Seeing with the Hands and with the Eyes: The Contributions of Haptic Cues to Anatomical Shape Recognition in Surgery

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Abstract

Medical experts routinely need to identify the shapes of anatomical structures, and surgeons report that they depend substantially on touch to help them with this process. In this paper, we discuss possible reasons why touch may be especially important for anatomical shape recognition in surgery, and why in this domain haptic cues may be at least as informative about shape as visual cues. We go on to discuss modern surgical methods, in which these haptic cues are substantially diminished. We conclude that a potential future challenge is to find ways to reinstate these important cues and to help surgeons recognize shapes in the restricted sensory conditions of minimally invasive surgery.

Object Recognition by Touch and Vision

Many of our everyday interactions with the world involve coordinated visual-haptic perceptions. We use both vision and haptics in concert to reach towards and grasp objects. By handling an item as well as looking at it, we get access to additional information about its 3D shape (Newell, Ernst, Tjan & Bulthoff, 2001), as well as material properties such as compliance, weight, warmth, and surface texture (Klatzky, Lederman, & Reed, 1987).

Evidence suggests that we have evolved to interact with objects using seen hands. The brains of humans and other dexterous primates contain specialized bimodal "visuotactile" neurons that coordinate information from vision and touch (Grazanio & Gross, 1993; Leinonen, Hyvarinen, Nyman, & Linnankoski, 1979). At a higher level of representation, human memory uses similar parameters to code information from the eyes and from the hands. The two modalities share common spatial reference frames, with similar memory representations arising for objects regardless of whether they are perceived through vision or through touch. As a result, cues presented though one modality can benefit memory for objects recognized through the other modality. Crossmodal visual-haptic priming has been found in a number of studies, with haptic cues benefiting visual recall, and visual priming enhancing haptic recognition (Ballesteros, Reales, & Manga, 1999; Easton, Greene, & Srinivas, 1999; Easton, Srinivas, & Greene, 1997; Reales & Ballesteros, 1999). Studies using fMRI have shown activation in visual processing areas during haptic exploration of objects, suggesting that representations in the visual system are involved in tactile object recognition (Diebert, Kraut, Kremen, & Hart, 1999). Consistent with this, the disruptive effect of transcranial magnetic stimulation, when applied to the occipital cortex (known to be involved in *visual* processing), also interferes with *haptic* discrimination, indicating that at least some visual processing areas are essential to tactile perception (Zangaladze, Epstein, Grafton, & Sathian, 1999).

At the relatively high level of object recognition, then, it seems that information acquired through vision and touch feed into common representations, and that these sensory modalities complement each other. But each of these systems also has unique properties. We later argue that it is these special modality-specific affordances that make the sense of touch so valuable for shape recognition in surgery.

Learning about Anatomical Shapes

One of the key goals of medical education is to provide future medical professionals with an expert knowledge of anatomy. They must be able to identify the shapes of anatomical structures and understand the relations among them. They also need sufficient knowledge to recognize abnormalities or changes to anatomical shapes resulting from tumors, adhesions, injury, damage, or atypical growth and development. An important question for cognitive scientists is how anatomical knowledge is acquired and stored in long-term memory.

In medical education, anatomical information is usually presented using analog visuospatial or 3D representations,

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which capture shape in a direct one-to-one mapping. Diagrams have been used for centuries, and typically present key visuospatial information in a minimalistic form, with superfluous details removed or reduced. Even with high-definition color photography now available, textbook diagrams have retained largely the same principles. They generally include one or two key views of the target object, often with a cross-sectional view to show hidden internal structure and external shape. Medical educators recognize that simplified representations focusing on three-dimensional qualities are the most effective representational formats, and this principle of "omitting the irrelevant" is consistent with received wisdom among graphical designers and cognitive scientists (Tversky, Heiser, Mackenzie, Lozano & Morrison, 2008).

Given the close relationship between vision and touch, it seems plausible that having access to both visual and tactile information during learning should help to generate an effective mental representation, which can later be recognized through either modality or a combination of both. In dissection classes, medical students interact with 3D models or real human cadavers using their hands and dissecting tools, exploring the shapes and relations of internal organs, joints and musculature. Medical educators claim that dissection is a critical part of the student learning experience, since lectures and textbooks cannot replicate the 3D structural and material information gained from these experiences.

Anatomical Knowledge is Spatial

Research shows that tests measuring spatial visualization abilities are correlated with success in learning anatomy. Such findings indicate that shape-related and other spatial information is represented in mental models of anatomy. Rochford (1985) found that low-spatial medical students achieved consistently lower grades than high spatial students in practical anatomy exams and multiple-choice anatomy tests. Importantly, spatial visualization ability was predictive of success only on exam questions classified as spatially three-dimensional by experts – items that involved propositional knowledge did not correlate with this ability, indicating that this finding was not simply an artifact of general intelligence differences. Similarly, mental rotation test scores predict medical students' success in learning the complex shapes and configurations of anatomical structures from 3D computer models, including the carpal bones of the wrist (Garg, Norman, & Sperotable, 2001) and human cervical vertebrae (Stull, Hegarty, & Mayer, 2009). Findings such as these indicate that success in acquiring long-term knowledge of anatomy depends on the ability to mentally represent and manipulate shapes and spatial relations, strongly suggesting that what is learned is substantially spatial in nature, and is not merely propositional or semantic knowledge.

Spatial ability also predicts performance in medical specialties that are anatomically demanding, such as surgery and dentistry. In the field of dentistry, entrants are pre-screened for strong spatial abilities. In this domain, the ability to mentally generate, maintain, transform, and recognize structures is viewed as critical for success. For example, the hidden shapes of tooth roots and their internal pulp canals cannot be directly seen, and therefore a mental representation of their 3D shape has to be inferred using 2D cross-sectional X-ray images taken from different orientations. Studies have shown that spatial reasoning predicts success in anatomically demanding sub-fields such as operative dentistry, endodontics, anatomy, and dental anatomy (Just, 1979). Spatial ability is important in restorative dentistry, in which the three-dimensional shapes of teeth have to be recreated from knowledge of their structure and an understanding of how they fit with the complementary shapes of abutting teeth (Hegarty, Keehner, Khooshabeh, & Montello, 2009). Hegarty and colleagues found that advanced dentistry students performed better than beginning dentistry students and novices on tests that involved mental transformations of 3D tooth shapes, but were no better when the transformations involved unfamiliar 3D shapes. Thus, what is learned in dentistry education, and probably in medical education generally, is spatial mental models of the shapes of anatomical structures.

Shape Identification in Surgery

In surgery, the objective is to plan and conduct operative procedures. Surgeons use expert knowledge of anatomy to identify, manipulate, navigate, and perform complex actions on anatomical structures. Anecdotally, surgeons claim that the sense of touch is critical for identifying anatomical shapes. They report that "seeing" with their hands is just as important as seeing with their eyes. Yet the sense of touch is usually considered a relatively unreliable source of geometric information (Rock & Victor, 1964; Hay, Pick, & Ikeda, 1965; Warren & Rossano, 1991; Welch & Warren, 1980), and tactile perception is less accurate than vision in judgments of shape-related features such as curvature (Kappers, Koenderink, & Oudenaarden, 1997). So, how can we reconcile the anecdotal claims of surgeons with empirical findings that cast doubt on the ability of touch to provide veridical shape information? One plausible argument is that the domain of surgery provides unique conditions that particularly favor haptic perception.

In traditional open surgery, it would be difficult to identify anatomical structures using vision alone. Blood vessels can be hard to distinguish from other tubular structures by sight. Adhesions (scar tissue) from previous procedures can change the shape and appearance of structures. During surgery, bleeding at the operative site often hampers visual information about shape, size, and color. Basic research in perception shows that sensory

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inputs are weighted according to the quality of information they provide. If visual cues are ambiguous or weak, or degraded by extraneous visual noise, they carry less weight, and haptic cues come to dominate (Ernst & Banks, 2002). Atkins, Fiser, & Jacobs (2001) have shown that we vary the way we combine visual and haptic cues depending on contextual constraints. When two conflicting visual cues are presented and haptic information correlates with only one of these, the information received through touch moderates the interpretation of the visual information. Thus, “haptic percepts provide a standard against which the relative reliabilities of visual cues can be evaluated” (p. 459). Similarly, Ernst, Banks, & Buelthoff (2000) have demonstrated haptic dominance in slant judgments, when conflicting visual cues created an ambiguous visual signal. In the unusual conditions of surgery, therefore, it is possible that haptic information carries more weight than usual in shape-related judgments.

But the potential advantages of haptic cues go beyond merely compensating for poor vision. The sense of touch provides additional affordances that are highly relevant in this domain. The eyes have a single viewpoint, but the hands have multiple ‘touchpoints’ (Lowe & Keehner, 2008), and thus the fingers and palm can work in concert as a 3D ‘shape gauge’. This shape-gauging mechanism is something for which there is no direct equivalent in visual exploration. It is true that vision has the advantage in acuity and resolution, due to its greater bandwidth. But the hands have multiple cutaneous mechanoreceptors that sense touch at many different locations across the palm and finger surfaces. Moreover, kinesthetic sensors detect the operation of muscles and tendons and the angle of bend in the finger joints, providing information about the shape of the structure around which the hand is wrapped (Lederman & Klatzky, 2009). These multiple simultaneous sensors give touch some very special and unique affordances.

Haptic exploration allows objects to be identified surprisingly rapidly and accurately. Even a very brief interaction, or *haptic glance*, allows recognition, especially when top-down information such as long term knowledge is available (Klatzky, Lederman & Metzger, 1985; Klatzky & Lederman, 1987; 1999). The effectiveness of haptics for object recognition has been attributed to its unique ability to encode many different object properties simultaneously. In a study by Klatzky, Loomis, Lederman, Wake and Fujita (1993), two factors emerged as particularly important for recognizing objects: 3D shape information (acquired most efficiently by enveloping and manipulating the object with the whole hand) and integration of information across the fingers. Consistent with this, it has been shown that we use intelligent exploration routines and systematic hand movements to classify objects sensed through touch, and that these active *exploratory procedures* enhance the perceptual performance of the haptic modality, especially for 3D shape information (Klatzky & Lederman, 1987).

These affordances are very relevant to the process of anatomical shape perception. In surgery, active haptic exploration often provides more information about the 3D shape of a structure than vision can, since it is often not possible to move the viewpoint around the object to see a different side, and it is rarely feasible to rotate the object around to expose the back view. Direct haptic exploration, by contrast, allows the hands to be rotated around the shape to explore the non-visible back and sides. In fact, research indicates that the hands are especially well suited to this function (Ernst, Lange, & Newell, 2007; Newell et al., 2001). Furthermore, studies show that if we use touch to obtain and make decisions about shape-related information and we direct our attention to information from the hands, this sense is allocated more weight and can provide more accurate perception than it does under other circumstances (Heller, Calcaterra, Green, & Brown, 1999; Hershberger & Misceo, 1996).

It is also important to bear in mind the unusual nature of anatomical objects. While most studies showing visual superiority in shape perception have used rigid, regular, geometric shapes, anatomical regions such as the thorax, abdomen, and pelvis are packed with 3D shapes made of soft tissues, which deform and displace when pressure is applied. Lederman, Summers, and Klatzky (1996) have shown that haptic encoding of objects favors the cognitive salience of material properties. It is clear that deformability, an essential characteristic of anatomical shapes, can only be properly perceived through touch. Furthermore, each individual patient is unique, and surgeons must take into account anatomical variability when identifying structures. With visual cues such as size, color, and location varying across cases, identifying structures by sight alone is not easy. Haptic exploration attenuates the salience of some properties and heightens others (Klatzky et al., 1987), which might help to single out more relevant attributes for anatomical shape recognition. With the unique conditions of surgery, it therefore seems plausible that haptic information adds substantially to shape perception processes in this domain.

Modern Surgical Methods: Implications for the Roles of Haptic and Visual Cues

Recent developments in operative techniques have led to dramatic changes in the sensory information available to surgeons. In minimally invasive or “keyhole” methods, surgical procedures are conducted using long instruments passed through small ports in the patient’s body. In contrast to open surgery there is no large incision, so the operative site is neither directly visible nor directly accessible to the hands. A miniature camera or laparoscope provides visual information via a monitor, and the instruments (operated from outside the body) provide the only physical connection to the operative site. These methods have become increasingly popular, and are now the norm for many procedures. They are beneficial to patients, with lower morbidity rates and faster recovery. But for surgeons, they have introduced new challenges.

Because of the physical disconnection between the surgeon and the operative site, the quality of sensory feedback is substantially degraded. Direct touch with the hands is not possible, and distal feedback from the instrument tips is distorted by friction in the cannulae (where the instruments enter the body). The haptic cues that surgeons say are so important for recognizing anatomical shapes are substantially diminished under these conditions. Bholat, Haluck, Kutz, Gorman, and Krummel (1999) asked surgical interns to recognize familiar 3D shapes using direct palpation with one hand, palpation using a conventional surgical instrument, or palpation using a long-handled laparoscopic instrument. Accuracy for shape characterization with the laparoscopic instrument dropped to 35.0%, compared to 98.3% for the hand and 56.7%, for the conventional instrument. Notably, the decrement was greater for shape discrimination than for judgments of either surface texture or hardness.

An important question for researchers is whether surgeons can learn to usefully interpret the distal information they receive from the tips of long instruments. Basic research has shown that, with extended experience, a tool held in the hand can become encoded as if it is an extension of the limb (Iriki, Tanaka, & Iwamura, 1996; Maravita, Spence, Kennett, & Driver, 2002). It is not currently known whether this can also happen under the indirect and somewhat distorted viewing conditions of laparoscopic surgery, how long this adaptation would take to accrue, or whether it is facilitated by particular operating conditions or individual factors. With increasing use of minimally invasive methods for many procedures, these will be important questions for future research. However, even if some adaptation occurs, it is unlikely that laparoscopic instruments could ever provide the same richness of information about objects as direct touch with the hands. The issue is not only the additional distance and bluntness of cues. These rigid, single-probe tools simply cannot provide the rich information about shape that can be determined by exploring objects with the multiple touchpoints of the fingers and palm.

Turning to visual cues, the effects of laparoscopic methods on these are mixed. On the plus side, the use of inert gas to inflate the abdomen reduces the problem of blood loss occluding structures, since the pressure prevents much blood from escaping. However, there are numerous factors that make visual object recognition more challenging. The camera is much closer to anatomical structures than in direct view, producing a magnification effect. The 2D view on the monitor contains no binocular depth cues, which are usually important for perceiving relative size and distance of objects. The laparoscope may be inserted at an angle that differs from the surgeon's perspective, so that the surgeon has to mentally compensate for this offset view, presumably with some kind of spatial transformation such as a mental rotation of the view or an imagined shift of their own perspective. Moreover, an assistant holds the camera, so the surgeon does not even have direct information about the degree of viewpoint offset, and must infer this from observing the laparoscope's point of entry into the patient's body. The viewing angle of the camera can vary between and within procedures, and this has implications for visual object recognition more generally. Basic research shows that when we learn the structure of an object, we acquire a long-term representation from a default or canonical viewpoint, and therefore recognizing the object from other viewing perspectives has some cost attached (Tarr, Williams, Hayward, & Gauthier, 1998). Studies in the medical domain suggest the same principle applies when we learn the shapes of anatomical structures (Garg et al., 2001). In videoscopic procedures, the surgeon may be seeing images of structures from quite unusual viewpoints. These factors are likely to increase the cognitive load involved in recognizing familiar shapes.

One example of a life-threatening recognition error that occurs much more frequently in laparoscopic surgery than in open surgery is the misidentification of the common bile duct as the cystic duct in laparoscopic cholecystectomy (removal of the gallbladder). The traditional indicator for identifying the cystic duct is its characteristic funnel-like shape, and for decades (in open surgery) this has been a sufficiently unambiguous cue. However, in laparoscopic conditions, where the perceptual information is limited or distorted, this shape-recognition method is much less reliable. In a review of human and cognitive factors in published reports of laparoscopic bile duct injury between 1997 and 2007, misidentification was found to be the cause of injury in 42 of the 49 cases reviewed, and cue ambiguity and visual misperception were identified as important factors (Dekker & Hugh, 2008). Surgeons are now being urged to adopt alternative methods, because the traditional technique, based exclusively on shape recognition, leads to errors in laparoscopic viewing conditions.

Looking to the Future: Possible Compensatory Technologies

Given that access to helpful perceptual information (especially haptic cues) is so restricted, are there ways to help surgeons better recognize shapes in minimally invasive conditions? One possibility might be stereoscopic viewing, to reinstate binocular depth cues. Although this does provide some additional 3D shape information, to date no studies have shown a conclusive advantage over monocular viewing. In any case, stereo vision cannot replace the 3D object information that can be gained by exploring shapes with the hands in open surgery.

Training with simulators that mimic the sensations of laparoscopic surgery might help surgeons learn to interpret distal haptic cues from the instrument tips. However, suitable technology for providing truly realistic haptic feedback does not yet exist. Even if it did, and we could use it to help surgeons more accurately interpret these distal cues, the resulting information would still be extremely impoverished compared to the rich and subtle cues available through direct touch with the hands.

In the distant future, could we simulate direct touch? Virtual palpation is being developed for applications such as remote diagnosis of medical conditions, for use in rural locations or space exploration. In these systems, a sensing device explores the object and sends feedback to a data glove or other wearable device that provides stimulation to the hand in real time (e.g., Kron & Schmidt, 2003). If such a system could be developed for minimally invasive surgery, it could help to reinstate some of the haptic cues that surgeons find so valuable. Given what we have already said about the clear advantages of receiving information from the hands' multiple touchpoints, the optimal design for such a sensing device would probably be broadly similar to the human hand in structure, mechanics, and placement of sensors.

A sensing device controlled by a master-slave system, in which exploratory movements of the surgeon's hand are reproduced by the device in real time, could help to enhance the illusion of direct touch. Studies using false hands have shown it is possible to produce the subjective sensation that our hand is somewhere it is not, provided the visual and haptic cues are reasonably congruent (Pavani, Spence, & Driver, 2000). This illusion occurs because vision usually provides reliable information about limb posture and because haptic and visual cues from our hands usually correspond. Consequently, if we see a plausibly placed false hand receiving touch stimulation that appears to match the sensations from our own hand, we will perceive it as if it is our own. Similarly, when we see a hand making movements that correspond to our own hand movements, this visual cue elicits automatic imitation effects. This is true even when we see a non-human robotic hand whose appearance is only minimally hand-like, and with training this effect can become as powerful as for a real human hand (Press, Bird, Flach, & Heyes, 2005; Press, Gillmeister, & Heyes, 2007). Such findings suggest that viewing a hand-like object making movements that correspond to our own hand movements produces a kind of resonance in the mirror system. Perhaps this resonance could enhance the perception of haptic information received from a remote sensing device.

Future research could focus on developing and testing minimally invasive touch probes with characteristics that approximate those of the hand. Miniature force sensors have already been designed that can fit inside an instrument tip (Berkelman, Whitcomb, Taylor, & Jensen, 2003). One difficulty is that any grasper with multiple degrees of freedom (analogous to the hand) requires a relatively complex control mechanism that might be too large for the narrow incisions of minimally invasive surgery. However, recent developments in modular "micro-robots" allow several small, tube-shaped units or joints to be placed inside the body where they intelligently self-assemble into various configurations. These flexible arrangements of multiple moveable joints can perform simple actions such as locomotion or grasping (for an overview, see Cuschieri, 2005). Drawing on new technologies such as these, perhaps it will be possible to build simple but flexible hand-like shapes with basic haptic-sensing capabilities that can be controlled wirelessly from a data glove worn by the surgeon. Although this may currently sound like science fiction, the technologies that could make it possible are already available. A system such as this could one day allow us to combine the clinical benefits of minimally invasive procedures with the rich haptic information about shape-related properties that surgeons value so highly.

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