: a dentist performing a root canal, a physician employing palpation as part of a diagnosis, a mechanic working on a hidden engine part, a musician feeling the vibration of her instrument, or a pitcher finding the seams on a ball hidden in his glove. When vision alone is inadequate or not possible, touch becomes an efficient device for obtaining information. Yet, despite its everyday importance, touch has not received the research attention that sight perception enjoys (Heller, 1991), a bias that was noted as far back as 1891, by Fraser.

Perceptual Power

Touch provides information on the "innards of objects, whereas the eye, remaining fixed on outer surfaces, plays a lesser role in developing the belief in the reality of the external world. Such basic concepts of physics as force, impenetrability, resistance and friction are rooted in touch" (Katz, 1989, p. 3). The sensory channel of touch receives information, not just sensations (Kennedy, Gabias, & Heller, 1992). This information is obtained across time and provides details about properties such as distance, size, shape, hardness, wetness, elasticity, and texture. Heller (1982) notes Reid's early proposition (1764/1970) that vision enables the learner to perceive only indirectly attributes such as hardness, softness, size, motion, and texture, which originally are known directly to the tactual sense. Touch has been described as an active discovery sense (Loomis & Lederman, 1986; Lederman & Klatzky, 1987). Taylor, Lederman, and Gibson (1973) suggested that something touched is more real than something seen. Given its perceptual power and the wealth of sensory information it affords us, the sense of touch has emerged as an understudied and perhaps underused teaching and learning tool.

Methodology

Framing the Review

This integrative review of literature examines much of the existing research on haptics and focuses primarily on the potential impact of that research on education. We include both theoretical and empirical studies and attempt to synthesize what is currently known about the perception and processing of haptic information as it pertains to teaching and learning. As previously suggested, the literature on haptics has grown rapidly, and a comprehensive review is beyond any one article. Thus the scope of this piece is deliberately narrow. We begin with a developmental look at haptic perception and the role that the sense of touch plays in cognition. Next, we turn to visual–haptic information interactions, discussing selected studies that have investigated the relationships between vision and touch; in this context, we try to shed light on how the addition of haptic feedback influences the ways in which individuals perceive, process, and make use of this sensory information. We then look at how haptics might affect learning, considering the few intervention studies that have examined the efficacy of haptic augmentation in school contexts. Finally, we discuss findings and constraints and look into the future of haptics in education as we see it.

Given the intended audience, this article does not delve too deeply into the neuropsychology of the perceptual processes associated with haptics, nor does it contain a discussion of the biological or physiological basis of touch in any great detail. For the same reason, it does not address the computer hardware or software requirements for the rendering of virtual objects or the capture, storage, or retrieval of haptic data.

TABLE 1
Composition of selected studies according to literature type

Type of literature	Number
Empirically based, peer-reviewed journal	43
Empirically based book	3
Theoretically based, peer-reviewed journal	11
Theoretically based book	31
Empirically/theoretically based book	1

Selection of Studies

The initial phase of the review process involved identifying potentially relevant publications from two electronic databases, ERIC and PsycINFO. Perhaps surprisingly, searching these databases using *haptic* as the only keyword or subject term yielded 1,151 results (187 from ERIC and 964 from PsycINFO). To refine this list for our intentions, two subsequent searches were conducted in the same databases. First, the terms *haptic* and *learning* were used in the keyword or subject fields. This query uncovered a total of 279 references, 185 from PsycINFO and 94 from ERIC. The next search employed the terms *haptic* and *education* in a similar manner. Tellingly, this resulted in only 126 references, 90 from ERIC and 36 from PsycINFO. The results of these searches were printed out and compared, and duplicate references were eliminated.

This left us with 144 pieces of literature to examine more carefully and select from, guided by the framework detailed in the previous section. That is, we focused our attention on research articles from the field of psychology that systematically investigated and described the development of haptics and its role in cognition. We also scrutinized studies that dealt specifically with the interactions of visual and haptic percepts, as well as any work that directly investigated the use of haptics in the context of teaching and learning. This initial selection process did not eliminate any work based on its publication date, but position papers and publications that simply described haptics were disregarded. Also eliminated were works that used the term *haptic* solely as a means to describe various learning styles or multiple intelligences. In the end, 78 pieces of literature were selected (from the 144) to be included in this review.

A second phase of the search and selection process was brought on by the discovery of a number of older but highly pertinent references found in the bibliographies of the 78 selected publications. Many of these older studies, primarily from the fields of psychology and cognitive science, were available through our institutions' archives. Applying the same guidelines as before, we selected an additional 11 publications from among the older studies. All told, the present review includes 89 pieces of literature, the composition of which is summarized in Table 1.

Description of Selected Studies

We preface this section by again stating that the literature cited and discussed in this article is by no means exhaustive. The studies detailed in the upcoming section "Haptic Perception" are representative of the larger body of research in the field of psychology that has investigated the development of the haptic sense. The chosen pieces are intended to mirror the stages of haptic development from infancy to adulthood. The next major section, "Visual–Haptic Information Interactions," contains a detailed examination of several studies that have explored the cognition of combined visual and haptic perceptions. These two sections of the review are selective, primarily because of the vastness of the prior research conducted in those areas. In both cases we chose to focus on particular empirically based pieces because, in our estimation, they are some of the most cited and most influential studies in their respective areas. In contrast, the section "How Might Haptics Affect Learning?" is comprehensive rather than selective, because its portion of the literature base is far less extensive. It includes all of the articles that have directly investigated the impact of incorporating haptics and haptic technology into the learning process.

In short, we provide an in-depth examination of 16 empirical studies, and our review is in a sense a hybrid, combining selective and comprehensive reviews of the literature. In addition, a number of studies (both empirical and theoretical, from vetted journals and books) are included in an attempt to build a framework to aid the reader in synthesizing the diverse ideas and questions that we present.

Haptic Perception

Early On

Touch is thought to be essential to human development and cognition; from an early age we act on objects and they act on us through forces (Bussell, 2001). Haptics serves as a primary sensory modality in the early years; during the first several months of life the oral exploration of the properties of objects dominates. Subsequently, around the age of 5 months, young children begin to pick up objects within their reach and explore them both orally and manually. Research (e.g., Ruff, 1982; Streri, 1987; Bushnell & Boudreau, 1991) has suggested that babies are able to encode, hold in memory, and recognize a certain amount of information about an object's haptic properties, such as shape, substance, weight, size, and volume. Haptic exploration, according to Piaget (1954), enables a child to gather information about the environment, which the child uses to form organizational action schemes and to gain a greater understanding of the environment (Piaget & Inhelder, 1967).

As the child matures, the early manipulations evolve considerably, in essence becoming more deliberate. This development coincides with gains in differential arm and shoulder muscle accommodations and substantial gains in fine motor control. At an age as early as 7 to 8 months, infants seated in the dark can discriminate object properties through touch and use distinct hand movements to explore specific object properties. In a review of studies on infant haptic abilities, Bushnell and Boudreau (1993) noted that infants touched the textured surface of an object longer than its plain surface, suggesting that they discriminated between the two. In addition, infants' exploratory strategies varied as a function of the nature of the stimulus. That is, infants alternately flexed and extended their fingers on a patch of brush bristles more than on a shallow well of water, and they banged the water more than the brush.

The emergence of rudimentary *exploratory procedures* (discussed later in more detail) has been reported in infants, as sensitivity to texture differences develops. Stack and Tsonis (1999) examined the haptic perception of texture in 48 infants at the age of 7 months (24 males, 24 females); the majority of infants were White and from middle-class families. The infants in this study participated in a *familiarization–novelty–return-to-familiar* procedure. The textures provided as stimuli were corduroy, scouring pads, foam, glossy tape surface, masking tape surface, silk, dish sponge, make-up sponge, cotton flannel, and carpet lining. These stimuli were identical in size, shape, and weight. In addition, the surfaces were painted white to control for color.

Infants were randomly assigned to one of two conditions: *touch-no-vision* or *touch-plus-vision.* Visual examination of the stimuli in the touch-no-vision condition was occluded by a rectangular opaque plastic cover attached around infants' necks and extending horizontally in front of them. During the familiarization phase, infants were prompted to establish and maintain contact with the objects and were able to manipulate them freely; this phase lasted until 30 seconds of tactile contact were accumulated.

Infants in the two experimental groups (one group in each of the above conditions) received a novel texture during the novelty phase, followed by the original texture in the return-to-familiar phase. Control group participants received the same texture throughout the three phases. The order of stimulus presentation was counterbalanced so that half of the infants in the two control groups received the smooth textures and half the rough textures. Conversely, during the three phases, half of the infants in the experimental group received the textures in the order of smooth-rough-smooth and half in the order of rough-smooth-rough. Infants were allowed to freely explore the textures in each phase, and all testing sessions were video-recorded and subsequently analyzed by means of frame-by-frame coding. The dependent measures in this study were manual contact, bimanual contact, "scrumbling" (flexing and/or extending one or more fingers in a repetitive manner over the surface of the stimulus), fingering (running one or more fingertips over the surface of the stimulus), total visual attention, and visual fixation.

Perhaps surprisingly, it was only in the return-to-familiar phase that any group differences were found, and only on the manual contact measure. This finding suggests that 7-month-olds are able to use manual contact as a means of acquiring haptic information. Moreover, the group difference may be an indication of these infants' ability to recognize a familiar texture through a representation of the original texture formed and retained in memory. The results of this analysis also showed that both experimental and control infants displayed high and sustained levels of manual contact during the novelty phase. The high levels of manual contact observed in control group infants (having received the same texture) during this phase may suggest that the texture stimuli continued to be of interest and that the processing of the texture was incomplete. However, this is mere speculation because it is virtually impossible to determine whether the high levels of manual contact demonstrated by infants in the experimental group during the novelty phase were a true response to novelty in texture. Perhaps this would become clearer if the infants were given more familiarization time with the initial texture before presentation of the novel texture.

More recently, Klatzky, Lederman, and Mankinen (2005) studied the use of visual and haptic information during a perceptual comparison task in 10 children (5 boys, 5 girls) ranging in age from 3 years and 11 months to 4 years and 11 months. This experiment employed pairs of stimuli that contrasted with each other on five attributes: weight (two 35-mm film canisters, one empty and one filled with pebbles); size (a marble and a dried pea); roughness (a foam block covered with sandpaper and a foam block covered with cellophane); hardness (a piece of wood and a piece of compliant foam); and shape (a Styrofoam sphere of 6.2 cm diameter and a cone with a 5.6 cm diameter base and 10 cm height). The five pairs of items were given to participants in random order; in each case the child was asked which item was greater in terms of the given attribute (harder, rougher, etc.) or, for the shape pair, which item was more like a ball. The children were told that they could look at and touch the objects in any way but did not have to touch them. Their manual activities and voices were recorded on videotape for analysis, and a mirror was placed behind the objects, which allowed the backs of the hands to be seen.

The researchers recorded the accuracy of each judgment, as well as the way in which the judgments were made. They reported that performance in this perceptual comparison task was virtually error free, the only errors being on two roughness comparisons. They stated that the "children tended to explore as adults would" (Klatzky et al., 2005, p. 247). That is, these toddlers looked at the objects rather than touching them when comparing size and shape, lifted the objects to judge weight, and pressed or pinched them to compare hardness. Considering that this study was conducted with an extremely small number of students ($n = 10$) and no demographic information was provided, caution should be taken in generalizing the results.

Older Children

Berger and Hatwell have conducted several studies exploring the haptic discriminations of young children (ages 5 and 9). In 1995 they published a study of 32 children (half with a mean age of 5 years and 6 months, half with a mean age of 9 years and 7 months) and 16 adults (with a mean age of 21). Participants engaged in the free classification of 16 cubes that varied in hardness and texture density. Using only touch, they each explored a cube and were then asked to choose which of three comparison objects "goes better with" the original cube. Here, the researchers were most interested in whether the participants would use both properties (hardness and texture density) in their decisions or take only one of those properties into account.

It was found that the children relied on hardness in their discriminations more often than the adults, who selected texture more often. It was also found that the children's responses tended to be more dimensional (i.e., focusing on individual properties) than global (i.e., focusing on overall similarity). Berger and Hatwell (1995) maintain that the observed differences may be due to the sequential nature of haptic processing. That is to say, in young children haptic exploration is not yet systematically organized; only a few exploratory hand movements are used, resulting in an incomplete processing of the object. Berger and Hatwell suggested that perhaps adults are more capable of using haptic information to build a global reconstruction of the whole object, whereas the young children, with their incomplete representation, must rely on lower-level (i.e., dimensional) information to make their decisions.

Another group of researchers (Alexander, Johnson, & Schreiber, 2002) used a comparison task similar to that of Berger and Hatwell (1995), but they limited the participants' judgments to pairs of three-dimensional (3-D) models and simply asked the children to judge whether the two models were identical. Based on Berger and Hatwell's results, we might expect younger children to have difficulties in focusing on specific parts of the models when making their decisions. Alexander, Johnson, and Schreiber were also interested in the interactions between developmental level and domain-specific knowledge in haptic processing. Thirty-six children (ranging in age from 4 to 9 years) were assessed on their ability to categorize 3-D models of both familiar objects (dinosaurs) and unfamiliar objects (sea creatures) on the basis of haptic information alone. The children first participated in a training trial, using identical (two dogs) and nonidentical (gorilla–tiger) models, to familiarize them with the task. Next, the children were randomly assigned to receive the familiar (dinosaurs) or less familiar (sea creatures) domain first and were instructed to judge whether the two animals behind windows were the same or not the same. Although no time limits were imposed, they were told to use only their dominant hand to explore the models and to explore each of the models separately. In addition, the children were permitted to go back and recheck previously explored models before giving their final judgment (Alexander, Johnson, & Schreiber). The children's knowledge of dinosaurs' names and physical attributes were assessed separately by using pictures of the dinosaur models.

It was found that, in general, the older children identified more differentiating features because of more exhaustive haptic explorations of the models, with the result that they made fewer matching errors. It was also suggested that the children's domain-specific knowledge (about dinosaurs, in this case) was related to the exploration strategy they employed. Children with less content knowledge were more likely to use a full comparison strategy (described as a comprehensive exploration and identification of the salient features of both models being compared); children who had more content knowledge relied on hypothesis testing (defined as a relatively thorough exploration of the first model and identification of its prominent features followed by a brief search for these same features in the second model, which is explored less exhaustively; Alexander et al., 2002). It should be noted that this study sample was comprised of 32 boys and only 4 girls, a disparity noted by the authors and attributed to their recruitment of participants with "an interest in dinosaurs." The authors also admit that the novelty of the procedural task (identifying models based on touch and making decisions concerning the similarity of those models) may have affected the results.

The research evidence presented here suggests that there may be a dichotomy or duality that exists when one considers haptics from an educational perspective. More precisely, is the haptic sense best suited for the exploration of unknown properties and principles, or do students need a certain degree of existing knowledge about the properties and principles before they can fully capitalize on the wealth of information that haptics can afford them? This is an issue that we will revisit in subsequent sections of the review.

Adolescents and Adults

To date, there is little written about how adolescents perceive objects through the sense of touch. It is believed, however, that with an increase in age and presumably an increase in knowledge comes more systematic and purposeful haptic processing. In their seminal work, Lederman and Klatzky (1987) identified and coined the term *exploratory procedures* to describe stereotypical and formulaic hand movements that adult individuals performing haptic explorations instinctively employ to extract information regarding an object's properties (Figure 2).

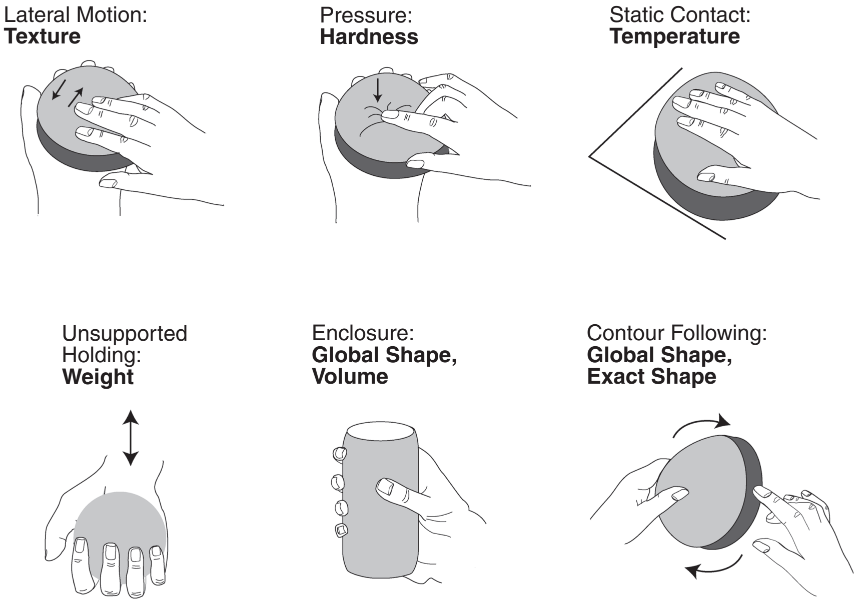

FIGURE 2. *A depiction of the exploratory procedures described by Lederman and Klatzky, 1998 (p. 27, Figure 2.3). Adapted from Lederman & Klatzky, 1987 (p. 346, Figure 1), with permission. Copyright 1987 by Elsevier.*

This study involved 18 blindfolded participants (11 female and 7 male, with a mean age of 26) completing a match-to-sample task. The experiment involved 36 sets of 3-D objects that could be enclosed in one or two hands; each set included a standard object and three comparison objects that varied along one of nine attributes of interest (e.g., general and exact shape, volume, weight, texture, hardness, temperature, part motion, and function). Participants were asked to explore the standard object haptically and then choose the best match from the comparison objects, being as accurate and as fast as possible. Their hand movements and accuracy in matching were analyzed. It was found that participants commonly used an exploratory procedure (associated with a particular attribute), which was the optimal and preferred method for determining the attribute under unconstrained haptic exploration. For example, *pressure* (described as applying torque or normal forces to one part of the object while the object is stabilized) can be used to gain information about the object's *hardness. Lateral motion,* associated with *texture* encoding, is characterized by production of shearing forces between skin and object. *Contour following,* where the hand maintains contact with a curve on an object, provides salient information about the *shape* and *volume* of the object.

It is believed that these exploratory procedures maximize the sensory input corresponding to a certain property of an object, permitting increased ease of encoding (Klatzky, Lederman, & Reed, 1987; Lederman & Klatzky, 1987, 1990). On the basis of findings from more than 20 years of research (e.g., Lederman & Klatzky, 1987, 1990; Klatzky & Lederman, 1987, 1993, 1999, 2002) in haptic perception, Lederman and Klatzky argue that these haptic exploratory procedures can serve as a window into our representations in memory.

The studies described above, representative of a much larger body of work and summarized in Table 2, were conducted in an attempt to identify and describe how haptic perception allows human beings to gain useful information about objects.

Despite their importance and their ability to help educators and education researchers better understand the link between touch and cognition, these developmental studies unfortunately do not directly contribute any evidence for the impact that incorporating touch has on student learning. We next turn our attention to some of the prior research that has endeavored to develop an understanding of the nature and persistence of haptic representations in memory, which we hope will further inform the reader as to the potential role of haptics in education.

Visual–Haptic Information Interactions

It has been suggested that haptics is superior to vision in the perception of properties such as texture (roughness/smoothness, hardness/softness, wetness/dryness, stickiness/slipperiness) and microspatial properties of pattern, compliance, elasticity, and viscosity (Lederman, 1983; Zangaladze, Epstein, Grafton, & Sathian, 1999), whereas vision dominates in the perception of macrogeometry (shape) and color (Sathian, Zangaladze, Hoffman, & Grafton, 1997; Verry, 1998). Despite such differences, the simple fact that in *everyday perception* touch and vision operate together should prompt one to consider the interactions between haptic and visual information with respect to their representations of the perceived world and memory. The review next describes some of the research that has examined how individuals attend to and process information through the visual and haptic modalities.

Multimodality

There exists an extensive body of literature, beyond the scope of this review, that examines the influences of various instructional designs on student performance in multimedia learning environments. Unfortunately, much of the multimodality literature tends to overlook the haptic sense and is instead dominated by research using stimuli in the auditory and visual modalities. However, the underpinnings of this existing research may provide a framework for investigating the impact of haptics in education. More specifically, the dual-coding theory suggests that there are two main codes or types of information, one nonverbal (imaginal) and the other verbal (Paivio, 1986). The dual-coding theory also maintains that visually presented information is processed in visual working memory and auditory information is processed in auditory working memory. Considering the cognitive architecture of human beings, the cognitive load theory (Sweller, 1994) assumes that these memory stores are limited and that, for effective information processing and subsequent learning to take place, individuals need to reduce unnecessary cognitive loads. To date, it remains unclear how introducing a third sensory channel for touch affects students and learning.

Multimodal Information Processing

One key question that remains regarding visual and haptic modalities is, What information is shared, and at what level? Three basic views may help to explain

TABLE 2
Descriptive summary of the selected developmental studies

Study	Participant ages	*N*	Stimuli	Task	Dependent variable(s)
Stack & Tonis (1999)	Infants (7 months)	48	Real objects with varying textures (e.g., corduroy, silk, dish sponge)	Familiarization–novelty–return-to-familiar	Manual contact, bimanual contact, scrumbling, fingering, total visual attention, and visual fixation
Klatzky, Lederman, & Mankinen (2005)	Infants (3 years and 11 months to 4 years and 11 months)	10	Real objects varying on five attributes (weight, size, roughness, hardness, and shape)	Perceptual-comparison	Method and accuracy of judgments (e.g., which is heavier, rougher, harder)
Berger & Hatwell (1995)	Children (5 years, 9 years); adults (21 years)	48	Cubes (16) varying in hardness and texture density	Free classification	Classification method (i.e., object property used)
Alexander, Johnson, & Schreiber (2002)	Children (4 to 9 years)	36	3-D models of dinosaurs and sea creatures	Free classification	Method and accuracy of judgments (e.g., are the two models the same)
Lederman & Klatzky (1987)	Adults (mean of 26 years)	18	Real 3-D objects (36 sets) varying along one of nine attributes (general and exact shape, volume, weight, texture, hardness, temperature, part motion, and function)	Match to sample	Hand movements and accuracy of matches

how these types of perceptual information are processed (Turkewitz, 1994). In the first view, information comes from separate sensory systems through independent pathways and thus is often presumed to be sense-specific at an "early" level. At a higher (conceptual) level, information from all perceptual modalities is thought to be jointly available. According to this view (Fodor, 1983), all visual processing would be independent of haptic processing, and each would require its own memory storage system.

A second notion is that perceptual information is maintained in an amodal representation (Gibson, 1966, 1979), which receives input from all sensory modalities. In this view, only one global representation is maintained and stored. Subsequently, each piece of information, no matter how detected, is included in a representation of what is perceived. This idea was alluded to in the work of Berger and Hatwell (1995) when they suggested that the younger children in their study were not able to integrate haptic information into a global representation of the explored objects.

A third, more recent view, which perhaps bridges the other two, postulates separate but interacting perceptual modalities (Stein, Meredith, & Wallace, 1994). In this view, information is easily exchanged and integrated, such that perceptual systems may influence one another's processing. According to this view, which parallels the dual-coding and cognitive-load theories, a functional organization or division of labor allows for cross-modal interactions among systems in concert with task demands (Damasio, 1989).

Haptic Memory?

An effort to develop an "information-processing systems approach" that would identify sensory stores and different forms of memory for haptic perceptions has met with limited success. One of the main issues in memory research is the nature of the internal representation. To be more precise, when information is encountered through the sense of touch, is the representation intrinsic to that modality or is it more general (i.e., spatial)?

Millar (1997) pointed to evidence for the existence of short-term memory in the tactual modality with a limiting span of two to three items; however, a counterpart to the very short-term iconic and echoic memories that are found in vision and audition has not been clearly demonstrated with touch (Watkins & Watkins, 1974; Millar, 1975). There is additional evidence for tactual coding during early learning of small patterns such as Braille forms—that is, coding in terms of tactual features, such as texture or dot density, without spatial mediation (Millar, 1997). We next expound on some of the research in this area; a summary of these studies is presented in Table 3.

In a 1999 study, Bushnell and Baxt investigated the perceptual representations of 5-year-old children ($n = 16$), half of them male and half female. The stimuli were four sets of 16 real, 3-D objects. Two sets consisted of familiar objects (e.g., toys, food items, articles of clothing, and household artifacts), and two sets included unfamiliar objects (e.g., specialized machine parts and tools). The items within each set differed in size, shape, color, surface texture, compliance and rigidity, weight, number of distinct parts, and mobility of the parts. It was assumed that the familiar objects were ones that the children had "held in their hands on many prior occasions, that probably had meaning for them, and for which they probably had conventional verbal labels" (Bushnell & Baxt, p. 1868). It was also assumed that the opposite was true of the unfamiliar objects.

TABLE 3
Descriptive summary of the selected studies investigating visual and haptic interactions

Study	Participant type	*N*	Stimuli	Task(s)	Dependent variable(s)
Bushnell & Baxt (1999)	Children (aged 5 years)	16	Four sets of 16 real, 3-D objects: two sets of familiar objects (e.g., toys, food items, articles of clothing, household artifacts); and two sets of unfamiliar objects (e.g., specialized machine parts, tools)	Recognition with target and distractor items in either the same or alternative modality	Accuracy of object recognition
Kiphart, Auday, & Cross (1988)	Undergraduate college students	308	30 different complex geometric objects made of plastic	Haptic recognition involving retention intervals and distractor experiences	Accuracy of object recognition
Srinivas, Greene, & Easton (1997)	Undergraduate college students	120	Novel 3-D raised-line shapes	Implicit and explicit tactual memory tests	Accuracy of shape identification
Reales & Ballesteros (1999)	Undergraduate college students	48	Common objects (e.g., spoon, clothespin, sponge)	Implicit tests (e.g., speed of object naming, level of completeness of a fragmented picture)	Degree of cross-modal and intra-modal priming

The children were tested for recognition with target and distractor items in either the same or the alternative modality. It was found that haptic, visual, and cross-modal recognition was nearly perfect with familiar objects. We find it interesting that although the children were also adept at haptic and visual recognition of the unfamiliar objects, their cross-modal recognition was far less accurate. The reason for their poor performance in cross-modal processing of unfamiliar objects may be that the representations formed when handling the objects keyed into features or properties that were different from those encountered during visual inspection (Bushnell & Baxt, 1999). Perhaps, when one explores unfamiliar objects, two distinct memories are formed and they fail to interact. We suggest that, regardless of where the memories are stored, teachers should strive to help students integrate the visual and haptic information into a more complete mental model.

Such representations were suggested by other experiments on haptic object categorization, which indicate that people use different attributes to group objects, depending on whether vision is available and whether the participants are instructed to think about what the objects *feel like* or what they *look like* (Klatzky, Lederman, & Reed, 1987; Lederman, Summers, & Klatzky, 1996). Kiphart, Auday, and Cross (1988) conducted a series of experiments with 308 college students. Participants felt 30 different complex geometric objects made of plastic and were tested for haptic recognition. During the experiments, retention intervals and distractor experiences were manipulated after the initial touching. The researchers reported that there was no evidence of a short-term memory delay function (over standard retention intervals that ranged from zero to 80 seconds) for the haptic modality. They went on to agree with Klatzky, Lederman, and Metzger's (1985) contention that this modality constitutes an *expert system.* They then extended that proposition by suggesting that in human beings the capacity to process information of a haptic nature is superior to the capacity to process visual and auditory information. In explanation, they noted that the haptic modality is not limited to a single sense organ or receptor but is instead a combination of several interrelated mechanisms—a system that is not subject to the same rapid decay of information as observed in the icon and echo of very short-term sensory memory (Kiphart, Auday, & Cross).

Implicit and Explicit Memories

A major distinction in memory systems is that between *implicit* and *explicit* memory. Implicit memory is characterized by "priming," or a change in the performance of some task because of prior exposure to the task materials, a sort of acquired "perceptual fluency." Explicit memory is thought to be the conscious recognition or recall of objects or events using knowledge in one's memory (Tulving & Schacter, 1990).

Srinivas, Greene, and Easton (1997) set out to determine whether "the two perceptual systems (vision and touch) represent perceptual information in an equivalent manner in memory" (p. 536). Studying undergraduate students' (n = 120) ability to haptically identify novel 3-D, raised-line shapes, they found that both implicit and explicit tactual memory tests were affected by changes in the orientation and size of the forms between study and test; when the forms were left/right reversed or resized, the priming produced by implicit memory vanished. In contrast, a visual version of the test was affected by orientation changes but not size changes. This suggests that the source of implicit memory in touch is not identical to that in vision and that the functional representation in touch preserves the physical structure and scale of the touched objects.

Haptic Priming

Also of interest to researchers is cross-modal priming (implicit memory representation that is accessible multimodally) between the visual and haptic modalities. In a study involving 48 undergraduate students, Reales and Ballesteros (1999) used common objects (e.g., spoon, clothespin, and sponge) as stimuli and various implicit tests (e.g., speed of object naming, level of completeness at which a fragmented picture could be identified, and speed of deciding whether a line drawing depicted a real object) to investigate implicit and explicit memory under both intra-modal (i.e., within one modality) and cross-modal (i.e., between modalities) conditions. The results indicated cross-modal and intra-modal priming (faster responses for previously studied objects); and, in some cases, the magnitude of the cross-modal and intra-modal priming effects were equivalent, leading to the speculation that visual and haptic object representations are so similar that they might actually be shared between the two modalities.

Neurological Interactions

Aside from the above-described behavioral studies, there is a growing body of neurological evidence indicating that visual and haptic object representations are so similar that they might actually be shared. Several neuroimaging studies have indicated possible interactions between the visual and haptic systems. Researchers have used functional magnetic resonance imaging (fMRI) to measure the effects of cross-modal haptic-to-visual priming on brain activation (Sathian et al., 1997; Deibert, Kraut, Kremen, & Hart, 1999; Zangaladze et al., 1999; Amedi, Malach, Hendler, Peled, & Zohary, 2001). Results of these studies suggest that the neural substrate underlying both visual and haptic object recognition is found within the occipital cortex associated with visual processing. This overlap in some of the neural structures mediating haptic and visual processing of object structure suggests that the haptic system may exploit the highly developed object representation systems of the ventral visual pathway.

In light of this research, it remains unclear whether information from the haptic modality and its resulting representations are processed and stored in their own distinct form of memory (perhaps serving to reduce the cognitive load during a perceptual task) or the information is processed and stored in a region shared with visual information (subsequently creating the possibility of increasing the cognitive load).

How Might Haptics Affect Learning?

The studies discussed thus far suggest that touch, although not fully understood from an information-processing standpoint, is a fully functional cognitive system (Klatzky & Lederman, 2002). However, to date, very little empirical research has systematically investigated the value of adding haptic feedback to the complex process of teaching and learning.

Theoretically speaking, the use of multiple senses in learning is thought to be involved in the development of more generalized cognitive processes, that is, in moving from concrete to abstract thinking (Loucks-Horsley et al., 1990). It has been noted that "hands-on" or sensory-motor experiences are necessary elements in the development of formal operations (Wadsworth, 1989). The haptic experience goes beyond *passive touch,* such as the experience of an object being pressed against the skin. In such a case, the observer does not necessarily move, and information is imposed upon the skin. In contrast, haptics involves *active touch:* The individual deliberately chooses his or her actions in the exploration and manipulation of an object. In turn, those actions provide information about the properties of the object. The distinction between active and passive touch becomes important when haptics is examined in an educational setting. Sathian (1998) has suggested that involving students in consciously choosing to investigate the properties of an object is a powerful motivator and increases attention to learning. The existing research on haptics in education often highlights such affective influences; however, what seems harder to ascertain is whether incorporating haptics actually improves students' understandings.

Early on, Fitts and Posner (1967) defined three phases of learning: cognitive, associative, and autonomous. The cognitive phase is the explanatory stage of learning, where participants acquire an understanding of what is required. In this initial stage of learning, especially with a complicated motor task, haptics may significantly improve learning by allowing the participant to more easily make a connection between the instructions and the motor requirements. The associative stage is when the participant determines "how" to execute the motion or the task at hand, *learning by doing.* Haptics may also help during this stage by directly showing the participant how to accomplish the task; but we have found no studies that investigate this proposition.

Kinesthetic Knowledge

Some indirect evidence of how haptics may improve learning can bee seen in the technology's increasing use in flight and medical training. Many military and commercial pilots now are trained in flight simulators, which require the application of force or pressure on the controls corresponding to that occurring during actual flight. Likewise, many kinds of haptic interfaces are used for medical simulation, particularly for laparoscopic and endoscopic surgery. For example, the virtual environments for these applications can be programmed to resemble the soft tissue inside the human body, and the user can practice removing polyps and suturing tissue (Burdea, Zhuang, Rosko, Silver, & Langrama, 1992; Burdea, 1996). Although vision alone can provide useful anatomical information (such as tissue color and texture), touch seems to play a particularly critical role in minimally invasive surgery. Touch allows surgeons to identify hidden tissue planes and blood vessels, as well as to judge optimal forces to be applied for tissue manipulation.

It seems that many research groups have recognized the importance of touch in these situations, as evidenced by the appearance of more than two hundred articles addressing the medical application of haptic technology within the past 5 years alone. These works, beyond the scope of the present review, revolve around soft tissue modeling; robot-assisted, minimally invasive surgical techniques; needle insertion training; and the refinement of collision detection in virtual environments. Unfortunately, despite the increased attention, very little research has systematically and objectively compared haptic interfaces with each other or compared surgical trainings with and without haptics (Basdogan, De, Kim, Manivannan, Kim,

& Srinivasan, 2004). In addition, the perceptual cues that surgeons rely on, both visual and haptic, are complex and still poorly understood. To date, there has been little effort directed toward better understanding the perceptual–motor and cognitive processes that contribute to surgical performance (Tendick et al., 2000).

It is thought, however, that in these training scenarios the advantage of the addition of haptics is its impact on a person's kinesthetic memory (the ability to remember limb position, velocity, etc.). In a review of the research on kinesthetic memory, Clark and Horch (1986) suggest that human beings have a remarkable ability to remember the positions of their limbs quite accurately and for long periods. Haptic training is different from visual training in that the learning that takes place is body centered. This approach may also be useful for complex, three dimensional motor skills that are difficult to explain and describe verbally or even visually. Perhaps this active type of learning, encouraged by the use of haptics (with its physical practice), has benefits over more passive observational learning (Laguna, 2000). One would expect similar results in the context of the classroom; however, we have found only seven studies that provide empirical evidence to bolster such theoretical notions. These intervention studies are summarized in Table 4 and are discussed below.

Embodied Knowledge

The role of tactile perception in learning about forces and fields in the study of physics was investigated by Reiner (1999). Twelve graduate students (10 male and 2 female) with no background of formal study in physics volunteered for the experiment. Participants used a tactile trackball (a 5-cm ball seated on a ring and supported by four wheels). Two wheels were attached to a perpendicular motor to create a torque on the trackball. The learning environment included a computer simulation of a force field, and an object presented on a computer screen was subject to forces applied by an invisible field. The participants were able to manipulate the object in the field by rotating the tactile trackball, which required them to apply a force to it. This "feel of force" corresponded to the simulated forces "applied" by the field on the object; the stronger the simulated forces were, the stronger the force needed on the trackball.

Participants were asked to explore the structure of three predesigned invisible fields by using this tactile interface. The fields included a hidden attraction center or a hidden repulsion center, or both; the object was visible and arbitrarily located. After an exploration phase, participants were asked to draw maps that described the forces they experienced. They constructed one map that described the lines along which forces acted on the object on the screen and one that described lines along which forces exerted on the object felt the same. They were also asked to design and draw a map that described the force lines indicating an object energetically trapped in a particular area and a map that described the force lines showing that no matter where the object was located, it always moved horizontally, from left to right. These tasks were designed to explore students' conceptual representations of force lines, equal force lines, a particle trapped in a potential well, and a current.

Student drawings were analyzed qualitatively, and Reiner contends that the results "clearly show that patterns of forces exerted and felt by the participating subjects act as an external stimulus for constructing conceptual representations" (1999, p. 51). Reiner presented "embodied experiences" as a way to explain the

TABLE 4
Descriptive summary of intervention studies

Study	Participant type	*N*	Interface	Stimuli	Task(s)	Dependent variable(s)
Reiner (1999)	Graduate students	12	Tactile trackball	Computer simulations of force fields	Drawing force-field maps	Accuracy of drawings
Florence et al. (2004)	Children (mean age of 5 years and 7 months)	60	Index finger	Foam letters	Rhyme identification and phoneme tests	Understandings of the alphabetic principle
Brooks et al. (1990)	Experienced biochemists	12	Force-feedback device	Computer simulations of molecular interactions	Docking drugs into the active site of a protein molecule	Understandings of binding energy and docking positions
Jones et al. (2003)	High school students	50	NanoManipulator (nM)	3-D computer-generated images of a virus sample	Knowledge tests, opinion questionnaire, clay modeling, and interviews	Understandings of viruses and microscopy
Clark & Jorde (2004)	Middle school students	120	Simulated tactile model	Computer-based thermal equilibrium visualizations	Knowledge tests and interviews	Understandings of thermodynamics
Williams, Chen, & Seaton (2003)	Elementary school and college undergraduate students	56	Force-feedback joystick	Virtual simple-machine simulations	Opinion questionnaire	Perceived value of program
Okamura, Richard, & Cutkosky (2002)	College undergraduate students	Not given	Haptic paddle	Virtual dynamic systems	Opinion questionnaire	Perceived value of program

positive educational impact of haptics. That is to say, this learning environment stirs up tacit embodied knowledge, previously unexploited nonpropositional knowledge. This type of knowledge is in immediate relation (i.e., without the mediation of symbols and concepts) to objects and bodily acts. Reiner goes on to suggest that haptic devices are interfaces that promote the use of bodily, nonpropositional knowledge in the building of more accurate mental models and representations. These claims may be a bit bold given the absence of a control group, the small sample size, the lack of any quantitative analysis of learning outcomes, and the inherently subjective nature of the evaluation of student drawings.

Tactile Knowledge

Additional insight into the potential value of haptic stimulation in learning is provided by a study that examined the effects of incorporating actual (nonvirtual) haptic exploration of letters into a training program designed to develop understandings of the alphabetic principle among pre-reading kindergarten children (Florence, Gentaz, Pascale, & Sprenger-Charolles, 2004). Here the authors note that reading acquisition is broadly thought to consist of the development of phonological and orthographic representations, as well as the establishment of connections between these two types of representation. Yet much of the research assumes that this is an "implicit" process that is triggered by the learning of letter–sound correspondences. It is commonly thought that one source of difficulty in learning to read is the child's inability to establish a connection between the visual image of a word and its auditory image (Florence et al., 2004). In an attempt to overcome this difficulty, a "multisensory" learning method (largely based on Montessori's principles) involving not only on the visual and auditory modes but also the manual and active haptic mode was used. This teaching technique, known as the "multisensory trace" (Fernald, 1943), involves the child in tracing a written word with an index finger while pronouncing the word and looking at it.

Sixty monolingual French children (25 girls and 35 boys) with a mean age of 5 years and 7 months took part in this study; all were pre-readers and had no prior training with phonological tasks. Three different seven-session training interventions were assessed: In one, letters were explored visually and haptically; in the second, they were explored only visually; in the third, they were explored visually but in a sequential manner. Children in the visual and haptic training were told to explore the relief of foam letters with their fingers and to run their index finger along its outlines in a fixed exploratory order corresponding to the way it would have been written if by hand. All three interventions made use of the same phonological exercises, and children were matched according to age, vocabulary level, nonverbal performance level, metaphonological ability, knowledge of the alphabet letters, and pseudoword decoding (Florence et al., 2004). Participants' understanding and use of the alphabetic principle and their metaphonological abilities were individually assessed between 1 and 2 weeks before and after the interventions. The assessments were conducted by the same experimenter, who had no knowledge of the training assignments. The understanding and use of the alphabetic principle were measured by using a pseudoword decoding test and a test requiring the recognition of the alphabet letters. The pseudowords were composed of the letters studied during the training sessions. In the letter recognition test, the experimenter said the name of a letter, and the child had to indicate on a presentation card (composed of six letters) the letter he or she had just heard. The children's metaphonological abilities were measured by means of three tests: a rhyme identification test and two phoneme identification tests (Florence et al.).

The results of this study showed that incorporating the haptic exploration increased the positive effects of the training on the understanding and use of the alphabetic principle in young children and on their decoding skills. Perhaps more important, the haptic exploration appeared to help students establish the link between the orthographic representations of the letters and the phonological representation of the corresponding sounds. It was suggested that the beneficial effect of incorporating the haptic modality could be due to various functional specificities of the sensory modalities (Gentaz & Rossetti, 1999; Hatwell, Streri, & Gentaz, 2003; Lederman & Klatzky, 1987). Including the haptic exploration led the children to process the letters in a more sequential way, which children do not do implicitly when the letters are presented in a visual form only.

Simulated Learning Environments

Many education researchers, in particular science educators, assert that simulations and virtual models are an extremely powerful resource for the advancement and application of science (e.g., Linn, 1997, 2003). It is thought that students immersed in interactive computer "microworlds" may acquire hands-on and "minds-on" experiences that allow them to develop a deeper understanding of scientific concepts (White, 1992; Bransford, Brown, & Cocking, 1999). In an attempt to create a more "real" experience, the addition of haptic feedback to these simulated environments has been investigated in several studies.

Biological Sciences

In part of the influential study known as Project GROPE, Brooks, Ouh-Young, Batter, and Kilpatrick (1990) examined the impact of adding haptic feedback to a simple 6-D (i.e., *x, y,* and *z,* coordinates and pitch, yaw, and roll) docking task. The participants were 12 experienced biochemists; all had worked on molecular modeling problems for at least 2 years. Their task was to dock each of four drugs into the active site of a protein molecule by orienting the drug and adjusting up to six of its internal twistable bonds to give the lowest potential energy of the docked combination. They were expected to consider surface geometry, electrostatic forces, and hydrogen bonding. They were divided into two groups, one docking with force feedback and one docking without force feedback; the same visual display was used for both groups. After a training session with two "training" drugs, the participants were allowed 2.5 hours to dock the four test drugs from random starting positions and given 5 minutes of rest between trials. They were also given 3 minutes to study the geometries of each test drug before beginning actual manipulation of it (Brooks et al., 1990).

It was found that adding forces (simulated by means of haptic feedback) to a visual display enhanced the users' understanding of the binding energy of a drug molecule, their perception of valid docking positions for drugs, and their conception of why a particular drug docks well or poorly (Brooks et al., 1990). It is worth noting that in this study the participants could be considered "experts," with extensive domain-specific knowledge. One wonders whether the results would be similar with adults whose prior knowledge of biochemistry and molecular models was limited.

More recently, the effects of incorporating haptics into school biology instruction were investigated by Jones and colleagues (Jones, Andre, Superfine, & Taylor, 2003). The context for this exploratory research was a 5-day unit on viruses and microscopy and involved 50 students (24 male and 26 female) from two high school biology classes. As part of the study, students had the opportunity to use a nanoManipulator (nM), which combines an atomic force microscope (AFM) with software, a desktop computer, and a haptic PHANToM desktop device (Figure 3). By using this interface students were able to push, cut, and poke an actual virus.

Aside from studying the overall educational impact of using this innovative tool, the researchers were particularly "interested in exploring whether feeling an object that one cannot ordinarily see with the unaided eye would alter an individual's conception of that object" (Jones et al., 2003, p. 309). Thus students in one of the two classes involved were randomly assigned to a full-tactile condition and were able to feel the interaction between the virus sample and the probing tip of an AFM. Students in the second class were able to use the device in much the same way but did not receive any haptic feedback. This was achieved through a "software switch" that would either send or not send the appropriate tactile signals to the nM.

All participants completed pre- and post-assessments (e.g., knowledge test, opinion questionnaire, clay modeling task, and interviews) and a series of instructional activities. The instructional activities included whole-class instruction (covering metric scale, microscopes, and an in-depth description of how the nM and AFM work to provide magnified images and tactile feedback); using the nM–AFM interface; using a mechanical simulation of the AFM; and writing a newspaper story about the experience of participating in the study.

Analysis of the written assessments involved a pre-to-post-instruction comparison across the two treatment groups. Students' clay models of viruses were photographed and coded on the basis of their morphologic attributes (e.g., number of angles, number of spatial dimensions, and shape). The results suggest that students from both treatment groups had improved their understandings of the microscale, of virus morphology, and of virus dimensionality as a result of their participation. The study results also showed that haptics had a positive affective impact, in the sense that students who received the haptic feedback reported being more interested in the experience and feeling that they could participate more fully. However, cognitive differences between the two groups were not detected. In an attempt to explain this finding, the authors suggested that the small sample size may have resulted in a limited power to detect group differences. Perhaps more pertinent to this review, they also acknowledged that the "mere novelty of participating in this type of unusual instructional experience" may have altered students' motivation and interest, and that "the assessments were not able to assess haptic features of viruses directly" (Jones et al., 2003, p. 319). Limitations such as these are not unique to this study and are, in fact, endemic to the research involving the use of haptics in education.

Physical Science

Haptic augmentation may also help students to develop conceptions of "invisible" phenomena in the physical sciences. Clark and Jorde (2004) studied the impact of integrating a tactile sensory model into a thermal equilibrium visualization. The visualization was embedded in a weeklong inquiry project, and 120 eighth-grade

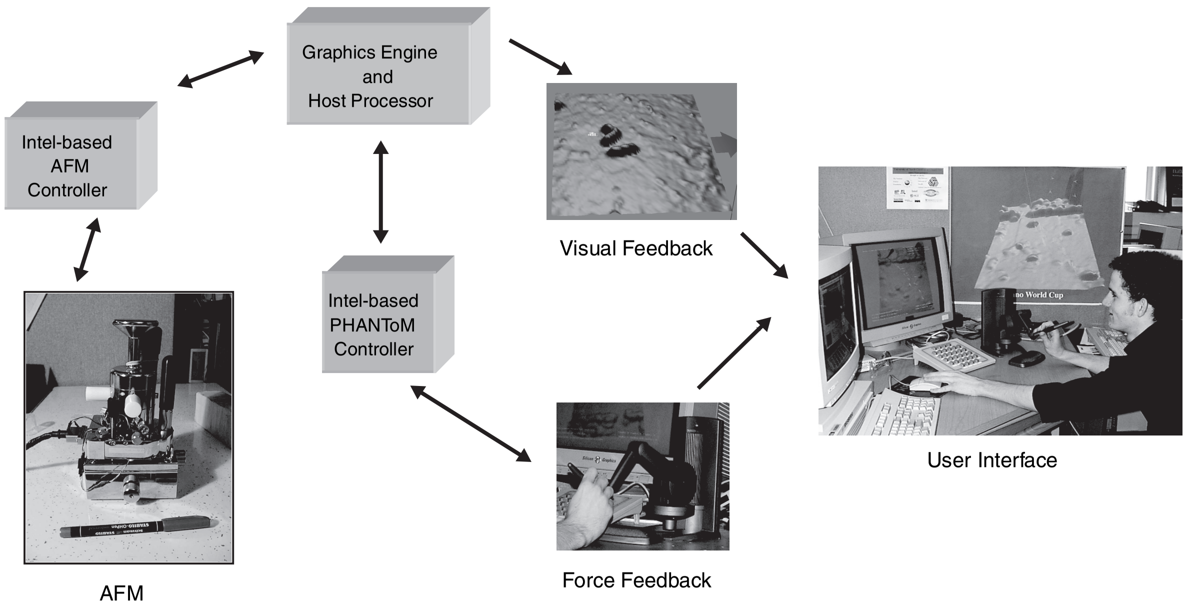

FIGURE 3. *The nanoManipulator system incorporating an atomic force microscope (AFM), software, desktop computer, and a PHANToM desktop device. Adapted with permission from Russell M. Taylor.*

students from four intact classes participated. The classes were randomly assigned to two treatment groups ($n = 60$ each). Both groups engaged in all of the core components of the project (e.g., a lab, discussions, and the thermal equilibrium visualization); the only difference between the conditions was that the visualization in the experimental group included the simulated integrated tactile model. This tactile model did not incorporate actual haptic feedback; instead, in an attempt to indicate how hot or cold an object feels, it showed a hand next to the object with heat-flow arrows flowing to or from the hand at varying rates depending on the temperature gradient between the hand and object. In addition, the visualization used audio and text messages that described how the object felt (e.g., "This feels burning hot!").

Data were generated using written pretests, posttests, and delayed posttests designed to measure students' understandings of thermal equilibrium. Students' mean test scores were compared across the groups through analysis of variance. In addition, interviews were conducted (after both pretest and posttest) with a subset of the participants (students who made up the middle third of their class, as determined by their performance on the pretest). The intent of the interview questions was to probe students' understanding of thermodynamics in the context of everyday situations. In this study the mere simulation of tactile feedback was associated with middle school students' improved understanding of thermal equilibrium, in the sense that the students who experienced the tactile model of thermal sensation showed a greater ability to describe in terms of thermal equilibrium why objects "feel" the way they do. However, one might question the veracity of these results, in part because of an overemphasis on results from objective written assessment items and the use of a simple gain score approach as the sole means of statistical analysis.

Another group, working with the Learning Technologies Project at NASA's Langley Research Center, has developed and pilot-tested a series of haptically augmented software programs for teaching elementary school students simple-machine concepts (Williams, Chen, & Seaton, 2003). The investigators assert that "since force is central to the teaching of simple machines the use of haptics in virtual simple-machine simulations has the potential for deeper, more engaging learning" (p. 1). The program uses a low-cost force-feedback gaming joystick and includes five interactive activities that were designed to reinforce concepts presented in a standard simple-machine curriculum. The activities feature various simple-machine configurations, and students are able to "feel the effects of different choices" (p. 10) on the modeled system. For example, one activity (Figure 4) allows the user to feel the force required to move a load with a lever.

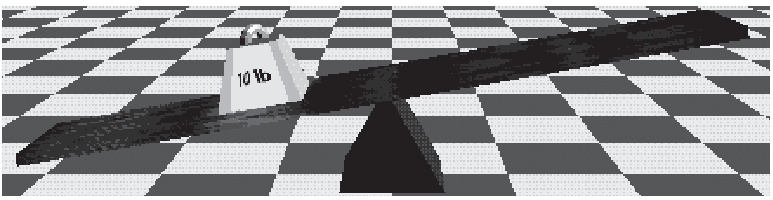

FIGURE 4. *A computer-screen view of The Lever, an activity developed by Williams, Chen, and Seaton, 2003 (p. 4). Reprinted with permission. Copyright 2003 by Springer Netherlands.*

Here, the fulcrum and applied force locations are fixed, but the user may change the distance from the load to the fulcrum. Moving the haptic interface causes the virtual lever to operate. The student "feels" the effort required, sees the load distance moved, and can compare the results for varying fulcrum lengths.

Although the researchers themselves recognize that the findings of this study are not the result of rigorous statistical analysis, they urge that the work accurately portrays the positive opinions of the student users. Through post-experience surveys, 56 students (second through sixth grades) from two elementary schools and an undergraduate robotics/haptics class reported that they felt the haptically augmented projects were effective; the students also provided suggestions for improvements to the software (Williams, Chen, & Seaton, 2003).

In an attempt to "provide an intuitive connection between the physical world and mathematical concepts" involved in teaching about dynamic systems, a team of researchers from Stanford University developed a low-cost haptic interface (Okamura, Richard, & Cutkosky, 2002, p. 345). The *haptic paddle* is similar in basic function to more sophisticated and costly commercial interfaces, in that it is able to simulate the interaction forces that occur when human beings come into contact with physical systems. However, a key difference is that it offers only one degree of freedom (the directions and rotations at which an object can move in relation to its axes) as opposed to the six degrees of freedom afforded by more expensive haptic devices. It should also be noted that the fidelity of the force feedback provided by the haptic paddle is not as high as that provided by the high-end devices.

To evaluate the impact of this low-cost (roughly $70) device, groups of students enrolled in a 10-week course on dynamic systems were engaged in the modeling, assembling, and use of haptic paddles. As the user moved the handle of the haptic paddle from side to side, the position of the handle was sensed. On the basis of the position and velocity of the handle, varying amounts of force were translated back to the user (Okamura et al., 2002). The participants were able to estimate the parameters of a system model, analyze responses in a second-order system, and interact with computer simulations of these dynamic systems. On completion, the participants were surveyed about their perception of the value of the haptic paddle laboratories. Most of the lab activities involved the device, but only two labs provided haptic feedback.

It was found that the highest mean ratings were for the labs that allowed students to "feel the effects" of feedback control and to interact with the virtual dynamic systems. Unfortunately, no additional data were reported in this short educational brief. The researchers noted the need for a more rigorous analysis of the cognitive impact of the technology, stating that "to determine objectively the understanding enhanced by the haptic paddles, we would have to compare the exam performance of groups of students in the same class with and without the addition of haptic paddle laboratories and demonstrations" (Okamura et al., 2002, p. 348). Also making the results of the investigation difficult to interpret was the absence of information on sample size, sample demographics, or students' initial knowledge of dynamic systems.

From a constructivist's perspective, the haptic augmentation of computer-generated 3-D virtual environments in which the student is an active participant can be an extremely powerful teaching tool (Lochhead, 1988; Glasson, 1989; Loucks-Horsley et al., 1990; Brooks & Brooks, 1993). Learning is often defined as the construction of knowledge, on the assumption that sensory data are given meaning in terms of prior knowledge (Tobin, 1990). The addition of haptics may afford students the opportunity to become more fully immersed in this process of meaning-making, by taking advantage of tactile, kinesthetic, experiential, and embodied knowledge in new ways. But, as demonstrated here, the studies that have directly investigated these ideas tend to be strong on claims but somewhat weak in supporting evidence.

Findings, Constraints, and the Future of Haptics in Education

In this article we have explored how the active manipulation of both real and virtual objects and events potentially leads to a more complete understanding of them. In light of the research presented here, a sophisticated understanding of the impact that haptics has on teaching and learning still eludes us. Does the unique bidirectional exchange of information between a user and a haptic device somehow enhance the learning experience? It is still largely unknown whether augmenting instruction with the sense of touch can exploit experiential, embodied, and tactile knowledge that might not otherwise be called upon by students. Moreover, it is unclear whether haptic technology is best suited for the augmentation of existing knowledge or for the discovery of new knowledge.

This review has, at times, portrayed haptics as an exciting and innovative way to enhance the learning environment. Although that picture may be accurate, there are formidable barriers to the adoption and widespread use of haptics in education. We classify these impediments as perceptual, technological, and methodological in nature.

Perceptual Impediments

Much of the earlier research investigating haptic perception (e.g., Lederman & Klatzky, 1987, 1990; Klatzky & Lederman, 1999) was conducted with participants in controlled settings that deprived them of the ability to use vision, making haptic clues more vital. Conversely, the circumstances created in most of the work done in educational settings (e.g., Brooks et al., 1990; Reiner, 1999; Jones et al., 2003; Williams, Chen, & Seaton, 2003) were quite different. There, individuals received bimodal feedback and could take advantage of both visual and haptic information as they progressed through the various instructional programs. Although there is mounting evidence that the visual and haptic perceptual systems are inextricably intertwined, the exact nature and functioning of the association is still under investigation.

Klatzky, Lederman, and Matula (1991) raised this issue of "modality specificity in perceptual encoding," which they discussed in terms of the differential appropriateness of visual and haptic information. They suggested that when vision is available and adequate for a task, haptic exploration may not be evoked because of its relatively high processing cost. In addition, the visual recognition of an object may rapidly trigger the retrieval of information about its properties stored in memory that is semantically accessible, thus eliminating the need for direct perceptual encoding by visual or haptic exploration (Klatzky, Lederman, & Matula, 1993).

With this in mind, it can be postulated that students instinctually rely more heavily on the visual information that they receive, such as an object's geometric properties and color. Considering that teachers traditionally present information and concepts using only verbal and visual stimuli, it may be reasonable to suspect that the additional perceptual information made available through haptic explorations is not salient for students. Thus further exploratory research into the nature and persistence of visual–haptic information interactions is certainly warranted.

Technological Constraints

In general, perception and subsequent performance are of lower quality in a virtual environment than in a live environment. As suggested earlier, there are numerous everyday situations that require us to be proficient in identifying objects with our bare hands, even without the aid of vision. In such unconstrained haptic explorations, a multitude of tactile and kinesthetic inputs are available for further processing. However, our haptic perception is impaired considerably when manual exploration is constrained (Klatzky & Lederman, 1993; Lederman & Klatzky, 2004). Manual exploration was severely constrained in the research studies where students were expected to remotely explore objects or events by using the rigid point-probe of a haptic device (e.g., Brooks et al., 1990; Jones et al., 2003). The degradation in the quality of perception and performance was due primarily to a substantial decrease in the number and size of contact areas between the user and the object, caused by the point-probe itself as well as by the approximations inherent in the computer models of simulated contact. For example, using contour following (see Figure 2) to obtain shape information would be particularly difficult and inefficient using a single point of contact.

A logical next step for work in this area may be the continued development and testing of a haptic interface incorporating several points of contact (corresponding to the tips of different fingers) to facilitate more optimal acquisition of information regarding object properties. It may be possible to further increase the sensory information available to the user through the haptic channel by increasing the number of contact points between the user and the virtual world, enabling a more robust use of exploratory procedures. One imagines that, with two or more contact points, the user could execute grasping procedures, which could provide weight information by means of lifting, as well as information on frictional material properties through grasp strength and slip sensing. Thus simulated environments could be brought closer to the real environments that they strive to represent (Barbagli, Salisbury, & Devengenzo, 2004).

We suggest that there exists another perceptual limitation that compounds this technological issue. Perhaps the brain's executive function, the ability to manipulate and integrate streams of information held in short-term memory, is not fully developed in many school-age children. This certainly would complicate the already difficult task of building complete understandings of objects and events on the basis of visual and haptic sensory information.

In addition, the cost of implementing haptic devices at present is quite high. Although the price of the interfaces have dropped considerably since their debut in the 1990s, it is unlikely that one could find an existing school computer lab outfitted with them. Perhaps the combined effects of a growing research base and more affordable interfaces will lead to an increased use of haptics in educational settings.

Methodological Limitations

In conducting this review, it became clear to us that a chasm currently separates two equally important types of research in the field of haptics. On one side lies the voluminous and rich literature regarding the development, perceptual power, and complexity of the haptic sense. Most of these studies, conducted primarily by developmental and cognitive psychologists, could be described as pure basic research—research conducted in an attempt to identify and detail the underlying principles and processes of haptics. This foundational research is often conducted in pristine and "uncluttered" laboratories with relatively small samples of eager participants. Again, generally speaking, these studies are methodologically rigorous, include sophisticated statistical analyses, and provide sound evidence-based results.

On the other side of the gap resides a scant collection of application or intervention studies that have investigated the efficacy of haptically augmented instruction. Here, the researchers are mainly educators and educational technologists whose work focuses on an in-context technological innovation with attention to issues of practice and users' experiences with the emerging technology. The research methodologies employed are varied and at times sound, often capturing valuable qualitative—and, to a lesser extent, quantitative—data. However, these studies seem unable to control for all of the confounding variables present in today's classrooms. As a whole, they have resulted in little empirical evidence for the existence of a cognitive impact of haptic technology.

The Future of Haptics in Education

Perhaps the true potential of haptics in education will not be realized until the research in this arena moves into what Stokes (1997) called the "use-inspired basic research" portion of Pasteur's quadrant. Such research would bridge the lacuna and systematically link the fundamental research on haptic perception and cognition with the research on haptics as an intervention for change. Then we might succeed in applying the knowledge creation of basic research to achieve beneficial effects in real-world classrooms.

It would be both interesting and informative if—armed with the theories and understandings of haptics built by psychologists and cognitive scientists—we could rigorously investigate the effects of using the latest technologies in the field to create haptically rich learning environments. Perhaps one day students will become immersed in a virtual animal cell, more fully exploring its structure and functioning. Perhaps physics instruction will use haptic feedback devices to teach students more effectively about invisible forces such as gravity and friction. Visually impaired students may learn math by touching data represented in a tangible graph and chemistry by feeling the attractive and repulsive forces associated with various compounds. There is a critical need for more in-school studies that pay attention to developmental, cognitive, and behavioral factors that contribute to student learning with this new technology. We need more research into how students perceive, process, store, and use haptic information in a variety of educational contexts and settings. Continued investment and research in this area have the potential to pay off not only in a more robust understanding of haptics in education but also, ultimately, in the creation of new ways to engage learners of all types and at all levels in the active construction of more meaningful understandings.

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