to hallucinations can be interpreted as “positive” symptoms of a disturbed brain function.

*Ruxandra Sireteanu*

*See also* Amblyopia; Auditory Imagery; Migraine; Nonveridical Perception; Olfactory Imagery; Sleep and Dreams; Visual Filling In and Completion; Visual Imagery

**Further Readings**


**Haptics**

The word *haptic* refers to the wealth of perceptual experience obtained from skin, muscles, tendons, and joints, especially through manual exploration. Haptic perception encompasses multiple distinct input sensations, resulting from different types of neural structures that receive stimulation from the world and convey it to the brain. Inputs from sensors within the skin are called *cutaneous*, or sometimes *tactile*, whereas those from sensors in muscles, tendons, and joints are called *kinesthetic*. This entry discusses several aspects of haptic perception.

**Neural Basis of Haptic Perception**

The foundation of haptic perception lies in sensory receptors, populations of neurons that convert events impinging on the body to electrical signals sent to the brain. A receptor consists of the axon of a nerve fiber, which in some cases originates in a specialized ending. Each type of haptic receptor (or sensor) responds to a particular kind of information and, hence, conveys a particular kind of interaction with the world.

The cutaneous subsystem of touch begins with receptors that lie within the skin. Some are found in the outer layer, the *epidermis*, whereas others lie more deeply in an underlying layer, the *dermis*. Some of these receptors are responsive to mechanical interactions with the skin, that is, to forces that press or vibrate against it. These *mechanoreceptors* can be categorized by the area of skin or *receptive field* that makes them active and by the duration of their activity once they are activated. Receptors that are spatially selective, that is, that selectively respond to stimulation only within a small region of skin, tend to be located near the surface in the epidermis, whereas receptors that respond to stimulation across a less-precisely bounded area of skin lie deeper, in the dermis. Receptors that continue to fire during sustained pressure of the skin are called slow-adapting, whereas those that cease until stimulation begins again are called fast-adapting.

These different receptor response characteristics inform us that the skin contains different signaling mechanisms depending on the type of stimulus. Light fluttering is sufficient to activate fast-adapting fibers near the skin surface, whereas vibrations that arise when the skin contacts an object activate deeper fast-adapting receptors. Slow-adapting fibers near the skin surface, by virtue of their small receptive fields, provide a spatial map of pressure on the skin, allowing a blind person to read a Braille character or an embossed sign.

Other cutaneous receptors, called *thermoreceptors*, respond to warmth or cooling of the skin. Unlike mechanoreceptors, these neural fibers lack specialized endings. Warmth fibers fire when the skin temperature rises as, for example, when you go outside on a sunny day. Cold fibers become active when your skin temperature decreases, as when you hold an ice cube. Warmth and cold fibers are useful for identifying the material from which an object is made. In a typical room, objects that do a good job of conducting heat away from your skin (e.g., steel) tend to feel cooler than do those that conduct heat poorly (e.g., wood).
Haptic receptors responding to mechanical stimulation are found in muscles, tendons, and joints, as well as in skin. Collectively, these constitute the kinesthetic system, telling you where your limbs are in space and their movements, along with the force your muscles are exerting. Kinesthetic receptors are essential for monitoring the activities of your body, whether you are playing tennis, walking upstairs, or simply standing.

Although it is an unpleasant subject, pain is also conveyed by fibers in the skin, muscles, tendons, and joints. These fibers, called nociceptors, are aroused by extremes of normal stimulation, whether pressure (a sharp pinch), heat, or cold. Recent research has indicated the existence of one additional type of fiber that plays a role opposite to the nociceptor by conveying pleasant or emotional touch and is most typically found in hairy skin. An optimal stimulus for this type of receptor appears to be light stroking or petting.

Mechanoreceptors, thermoreceptors, and nociceptors are at the beginning of a neural chain of events culminating in the activation of neurons in the brain. There are two major pathways from the peripheral receptors to the brain, corresponding to a division in evolutionary history. Roughly speaking, pain and temperature signals are sent along an older, slower pathway via the spinal cord, whereas sensations arising from mechanical interactions are sent more quickly via a newer system that enables the rapid initiation of action. Both neural pathways ultimately arrive at an area within the brain called the primary somatosensory cortex. If you place your right hand on the top of your head, with your middle finger crossing the center line, your index finger will lie approximately over the somatosensory area of the brain, and your fourth finger will lie over the area that conveys commands that go down to the muscles. This proximity of sensory to motor probably reflects the close functional relationship between haptic perception and action.

Haptic Perception in Relation to Action

The connection between haptic perception and action is a two-way street. First, haptic perception supports action. Anyone who has ever tried to manipulate an object with very cold hands knows that touch is integral to fine control of grasping and manipulating, for example, inserting a key into the lock in a door or simply holding the key without dropping it. In the laboratory, anesthetizing the skin on the hands has been used as an effective method for showing that tactile sensing is essential for action. People who lack skin sensations cannot maintain an object in a grasp. Measurements of neural signals from mechanoreceptors have shown just why skin sensation is so important for grasping: Fast-adapting fibers near the skin surface become active when an object just begins to slip from the fingers, and their signals are conveyed so rapidly that the grasp can be corrected before the object actually drops.

On the other side of our two-way street, action provides support for haptic perception. Want to find out what an object is made of? Act on it. If, for example, you want to feel whether a surface is rough or smooth, you are more likely to rub your fingers across it than to statically contact it. It has been shown that as you rub, the sideways movement of your fingertip across the surface enhances the activity in mechanoreceptors that convey information to the brain about how rough it feels.

More generally, specific links have been found between the way you manually explore (type of hand action) and the specific object property that you feel. For example, to find out if an object is soft, you press or bend it; to find out if an object is heavy, you pick it up and heft it. Each of these actions, termed haptic exploratory procedures, is a characteristic movement used to evaluate the associated property and has proved to be optimal for evaluating that property. Together, haptic perception and action form a powerful team, allowing us to learn about objects around us and to use this information for many different purposes.

Haptic Perception of Objects and Their Properties

Learning about the properties of objects by touch further enables us to identify them without looking. Although perhaps surprising, it is easy to demonstrate that most common objects placed in the hands can be identified within a couple of seconds. While en route to identification, people are often observed to rub, press, finger, and in general, handle the objects to execute informative exploratory procedures. Merely grasping and lifting an
object is often sufficient to name the object with its most common name, such as “pen.” More extensive exploration is used to identify the type of object with still greater precision, as in a “ballpoint pen.”

Studies of how the haptic system achieves rapid object identification reveal that haptic processing is highly complementary to vision. Vision conveys information about the geometric properties of objects—their curvature, elongation, or size. Touch is far less fast or precise at determining an object’s geometry, but it excels at ascertaining its material properties—hardness, roughness, stickiness, perceived warmth or coolness, and weight, for example.

The division of labor between haptic and visual perception is apparent from a number of scientific findings. One comes from observing whether people touch objects if vision is also available for identifying and discriminating among them. Faced with a difficult question about geometric properties, such as comparing the size of a coin and a circular battery, people will look closely but rarely touch. But when a difficult question about material properties is posed, for example, comparing the roughness of an egg and a sheet of rag paper, people tend to touch the objects, typically with the appropriate exploratory procedure.

When people both look at and touch objects, the two senses tell them about different surfaces. You can’t see through your fingers as you touch an object. Pick up your cell phone and look at it, and you are likely to find yourself looking at the keypad but feeling the back. When participants in a controlled experiment are asked to haptically identify objects they have previously seen, they do best when the test objects are reversed so that participants can touch the object surfaces they previously saw. Conversely, if tested visually with objects they previously felt, they had better be shown the back side.

What about “objects” such as Braille symbols, which vary meaningfully in their geometric pattern but must be recognized by touch? The Braille alphabet has been constructed so that a symbol fits within the fingertip and, hence, can be felt in its entirety at one time. The scaling of Braille to the finger size bypasses one of the principal problems with determining the shape of an object by touch, namely, that it must be explored piecemeal over time, and then somehow mentally pieced together. Despite the advantage of scaling, however, reading Braille remains a difficult skill to master. Even with extensive exposure, sighted teachers of Braille read the symbols with their eyes, rather than with their hands.

The human face is another type of object that is amenable to haptic recognition. People show considerable success at identifying specific live faces by touch, and at haptically recognizing live facial expressions of emotion. We should not be surprised at these findings, however, when we consider that facial features and their alterations under different emotional expressions are haptically, as well as visually, informative. Joe has high cheekbones and a broad nose; Jane’s eyes crinkle at the corner as she smiles. The structural and textural properties that enable us to visually recognize Joe or Jane, or to see them smile or frown, also leap to life under the hands.

**Haptic Perception of Space**

Receptors in muscles, tendons, and joints provide information about how our limbs are disposed in space, enabling us to reliably repeat movements, such as finding the gearshift in our car. (We become aware that we have this so-called muscle memory when we rent or borrow someone else’s car and reach in the wrong place.) Kinesthetic receptors do not, however, readily enable us to convert our limb positions into a “mental map” of the places we have previously touched. Close your eyes, reach out, and feel the objects around you. It is likely you can then make a sketch of their spatial arrangement. But just how accurate is it? The perception of spatial layout by touch turns out to be error-prone, and in ways that are informative.

Here is a nice demonstration. Without looking, put your left and right index fingers down on a tabletop separated by some arbitrary distance, and ask yourself how far apart they are. You are likely to make a sizable error, on the order of 10% or more. That error in estimating the distance between the two fingers will increase dramatically if you first put them together, then separate them by having one move along some wiggly path to its new stopping place, before making the response. The longer the path used to separate the fingers, the greater the judged straight-line distance between them tends to be. Such results suggest that when
using haptic exploration, the time taken by the moving hand is used as one way to estimate the distance between two points in space.

Errors in haptic space perception can be demonstrated by another task, adjusting the orientation of two bars so that they feel parallel. Place a pencil off to your left side on the table top at an arbitrary angle, put your hand on it, and then try to rotate a pencil off to your right side so that the two feel parallel. Depending on the positions of the pencils and the angle that is to be matched, such judgments can exhibit substantial misalignments. In some circumstances, people have been observed to place the two pencils so that they form an angle that is close to 90 degrees, rather than parallel!

Haptic space perception demonstrates a number of phenomena in common with visual perception, including illusions. For example, the horizontal/vertical illusion—the tendency to judge the vertical bar of a \( \perp \) shape as longer than the horizontal—is found when that shape is touched, as well as when it is seen. Matching the orientation of a touched bar is less accurate when it lies along an oblique (slant) than when it is horizontal or vertical. The active nature of haptic perception brings to these phenomena some influences not found in vision: The strength of the illusion may depend on how the object is explored, for example, whether the arm movements are toward and away from the body compared with arcs that encircle the observer’s body.

**Applications of Haptic Perception**

A haptic interface consists of a hardware system that delivers forces and vibrations to the fingers or hands of an operator, directed by software that programs the virtual characteristics (i.e., object shapes, sizes, textures, and compliances) at any moment in time. Typically, the user interacts with the device by holding a handle, or inserting a fingertip into a thimble-like holder, and explores the virtual world much as he or she would explore the world of physical objects and surfaces with a probe held in the hand. As the user moves through the workspace of the device (or is guided passively by means of a predesignated program), a force or vibration is computed according to interface software and delivered to the user. Contact with a virtual wall, for example, corresponds to a strong resistive force that the user encounters when moving the manual guide to its preprogrammed location.

The utility of a haptic interface is limited by many engineering and computer factors, including the device’s spatial resolution, update speed, mechanical structure, and algorithms for rendering and control. To effectively design haptic interfaces for virtual environments and remote operation, it is critical to match the hardware and software features to the capabilities and limitations of the human operator. The scientific study of human haptics is an integral part of the design and evaluation of an interface’s function. Conversely, interfaces have enabled new types of basic research on haptic perception by allowing the creation of surfaces and objects that would be unfeasible for physical manufacture, if not physically impossible. Virtual surfaces and virtual objects of arbitrary shape, size, and compliance can be rendered. Flat surfaces can be made to simulate resistive forces as if they were curved. Basic research on haptic perception is burgeoning with the help of these new facilities for creating new experimental tools.

As technology improves and new devices, both specialized and general-purpose, become available, the range of applications promises to be highly diverse. Already commercial and prototype interfaces have been developed to provide novice training in medical procedures (e.g., lumbar puncture, surgical repair), to create virtual environments for medical rehabilitation, and to control the directional movements of vehicles designed for planetary exploration.

*Robert L. Klatzky and Susan J. Lederman*

**See also** Action and Vision; Cutaneous Perception; Multimodal Interactions: Visual–Haptic; Perceptual Development: Touch and Pain; Reaching and Grasping; Virtual Reality: Touch/Haptics

**Further Readings**


Johnson, K. O. (2002). Neural basis of haptic perception. In H. Pashler & S. Yantis (Eds.), *Stevens’ handbook*
Hearing Aids

Approximately 30 million U.S. citizens have a magnitude of hearing loss that is sufficient to benefit from hearing aids. Unfortunately, for a variety of reasons, only 5 to 6 million U.S. citizens currently wear hearing aids. This entry reviews the basic function of hearing aids and provides information on some of the latest advances in hearing aid technology.

Basic Functions

Hearing aids consist of a microphone(s) that converts the incoming acoustic signal to an electrical signal that is a duplication of the acoustic spectrum of the incoming signal. This conversion is followed by an amplifier that magnifies the signal received from the microphone. This stage is typically followed by a multichannel digital signal processor (DSP) that manipulates the amplified signal to match the magnitude and configuration of the hearing loss of the aided ear(s). Finally, the digitally processed amplified signal is forwarded to a receiver that reconverts the amplified electric digitally processed signal back to an acoustical signal and sends it to the ear in a variety of ways.

Technological Advances

In the past decade, significant advances have been introduced to hearing aids, and these advances have accelerated so much that manufacturers introduce major changes every 3 to 6 months whereas in the past major changes occurred every couple of years. Current advances include multichannel signal processing. That is, the processing chip within the hearing aid divides the incoming acoustic signal into as few as 2 channels (low and high frequency) or as many as 20 channels (independent narrow frequency ranges). When divided in this manner, the incoming signal can be manipulated independently in each channel for improved control of amplification, noise reduction, and the management of feedback. Examples of the use of multichannel signal processing include the following: (a) digital signal processing, (b) feedback management to eliminate or dramatically reduce the presence of feedback and allow for greater available amplification, (c) noise reduction for improved listening comfort in noisy environments, and (d) automatic adaptive directional microphones for improved recognition of speech in noisy environments.

This type of microphone design contains two microphones where one is forward facing and the second faces the rear. In this design, the signal processor within the hearing aid will automatically activate the forward facing omni-directional microphone when there is a single talker in a quiet listening situation. Then the signal processor within the hearing aid will automatically activate the rear-facing microphone when the processor detects a second signal arriving from the side or back of the listener and when the level of the rear signal is greater than the level of the signal arriving from the front. The action of the rear facing microphone is to attenuate the sound from the side or rear so that the signal arriving from the front is amplified to improve the signal to noise ratio. Advances in directional microphones have greatly improved user satisfaction and benefit with hearing aids in noisy listening environments, and this technology is improving rapidly.

Other advances include expansion to reduce the amplification of annoying low-frequency energy