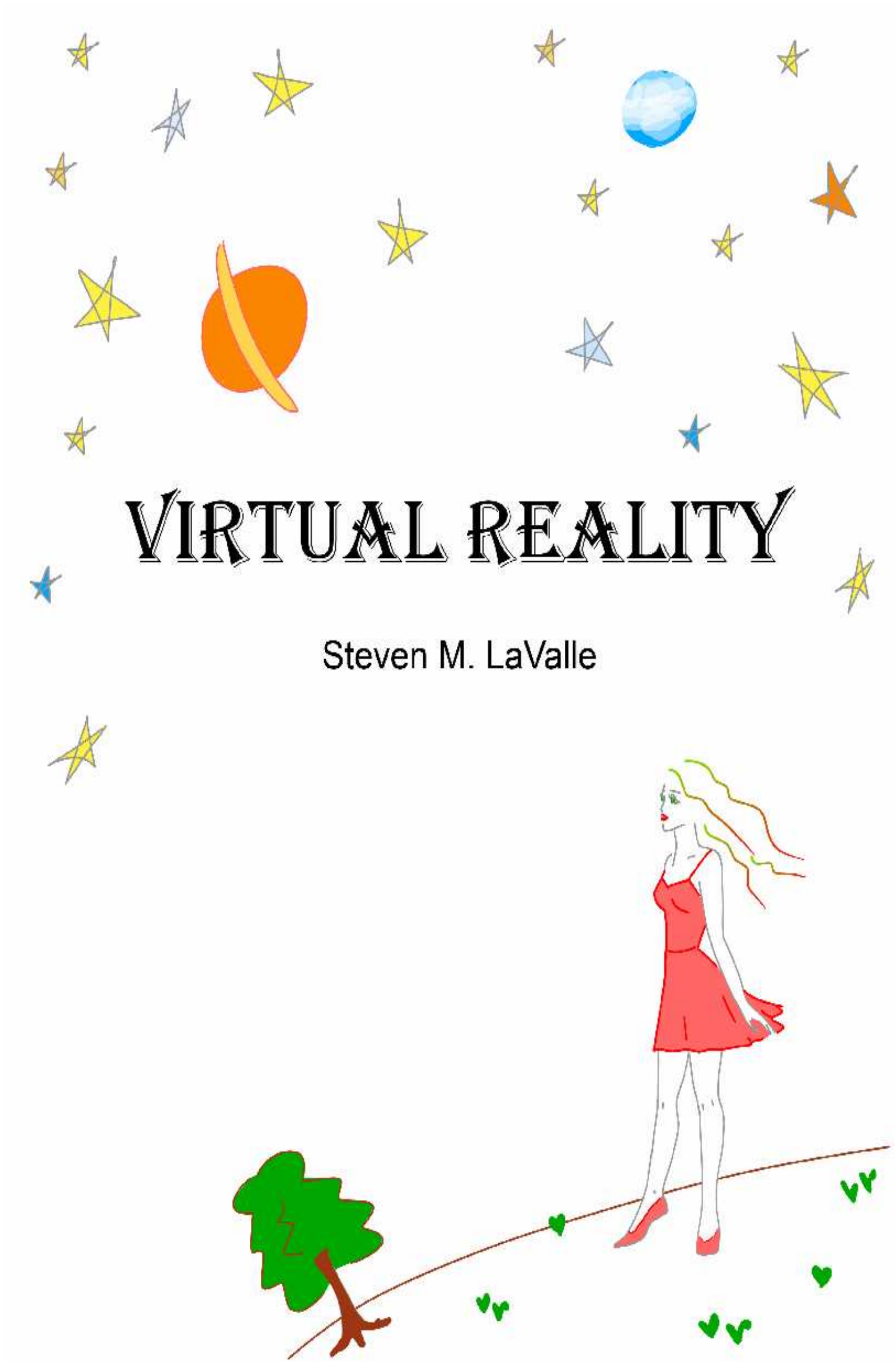


# Chapter 13

# Frontiers

**Steven M. LaValle**

**University of Illinois**

# Chapter 13

# Frontiers

We arrive at the final chapter, which surveys some topics that could influence widespread VR usage in the future, but are currently in a research and development stage. Sections 13.1 and 13.2 cover the forgotten senses. Earlier in this book, we covered vision, hearing, and balance (vestibular) senses, which leaves touch, smell, and taste. Section 13.1 covers touch, or more generally, the *somatosensory system*. This includes physiology, perception, and engineering technology that stimulates the somatosensory system. Section 13.2 covers the two *chemical senses*, smell and taste, along with attempts to engineer "displays" for them. Section 13.3 discusses how robots are used for telepresence and how they may ultimately become our *surrogate selves* through which the real world can be explored with a VR interface. Just like there are avatars in a virtual world (Section 10.4), the robot becomes a kind of physical avatar in the real world. Finally, Section 13.4 discusses steps toward the ultimate level of human augmentation and interaction: Brain-machine interfaces.

## 13.1 Touch and Proprioception

Visual and auditory senses are the main focus of VR systems because of their relative ease to co-opt using current technology. Their organs are concentrated in a small place on the head, and head tracking technology is cheap and accurate. Unfortunately, this neglects the powerful senses of *touch* and *proprioception*, and related systems, which provide an intimate connection to the world around us. Our eyes and ears enable us to perceive the world from a distance, but touch seems to allow us to directly *feel* it. Furthermore, proprioception gives the body a sense of where it is any in the world with respect to gravity and the relative placement or configuration of limbs and other structures that can be moved by our muscles. We will therefore consider these neglected senses, from their receptors to perception, and then to engineering systems that try to overtake them.

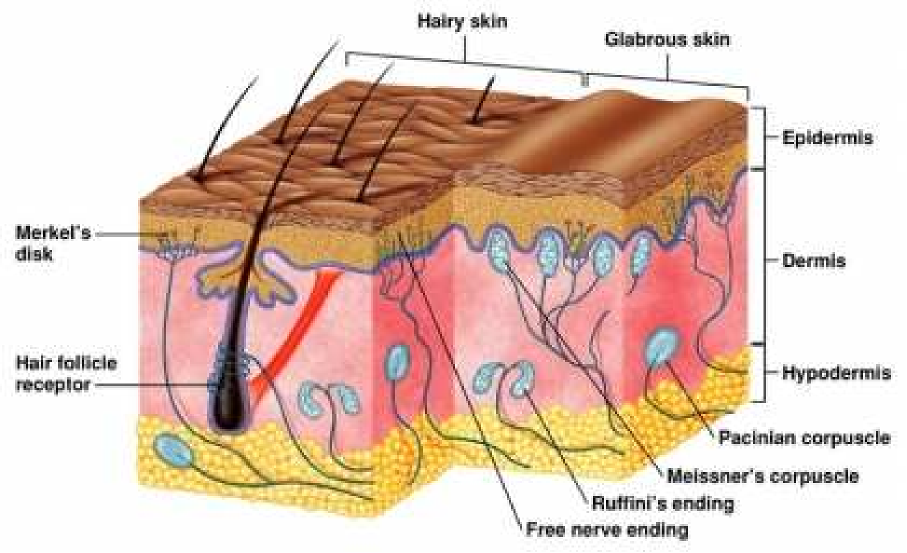


Figure 13.1: Six major kinds of receptors in human skin. (Figure by Pearson Education.)

**The somatosensory system** The *body senses* provide signals to the brain about the human body itself, including direct contact with the skin, the body's configuration and movement in the world, and the ambient temperature. Within this category, the vestibular system (Section 8.2) handles balance, and the *somatosensory system* handles touch, proprioception, and kinesthesis. Consider the human body and all of its movable parts, such as the legs, arms, fingers, tongue, mouth, and lips. Proprioception corresponds to the awareness of the *pose* of each part relative to others, whereas *kinesthesis* is the counterpart for the movement itself. In other words, kinesthesis provides information on velocities, accelerations, and forces.

The somatosensory system has at least nine major kinds of receptors, six of which are devoted to touch, and the remaining three are devoted to proprioception and kinesthesis. Figure 13.1 depicts the six main touch receptors, which are embedded in the skin (*dermis*). Their names, structures, and functions are:

- **Free nerve endings:** These are neurons with no specialized structure. They have axons that extend up into the outer skin (*epidermis*), with the primary function of sensing temperature extremes (hot and cold), and pain from tissue damage. These neurons are special (called *pseudounipolar*) in that axons perform the role of both dendrites and axons in a typical neural cell.

- **Ruffini's endings or corpuscles:** These are embedded deeply in the skin and signal the amount of stretching that is occurring at any moment. They have a sluggish temporal response.

- **Pacinian corpuscles:** These are small bodies filled with fluid and respond to pressure. Their response is fast, allowing them to sense vibrations (pressure variations) of up to 250 to 350 Hz.
- **Merkel's disks:** These structures appear just below the epidermis and respond to static pressure (little or no variation over time), with a slow temporal response.
- **Meissner's corpuscles:** These are also just below the epidermis, and respond to lighter touch. Their response is faster than Merkel's discs and Ruffini's corpuscles, allowing vibrations up to 30 to 50 Hz to be sensed; this is not as high as is possible as the Pacinian corpuscles.
- **Hair follicle receptors:** These correspond to nerve endings that wrap closely around the hair root; they contribute to light touch sensation, and also pain if the hair is removed.

The first four of these receptors appear in skin all over the body. Meissner's corpuscles are only in parts where there are no hair follicles (*glabrous skin*), and the hair follicle receptors obviously appear only where there is hair. In some critical places, such as eyelids, lips, and tongue, thermoreceptors called the *end-bulbs of Krause* also appear in the skin. Yet another class is *nocireceptors*, which appear in joint tissues and cause a pain sensation from overstretching, injury, or inflammation.

Touch has both spatial and temporal resolutions. The spatial resolution or acuity corresponds to the density, or receptors per square area, which varies over the body. The density is high at the fingertips, and very low on the back. This has implications on touch perception, which will be covered shortly. The temporal resolution is not the same as for hearing, which extends up to 20,000 Hz; the Pacinian corpuscles allow vibrations up to a few hundred Hertz to be distinguished from a static pressure.

Regarding proprioception (and kinesthesis), there are three kinds of receptors:

- **Muscle spindles:** As the name suggests, these are embedded inside of each muscle so that changes in their length can be reported to the central nervous system (which includes the brain).
- **Golgi tendon organs:** These are embedded in tendons, which are each a tough band of fibrous tissue that usually connects a muscle to bone. The organs report changes in muscle tension.
- **Joint receptors:** These lie at the joints between bones and help coordinate muscle movement while also providing information to the central nervous system regarding relative bone positions.

Through these receptors, the body is aware of the relative positions, orientations, and velocities of its various moving parts.

The neural pathways for the somatosensory system work in a way that is similar to the visual pathways of Section 5.2. The signals are routed through the thalamus, with relevant information eventually arriving at the *primary somatosensory cortex* in the brain, where the higher-level processing occurs. Long before the thalamus, some of the signals are also routed through the spinal cord to motor neurons that control muscles. This enables rapid motor response, for the purpose of withdrawing from painful stimuli quickly, and for the *knee-jerk reflex*. Inside of the primary somatosensory cortex, neurons fire in a spatial arrangement that corresponds to their location on the body (topographic mapping). Some neurons also have receptive fields that correspond to local patches on the skin, much in the same way as receptive fields works for vision (recall Figure 5.8 from Section 5.2. Once again, lateral inhibition and spatial opponency exist and form detectors that allow people to estimate sharp pressure features along the surface of the skin.

**Somatosensory perception** We now transition from physiology to *somatosensory perception*. The familiar concepts from psychophysics (Sections 2.3 and 12.4) appear again, resulting in determinations of detection thresholds, perceived stimulus magnitude, and acuity or resolution along temporal and spatial axes. For example, the ability to detect the presence of a vibration, presented at different frequencies and temperatures, was studied in [1].

**Two-point acuity** Spatial resolution has been studied by the *two-point acuity test*, in which the skin is poked in two nearby places by a pair of sharp calipers. The subjects are asked whether they perceive a single poke, or two pokes in different places at the same time. The detection thresholds are then arranged by the location on the body to understand how the spatial resolution varies. The sharpest acuity is on the tongue and hands, where points can be distinguished if they are as close as 2 or 3mm. The tips of the tongue and fingers have the highest acuity. For the forehead, the threshold is around 20mm. The back has the lowest acuity, resulting in a threshold of around 60mm. These results have also been shown to correspond directly to the sizes of receptive fields in the somatosensory cortex. For example, neurons that correspond to the back have much larger fields (in terms of skin area) than those of the fingertip.

**Texture perception** By running fingers over a surface, *texture perception* results. The size, shape, arrangement, and density of small elements that protrude from, or indent into, the surface affect the resulting perceived texture. The *duplex theory* states that coarser textures (larger elements) are mainly perceived by spatial cues, whereas finer textures are mainly perceived through temporal cues

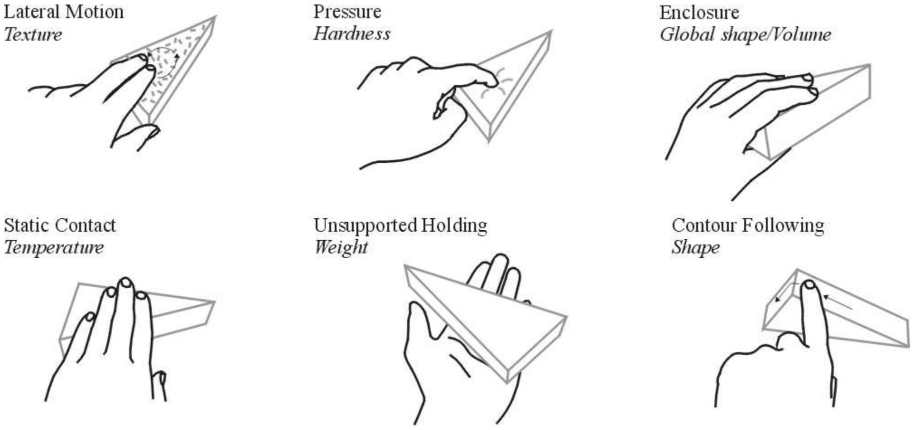


Figure 13.2: Haptic exploration involves several different kinds interaction between the hand and an object to learn the object properties, such as size, shape, weight, firmness, and surface texture. (Figure by Allison Okamura, adapted from Lederman and Klatzky.)

[16, 22]. By *spatial cue*, it means that the structure can be inferred by pressing the finger against the surface. By *temporal cue*, the finger is slid across the surface, resulting in a pressure vibration that can be sensed by the Pacinian and Meissner corpuscles. For a finer texture, a slower motion may be necessary so that the vibration frequency remains below 250 to 350 Hz. Recall from Section 12.1 that people can learn to improve their texture perception and acuity when reading Braille. Thus, perceptual learning may be applied to improve tactile (touch) perception.

**Haptic perception** For a larger object, its overall geometric shape can be inferred through *haptic exploration*, which involves handling the object. Imagine that someone hands you an unknown object, and you must determine its shape while blindfolded. Figure 13.2 shows six different qualitative types of haptic exploration, each of which involves different kinds of receptors and combinations of spatial and temporal information. By integrating the somatosensory signals from this in-hand manipulation, a geometric model of the object is learned.

**Somatosensory illusions** Recall from Section 6.4 that the brain combines signals across multiple sensing modalities to provide a perceptual experience. Just as the McGurk effect uses mismatches between visual and auditory cues, illusions have also been discovered by mismatching cues between vision and somatosensory systems. The *rubber hand illusion* is one of the most widely known [8]. In this case, scientists conducted an experiment in which the subjects were seated at a table with both arms resting on it. The subjects' left arm was covered, but a substitute rubber forearm was placed nearby on the table and remained visible so that it appeared as if it were their own left arm. The experimenter stroked both the real and fake forearms with a paint brush to help build up visual and touch association with the fake forearm. Using a functional MRI scanner, scientists determined that the same parts of the brain are activated whether it is the real or fake forearm. Furthermore, they even learned that making a stabbing gesture with a needle causes anticipation of pain and the tendency to withdraw the real left arm, which was actually not threatened [8, 53], and that hot or cold sensations can even be perceived by association [52].

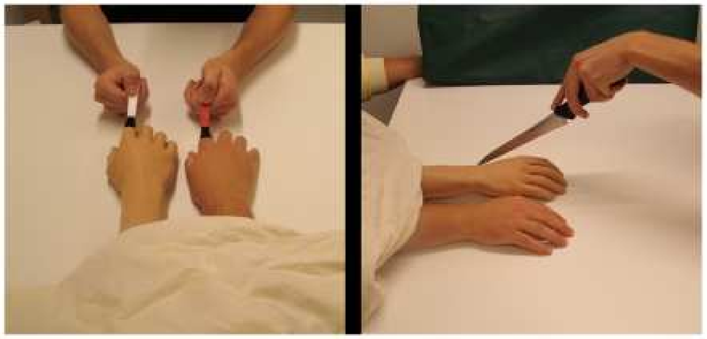


Figure 13.3: The *rubber hand illusion*, in which a person reacts to a fake hand as if it were her own. (Figure from Guterstam, Petkova, and Ehrsson, 2011 [13])

More generally, this is called a *body transfer illusion* [43, 53]. An example of this was shown in Figure 1.14 of Section 1.2 for a VR system in which men and women were convinced that they were swapping bodies, while the visual information from a camera was coupled with coordinated hand motions to provide tactile sensory stimulation. Applications of this phenomenon include empathy and helping amputees to overcome phantom limb sensations. This illusion also gives insights into the kinds of motor programs that might be learnable, as discussed in Sections 10.1 and 10.3, by controlling muscles while getting visual feedback from VR. It furthermore affects the perception of oneself in VR, which was discussed in Sections 10.4 and 12.2.

**Haptic interfaces** Touch sensations through engineered devices are provided through many disparate systems. Figure 1.1 from Section 1.1 showed a system in which force feedback is provided by allowing the user to push mechanical wings to fly. Furthermore, a fan simulates wind with intensity that is proportional to the speed of the person virtually flying. The entire body also tilts so that appropriate vestibular stimulation is provided.

Figure 13.4 shows several more examples. Figure 13.4(a) shows a PC mouse with a scroll wheel. As the wheel is rotated with the middle finger, discrete bumps

(a) (b)

(c) (d)

Figure 13.4: (a) The Logitech M325 wireless mouse with a scroll wheel that provides tactile feedback in the form of 72 bumps as the wheel performs a full revolution. (b) The Sega Dreamcast Jump Pack (1999), which attaches to a game controller and provides vibrations during game play. (c) Haptic Omni pen-guiding haptic device, which communicates pressure and vibrations through the pen to the fingers. (d) The KGS Dot View Model DV-2, which is a haptic pin array. The pins are forced upward to simulate various textures as the finger tip scans across its surface.

are felt so that a more carefully calibrated movement can be generated. Figure 13.4(b) shows a game controller attachment that provides vibration at key points during an experience, such as an explosion or body contact.

Many haptic systems involve using a robot arm to apply force or pressure at precise locations and directions within a small region. Figure 13.4(c) shows such a system in which the user holds a pen that is attached to the robot arm. Forces are communicated from the robot to the pen to the fingers. As the pen strikes a virtual surface, the robot provides force feedback to the user by blocking its motion. The pen could be dragged across the virtual surface to feel any kind of texture [40]; a variety of simulated textures are presented in [4]. Providing such force feedback in important in the development of medical devices that enable doctors to perform surgical procedures through an interface that is connected to a real device. Without accurate and timely haptic feedback, it is difficult for doctors to perform many procedures. Imagine cutting into layers of tissue without being able to feel the resistant forces on the scalpel. It would be easy to push a bit too far!

Figure 13.4(d) shows a haptic display that is arranged much like a visual display. A rectangular region is indexed by rows and columns, and at each location a small pin can be forced outward. This enables shapes to appear above the surface, while also allowing various levels of pressure and frequencies of vibration.

All of the examples involve haptic feedback applied to the hands; however, touch receptors appear all over the human body. To provide stimulation over a larger fraction of receptors, a *haptic suit* may be needed, which provides forces, vibrations, or even electrical stimulation at various points on the suit. A drawback of these systems is the cumbersome effort of putting on and removing the suit with each session.

**Touch feedback via augmented reality** Given the difficulties of engineering haptic displays, an alternative is to rely on real objects in the match zone to provide feedback to the somatosensory system. This is sometimes called a *tangible user interface* [58]. As mentioned in Section 8.3.3, a powerful experience is made by aligning the real and virtual worlds. At one extreme, a see-through display, such as Microsoft Hololens which was shown in Section 1.2, enables users to see and interact with the physical world around them. The display simply adds virtual objects to the real world, or visually enhances real objects. Such systems are commonly included as part of *augmented reality* or *mixed reality*.

## 13.2 Smell and Taste

The only human senses not considered so far are smell and taste. They are formally known as *olfaction* and *gustation*, respectively [7]. Furthermore, they are usually grouped together as the *chemical senses* because their receptors work by chemical interactions with molecules that arrive upon them. The resulting *chemoreceptors* respond to particular substances and sufficiently high levels of concentration. Compared to the other senses, much less research has been done about them and there are much fewer electronic devices that "display" stimuli to the nose and tongue. Nevertheless, these senses are extremely important. The design of artificial smells is a huge business, which includes perfumes, deodorants, air fresheners, cleaners, and incense. Likewise, designing tastes is the basis of the modern food industry (for better or worse).

**Smell physiology and perception** Odors are important for several biological purposes, which includes detecting prey and predators, selecting potential mates, and judging whether food is safe to eat. The *olfactory receptor* neurons lie in the roof of the nasal cavity, covering an area of 2 to 4 $\text{cm}^2$. There are around 6 million receptors, which are believed to span 500 to 1000 different types depending on their responsiveness to specific chemical compositions [33]. Airborne molecules dissolve into the olfactory mucus, which triggers detection by cilia (small hairs) that are part of the receptor. The olfactory receptors are constantly regenerating, with an average lifespan of about 60 days. In addition to receptors, some free nerve endings lie in the olfactory mucus as well. The sensory pathways are unusual in that they do not connect through the thalamus before reaching their highest-level destination, which for smell is the *primary olfactory cortex*. There is also a direct route from the receptors to the *amygdala*, which is associated with emotional response. This may help explain the close connection between smell and emotional reactions.

In terms of perception, humans can recognize thousands of different smells [50], and women generally perform better than men [2]. The discrimination ability depends on the concentration of the smell (in terms of molecules per cubic area). If the concentration is weaker, then discrimination ability decreases. Furthermore, what is considered to be a high concentration for one odor may be barely detectable for another. Consequently, the detection thresholds vary by a factor of a thousand or more, depending on the substance. Adaptation is also important for smell. People are continuously adapting to surrounding smells, especially those of their own body or home, so that they become unnoticeable. Smokers also adapt so that they do not perceive the polluted air in the way that non-smokers can.

It seems that humans can recognize many more smells than the number of olfactory receptors. This is possible because of combinatorial encoding. Any single odor (or chemical compound) may trigger multiple kinds of receptors. Likewise, each receptor may be triggered by multiple odors. Thus, a many-to-many mapping exists between odors and receptors. This enables far more odors to be distinguished based on the distinct subsets of receptor types that become activated.

**Olfactory interfaces** Adding scent to films can be traced back to the early 20th century. One system, from 1960, was called *Smell-O-Vision* and injected 30 different odors into the movie theater seats at different points during the film. The Sensorama system mentioned in Figure 1.28(c) of Section 1.3 also included smells. In addition, the military has used smells as part of simulators for many decades.

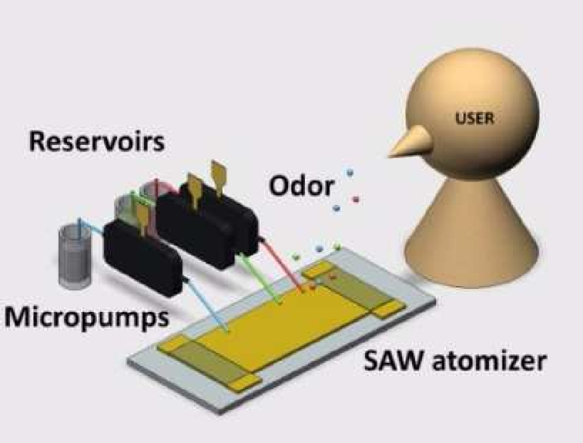


Figure 13.5: A depiction of a wearable olfactory display from [14]. Micropumps force bits of liquid from small reservoirs. The SAW atomizer is an surface acoustic wave device that converts droplets into an atomized odor.

A survey of previous olfactory displays and interfaces appears in [20], along with current challenges and issues. It is generally believed that smell is powerful in its ability to increase immersion in VR. It also offers advantages in some forms of medical treatments that involve cravings and emotional responses. Surprisingly, there is even recent evidence that pleasant odors help reduce visually induced motion sickness [23].

Olfactory displays usually involve air pumps that can spray chemical compounds into air. The presentation of such engineered odors could be delivered close to the nose for a personal experience. In this case, the canisters and distribution system could be worn on the body [63]. A recent system is depicted in Figure 13.5. Alternatively, the smells could be delivered on the scale of a room. This would be preferable for a CAVE setting, but it is generally hard to control the intensity and uniformity of the odor, especially in light of air flow that occurs from open windows and air vents. It might also be desirable to vary the concentration of odors over a large area so that localization can be performed, but this is again difficult to achieve with accuracy.

**Taste physiology and perception** We now jump from smell to taste. On the human tongue lie about 10,000 *taste buds*, which each contains a group of about 50 to 150 *taste receptors* [54]. The receptors live for an average of 10 days, with regeneration constantly occurring. Five basic types of taste receptors have been identified:

- **Umami:** This one is sensitive to amino acids, such as *monosodium glutamate* (*MSG*), and is responsible for an overall sense of tastiness. This enables food manufacturers to cheaply add chemicals that made food seem to taste better. The biological motivation is likely to be that amino acids are important building blocks for proteins.
- **Sweet:** This is useful for identifying a food source in terms of its valuable sugar content.
- **Salty:** This is useful for determining whether a food source has sufficient salt content, which is required for normal neural functions.
- **Sour:** This is useful for determining the amount of acidity in a food, which could imply useful vitamins, unripeness, or even bacteria in spoiled food.
- **Bitter:** This is often associated with toxic plants, which may trigger a natural aversion to them.

All of these work by dissolving food and generating a response based on chemical decomposition. The sensory pathways connect to through the thalamus to the *gustatory cortex* and to the amygdala, which affects emotional responses.

Taste perception is closely related to the taste receptor types. One of the most widely known models is *Henning's tetrahedron* from 1927, which is a 3D space of tastes that is generated using barycentric coordinates (Section 7.2) over four extreme vertices that each represent pure sweet, salty, sour, or bitter. Thus, each taste is a linear interpolation the four components. This of course, neglects umami, which was added to the list of receptor types very recently [3, 38]. Adaptation occurs for taste, including an aversion to foods that might have been coincident with sickness. The concept of *flavor* is a perceptual experience that combines cues from taste, smell, temperature, touch, vision, and sound. Therefore, it is challenging to understand the mechanisms that create a flavor experience [5].

**Gustatory interfaces** Relatively little has been done to date on simulating taste electronically. Figure 13.6 shows one recent example, in which electrodes are placed over and under the tongue to provide stimulation that simulates the main taste types. In another work, taste illusions are formed by accompanying eating with incorrect visual and olfactory cues [36]. It is generally difficult to develop *gustatory interfaces* for VR without actually causing people to eat food during the experience. There are clearly health and hygienic issues as well.

## 13.3 Robotic Interfaces

Robots are programmable devices that involve a mixture of sensors, actuators (motors), and computational devices. They are usually expected to interpret high-level commands, use sensors to learn about the world around them, and plan and execute actions that move them safely to accomplish the goals set out by their commanders. Their components mimic those of humans in many ways. Robots have sensors and humans have senses. For some specific correspondences, robots have cameras, IMUs, and joint encoders, whereas humans measure the same quantities via vision, vestibular, and proprioceptive senses. Most robots have motors and humans have muscles, both of which serve the same purpose. Robots perform computations to relate high-level goals to low-level motor commands while interpreting data from sensors. Humans reason about high-level goals as well, while sending motor signals to muscles and turning stimuli from senses into perceptual phenomena. After making so many parallels between robots and humans, a natural question is: Why not use VR technology to allow a human to inhabit the body of a robot? We could use robots as our *surrogate selves*.

Figure 13.6: A *digital lollipop* was developed at the National University of Singapore [45].

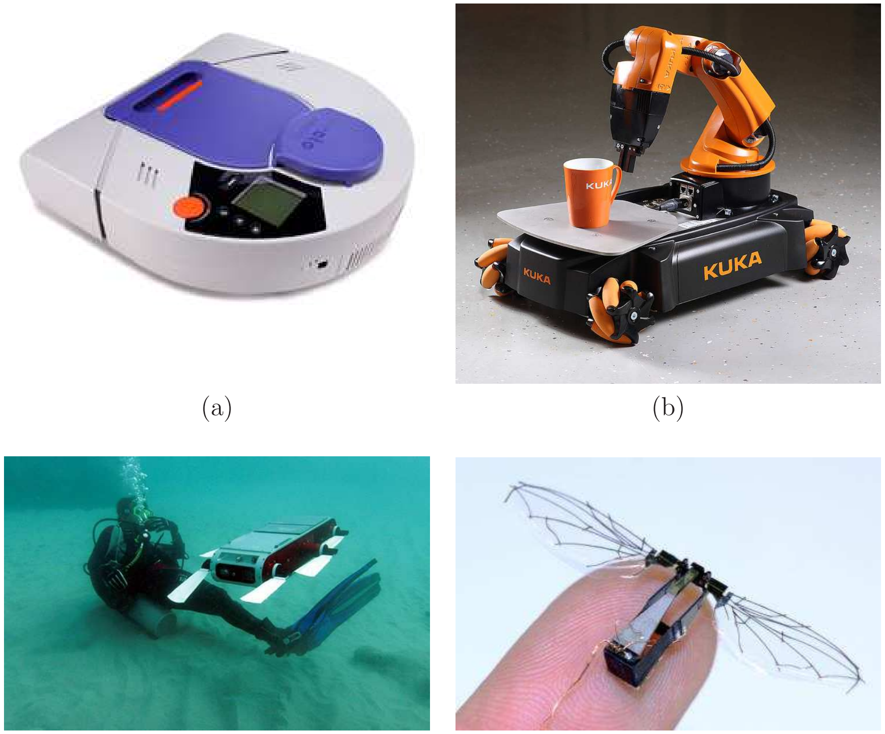
**Teleoperation** The first step toward this vision is to interact with robots over large distances. Vehicles have been operated by remote control for well over a century. One of the earliest examples is a radio-controlled boat that was publicly demonstrated in New York by Nicola Tesla in 1898. Across the 20th century, numerous teleoperated robots were developed for navigation in remote or hazardous situations, such as handling radioactive materials, space travel, undersea exploration. Space agencies (such as NASA) and militaries have conducted extensive research and development of remote controlled vehicles. Another intriguing example of teleoperation is the *TeleGarden* from 1995, which was a robot arm hovering over a real garden, at the University of Southern California, that was connected to the Internet. Remote visitors could plant seeds and generally take care of the garden. In 2001, teleoperated robots were deployed to the World Trade Center bombing site to search for victims. In current times, remote controlled vehicles of all kinds are widely available to hobbyists, including cars, fixed-wing aircraft, quadrotors (drones), boats, and submarines. Operation is often difficult because the user must control the vehicle from a third-person view while handling the controller. Therefore, many vehicles have been equipped with wireless cameras so

Figure 13.7: The HRP-4 *humanoid robots*, which are produced in Japan by National Institute of Advanced Industrial Science and Technology (AIST) and Kawada Industries.

that the user obtains a *first-person view* (*FPV*) on a screen. This is an important step toward telepresence. Teleoperation need not be limited to vehicles. Health care is one of the largest and growing fields for teleoperation, which usually involves fixed-based robot arm that manipulates medical instruments. For a general survey of networked robotics, see [55].

**Modern robots** Thousands of different robots have been designed and built, some with very special purposes, such as cleaning windows outside of a building, and others for more general purposes, such as assisted living. Figure 13.7 shows *humanoid robots* that strive for *anthropomorphic* or "human like" appearance. Figure 13.8 shows a sampling of other kinds of robots. Figure 1.11 in Section 1.2 showed two more examples, which were a stereoscopic pan-tilt module and a video-streaming drone.

In addition to hardware, substantial software infrastructure exists to help developers, such ROS (Robot Operating System) and Gazebo. Almost any robot



(a) (b)

(c) (d)

Figure 13.8: A sampling of commercial and university robots: (a) Neato XV vacuum cleaning robot. (b) Kuka YouBot, which is an omnidirectional mobile base with a manipulator arm on top. (c) Aqua, an underwater robot from McGill University [6]. (d) A flying microrobot from Harvard University [32].

Figure 13.9: The Double telepresence robot is a screen and camera on a stick. The robot costs around $2500, and the screen is a tablet, such as an iPad. The height can even be adjusted remotely so that the person may appear to be sitting or standing.

is a candidate platform from which a telerobotic VR interface could be attached. Cameras and microphones serve as the surrogate eyes and ears of the user. A gripper (also called *end-effector*) could serve as remote hands, if feasible and important for the application. The user can command the robot's motions and actions via keyboards, controllers, voice, or body motions. For a humanoid robot, the human body could even be tracked using motion capture (Section 9.4) and mapped directly onto motions of the humanoid. More generally, any anthropomorphic aspects of a robot could become part of the matched zone. At the other extreme, the robot allows many non-human experiences, such as becoming the size of a small insect and flying around the room, or swimming like a fish in the sea.

**Telepresence** The term and concept of *telepresence* is attributed to Marvin Minsky, pioneer of artificial intelligence [34]; see also [46, 51, 56]. In the most idealized case, which we are far from achieving with current technology, it could completely eliminate the need to physically travel. It could also revolutionize the lives of people who have limited mobility due to disabilities or advanced age. In terms of technical challenges, telepresence involves the integration of two components: *teleoperation* and VR.

Figure 13.9 shows a telepresence system that is commercially available and serves as a useful point of reference. Similar robots have appeared in telepresence research [21, 25, 42, 57]. The robot is controlled by the user through a tablet or smartphone, while at the remote site the robot carries a tablet that provides a wide-angle camera and a screen to show the user's face. The base is designed to roll through typical office spaces, and the tablet height is adjustable to allow face-to-face interaction. The vehicle is top-heavy, which results in a control problem called the *inverted pendulum* to stabilize the tablet.

Several aspects come to mind regarding a telepresence robot:

- **Sensory input:** What will it sense from the remote physical world? For visual input, it could contain cameras that directly map the eye viewpoints and are even matched to user head motions (as was shown in Figure 1.11(a)). Alternatively, it could capture and transmit an entire panorama. Going even further, this could be extended to depth and light fields. Auditory input is captured using one or more microphones, depending on the importance of localization. Some other possible inputs for telepresence are temperature, contact forces, humidity, odors, and the robot's remaining battery life.

- **Mobility:** Where can the robot go? With no mobility, telepresence is reduced to a stationary camera and microphone. If the task is to interact with people, then it should be able to move into the same places that people are capable of entering. In other settings, many modes of mobility may be desirable, such as flying, swimming, or even crawling through pipes.

- **Audiovisual output:** At one extreme, the telepresence system could seem like a "fly on the wall" and not disrupt life at the remote site. More commonly, it is designed to interact with people, which could be accomplished by a screen and a speaker. If the robot has some anthropomorphic characteristics, then it may also be able to make gestures that communicate emotion or intent with other people.

- **Manipulation:** The telepresence system shown in Figure 13.9 targets face-to-face interaction, and therefore neglects being able to manipulate objects at the remote site. A telepresence robot is much more powerful if it can grasp, manipulate, carry, and ungrasp objects. It could then open doors, operate elevators, go grocery shopping, and so on.

The remainder of this section covers ongoing challenges in the development of better telepresence systems.

**Tele-embodiment issues** Imagine how people would react to the robotic surrogate version of yourself. It is highly unlikely that they would treat you exactly in the same way as if you were physically present. Recall from Section 10.4 that social interaction in VR depends on the avatars that people chose to represent themselves. With telepresence, you would be perceived as a *robotic avatar*, which leads to the same kinds of social issues [41]. The remote person may seem handicapped or awkward in a way that causes avoidance by others. Unfortunately, there is much less freedom to chose how you want to look in comparison to interaction in a purely virtual world. You may have to be perceived by everyone as an awkward screen on a stick if that is the platform. Research in *social robotics* and *human-robot interaction* may be useful in helping improve social interactions through such a robotic avatar [10, 17, 48].

**Remote-control versus autonomy** Assuming that the robot may roam over a larger area than the matched zone, a locomotion method is needed. This implies that the user controls the robot motion through an interface. In Section 10.2, locomotion was presented for navigating in a large virtual world and was explained as controlling a cart (Figure 10.5). The robot in the real world behaves geometrically like the cart in the pure virtual world; however, some differences are: 1) The robot cannot simply teleport to another location. It is, however, possible to connect to a different robot, if many are available, which would feel like teleportation to the user. 2) The robot is subject to constraints based on its physical design and its environment. It may have rolling wheels or walking legs, and may or may not be able to easily traverse parts of the environment. It will also have limited driving speed, turning speed, and battery life. 3) A high cost is usually associated with crashing the robot into people or obstacles.

A spectrum of choices exists for the user who teleoperates the robot. At one extreme, the user may continuously control the movements, in the way that a radio-controlled car is driven using the remote. Latency becomes critical some applications, especially telesurgery [31, 62]. At the other extreme, the user may simply point out the location on a map or use a virtual laser pointer (Section 10.2) to point to a visible location. In this case, the robot could execute all of the motions by itself and take the user along for the ride. This requires a higher degree of autonomy for the robot because it must plan its own route that accomplishes the goals without running into obstacles; this is known in robotics as *motion planning* [24]. This frees the user of having to focus attention on the minor robot movements, but it may be difficult to obtain reliable performance for some combinations of robot platforms and environments.

**VR sickness issues** Because of the connection to locomotion, vection once again arises (Section 8.4). Many of the suggestions from Section 10.2 to reduce vection can be applied here, such as reducing the contrast or the field of view while the robot is moving. Now consider some robot-specific suggestions. Users may be more comfortable controlling the robot themselves rather than a higher level of autonomy, even though it involves tedious concentration. Furthermore, the path itself determined by a motion planning algorithm could be optimized to reduce sickness by shortening times over which accelerations occur or by avoiding close proximity to walls or objects that have high spatial frequency and contrast. Another idea is to show the motion on a 2D or 3D map while the robot is moving, from a third-person perspective. The user could conceivably be shown anything, such as news feeds, while the robot is moving. As in the case of locomotion for virtual worlds, one must be careful not to disorient the user by failing to provide enough information to easily infer the new position and orientation relative to the old one by the time the user has arrived.

**Latency issues** As expected, time delays threaten the performance and comfort of telepresence systems. Such latencies have already been discussed in terms of visual rendering (Section 7.4) and virtual world simulation (Section 8.3.2). A networked system causes new latency to be added to that of the VR system because information must travel from the client to the server and back again. Furthermore, bandwidth (bits per second) is limited, which might cause further delays or degradation in quality. For reference, the average worldwide travel time to Google to back was around 100 ms in 2012 (it was 50 to 60ms in the US) [35]. Note that by transmitting an entire panoramic view to the user, the network latency should not contribute to head tracking and rendering latencies.

However, latency has a dramatic impact on *interactivity*, which is a well-known problem to networked gamers. On the other hand, it has been found that people generally tolerate latencies in phone calls of up to 200 ms before complaining of difficulty conversing; however, they may become frustrated if they expect the robot to immediately respond to their movement commands. Completing a manipulation task is even more difficult because of delays in hand-eye coordination. In some cases people can be trained to overcome high latencies through adaptation, assuming the latencies do not substantially vary during and across the trials [9]. The latency poses a considerable challenge for medical applications of telepresence. Imagine if you were a doctor pushing on a scalpel via a telepresence system, but could not see or feel that it is time to stop cutting until 500 ms later. This might be too late!

## 13.4 Brain-Machine Interfaces

The ultimate interface between humans and machines could be through direct sensing and stimulation of neurons. One step in this direction is to extract physiological measures, which were introduced in Section 12.3. Rather than using them to study VR sickness, we could apply measures such as heart rate, galvanic skin response, and pallor to adjust the VR experience dynamically. Various goals would be optimized, such as excitement, fear, comfort, or relaxation. Continuing further, we could apply technology that is designed to read the firings of neurons so that the VR system responds to it by altering the visual and auditory displays. The users can learn that certain thoughts have an associated effect in VR, resulting in mind control. The powers of neuroplasticity and perceptual learning (Section 12.1) could enable them to comfortably and efficiently move their

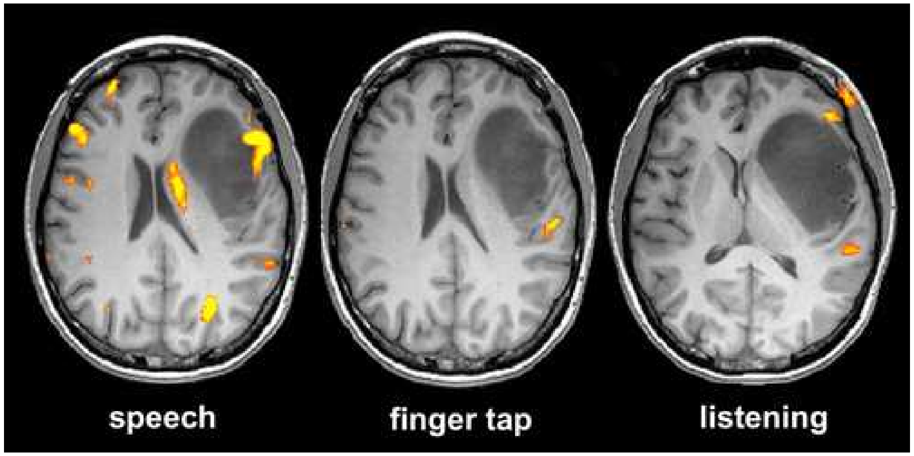


Figure 13.10: fMRI scans based on various activities. (Figure from Mayfield Brain and Spine)

avatar bodies in the virtual world. This might sound like pure science fiction, but substantial progress has been made. For example, monkeys have been recently trained by neuroscientists at Duke University to drive wheelchairs using only their thoughts [44]. In the field of *brain-machine interfaces* (alternatively, *BMI*, *brain-computer interfaces*, or *BCI*), numerous other experiments have been performed, which connect humans and animals to mechanical systems and VR experiences via their thoughts [26, 28, 29]. Surveys of this area include [12, 39, 61].

**Measurement methods** The goal of devices that measure neural activity is to decipher the voluntary intentions and decisions of the user. They are usually divided into two categories: *non-invasive* (attaching sensors to the skin is allowed) and *invasive* (drilling into the skull is allowed).

First consider the non-invasive case, which is by far the most appropriate for humans. The most accurate way to measure full brain activity to date is by *functional magnetic resonance imaging* (*fMRI*), which is shown in Figure 13.10. This is related to MRI, which most people are familiar with as a common medical scanning method. Ordinary MRI differs in that it provides an image of the static structures to identify abnormalities, whereas an fMRI provides images that show activities of parts of the brain over time. Unfortunately, fMRI is too slow, expensive, and cumbersome for everyday use as a VR interface [26]. Furthermore, users typically ingest a dye that increases contrast due to variations in blood flow and also must remain rigidly fixed.

Thus, the most common way to measure brain activity for BMI is via *electroencephalogram* (*EEG*), which involves placing electrodes along the scalp to measure electrical field fluctuations that emanate from neural activity; see Figure 13.11.


(a) (b)

Figure 13.11: EEG systems place electrodes around the skull: (a) A skull cap that allows up to a few dozen signals to be measured. (b) Emotive wireless EEG device.

The signal-to-noise ratio is unfortunately poor because the brain tissue, bone, and skin effectively perform low-pass filtering that destroys most of the signal. There is also significant attenuation and interference with other neural structures. The transfer rate of information via EEG is between 5 and 25 bits per second [26, 61]. This is roughly equivalent to one to a few characters per second, which is two orders of magnitude slower than the average typing rate. Extracting the information from EEG signals involves difficult signal processing [49]; open-source libraries exist, such as OpenVibe from INRIA Rennes.

For the invasive case, electrodes are implanted intracranially (inside of the skull). This provides much more information for scientists, but is limited to studies on animals (and some humans suffering from neural disorders such as Parkinson's disease). Thus, invasive methods are not suitable for the vast majority of people as a VR interface. The simplest case is to perform a single-unit recording for a particular neuron; however, this often increases the number of required trials because the neural response typically switches between different neurons across trials. As the number of neurons increases, the problem of deciphering the thoughts becomes more reliable. Numerous recordings could be from a single site that performs a known function, or could come from multiple sites to help understand the distributed processing performed by the brain [26].

**Medical motivation** It is important to understand the difference between VR users and the main targeted community for BMI. The field of BMI has rapidly developed because it may give mobility to people who suffer from neuromuscular disabilities [61]. Examples include driving a wheelchair and moving a prosthetic limb by using thoughts alone. The first mental control system was built by Jacques Vidal in the 1970s [59, 60], and since that time many systems have been built using several kinds of neural signals. In all cases, it takes a significant amount of training and skill to operate these interfaces. People with motor disabilities may be highly motivated to include hours of daily practice as part of their therapy routine, but this would not be the case for the majority of VR users. One interesting problem in training is that trainees require *feedback*, which is a perfect application of VR. The controller in the VR system is essentially replaced by the output of the signal processing system that analyzes the neural signals. The user can thus practice moving a virtual wheelchair or prosthetic limb while receiving visual feedback from a VR system. This prevents them from injuring themselves or damaging equipment or furnishings while practicing.

**Learning new body schema** What happens to the human's perception of her own body when controlling a prosthetic limb? The internal brain representation of the body is referred to as a *body schema*. It was proposed over a century ago [15] that when people skillfully use tools, the body schema adapts accordingly so that the brain operates as if there is a new, extended body. This results in perceptual assimilation of the tool and hand, which was confirmed from neural signals in [18]. This raises a fascinating question for VR research: What sort of body schema could our brains learn through different visual body representations (avatars) and interaction mechanisms for locomotion and manipulation?

**BMI in VR** In the context of VR, most systems have used one of three different kinds of EEG signals [11, 27, 29, 30, 47]: 1) motor imagery, 2) SSVEP, and 3) P300. The most common is *motor imagery*, which is a mental process that a person performs before executing an action. During this time, the person rehearses or simulates the motion in the brain, which leads to measurable activations in the primary motor cortex. Users imagine rotating in place or making footsteps to achieve locomotion in the virtual world. Unfortunately, most successful systems are limited to a couple of simple commands, such as starting and stopping walking. Nevertheless, users have been able to explore maze-like environments by simply imagining the motions.

One advantage of motor imagery is that it does require any interference or special stimulus from the system, thereby allowing the user to proceed without disruption or particular timing. The other two kinds of signals unfortunately require a stimulus to be generated, and then the response is measured by EEG. One of them is *SSVEP* (*steady state visually evoked potential*), which occurs when a flashing visual stimulus is presented in the range of 3.5 to 75 Hz. The signal-to-noise ratio is very strong for SSVEP, and the user can affect its outcome based on attention paid to the flashing. The decision of whether to pay attention is used as the basis of the command. The other signal is *P300*, which appears about 300ms after a rare and relevant stimulus is presented. Once again, the response is measured based on how much attention the user pays to the stimulus.

**Research challenges** Although BMIs are rapidly maturing, several challenges remain before they could come into widespread use:

- Better technologies for measuring neural signals while remaining non-invasive. Ideally, one would like to measure outputs of thousands of neurons with a high signal-to-noise ratio. One alternative to fMRI that is attracting significant attention in recent years is *functional near-infrared spectroscopy* (*fNIRS*). Such signals can be used in combination with EEG to enhance measurement [19, 37].
- Improved bandwidth in terms of bits-per-second that can be commanded by the user so that there are clear advantages over using body movements or controllers. VR systems with non-invasive BMI typically offer up to one bit per second, which is woefully inadequate [28].
- Better classification techniques that can recognize the intentions and decisions of the user with higher accuracy and detail. Modern machine learning methods may help advance this.
- Dramatic reduction in the amount of training that is required before using an interface. If it requires more work than learning how to type, then widespread adoption would be unlikely.
- A better understanding what kinds of body schemas can be learned through the feedback provided by VR systems so that the brain accepts the virtual body as being natural.

Thus, with the exception of helping people with motor disabilities, BMI has a long way to go before reaching levels of mind control that are expected from science fiction.

**Toward a brain in a vat** To build a widespread, networked VR society, it is tempting to consider invasive BMI possibilities in a distant future. Before proceeding, recall the discussion of ethical standards from Section 12.4 and consider whether such a future is preferable. Suppose that in addition to measuring neural outputs, direct neural stimulation were also used. This would forgo the need to place displays in front of senses. For the eye, signals could be sent directly to the photoreceptors. This technology is called *retinal implants*, and already exists for the purpose of helping the blind to see. Similarly, *cochlear* implants help the deaf to hear. Neuroscientists, such as David Eagleman from Stanford, have even proposed that we could learn to develop completely new senses. An example is perceiving infrared or radio signals by remapping their frequencies, amplitudes, and spatial arrangements to other collections of receptors on the body, such as the back. The limits of neuroplasticity have yet to be fully understood in this way.

Rather than stimulating receptors, the engineered stimulus could even be placed at higher neural levels. For example, why bother with stimulating photoreceptors if the optic nerve could be directly stimulated? This would involve mimicking the processing performed by the ganglion cells, which is challenging, but would also reduce the bandwidth requirements in comparison to stimulating the rods and cones. Ultimately, direct neural measurement and stimulation could lead to the brain in a vat, which was mentioned in Section 1.1.

How do you know you are not already a brain in a vat, and an evil scientist has been taunting you while you read this VR book?

# Bibliography

[1] S. J. Bolanowski, G. A. Gescheider, R. T. Verillo, and C. M. Checkosky. Four channels mediate the aspects of touch. *Journal of the Acoustical Society of America*, 84(5):1680–1694, 1988.

[2] W. S. Cain. Odor identification by males and females: predictions vs performance. *Chemical Senses*, 7(2):129–142, 1994.

[3] N. Chaudhari, A. M. Landin, and S. D. Roper. A metabotropic glutamate receptor variant functions as a taste receptor. *Nature Neuroscience*, 3(3):113–119, 2000.

[4] H. Culbertson, J. J. Lopez Delgado, and K. J. Kuchenbecker. One hundred data-driven haptic texture models and open-source methods for rendering on 3D objects. In *Proceedings IEEE Haptics Symposium*, pages 319–325, 2014.

[5] J. Delwiche. The impact of perceptual interactions on perceived flavor. *Food Quality and Perferences*, 15, 137–146.

[6] G. Dudek, P. Giguere, C. Prahacs, S. Saunderson, J. Sattar, L.-A. Torres-Mendez, M. Jenkin, A. German, A. Hogue, A. Ripsman, J. Zacher, E. Milios, H. Liu, P. Zhang, M. Buehler, and C. Georgiades. Aqua: An amphibious autonomous robot. *IEEE Computer Magazine*, 40(1):46–53, 2007.

[7] R. L. Doty (Ed.). *Handbook of Olfaction and Gustation, 3rd Ed.* Wiley-Blackwell, Hoboken, NJ, 2015.

[8] H. H. Ehrsson, C. Spence, and R. E. Passingham. That's my hand! Activity in premotor cortex reflects feeling of ownership of a limb. *Science*, 305(5685):875–877, 2004.

[9] S. R. Ellis, M. J. Young, B. D. Adelstein, and S. M. Ehrlich. Discrimination of changes in latency during head movement. In *Proceedings Computer Human Interfaces*, pages 1129–1133, 1999.

[10] T. Fong, I. Nourbakhsh, and K. Dautenhahn. A survey of socially interactive robots: Concepts, design, and applications. *Robotics and Autonomous Systems*, 42(3-4):143–166, 2003.

[11] D. Friedman, R. Leeb, C. Guger, A. Steed, G. Pfurtscheller, and M. Slater. Navigating virtual reality by thought: What is it like? *Presence: Teleoperators and Virtual Environments*, 16(1):100–110, 2007.

[12] S. Gao, Y. Wang, X. Gao, and B. Hong. Visual and auditory brain-computer interfaces. *IEEE Transactions on Biomedical Engineering*, 61(5):1436–1447, 2014.

[13] A. Guterstam, V. I. Petkova, and H. H. Ehrsson. The illusion of owning a third arm. *PloS ONE*, 6(2), 2011.

[14] K. Hashimoto, Y. Maruno, and T. Nakamoto. Brief demonstration of olfactory and visual presentation using wearable olfactory display and head mounted display. In *Proceedings IEEE Virtual Reality Conference*, page Abstract, 2016.

[15] H. Head and G. Holmes. Sensory disturbances from cerebral lesion. *Brain*, 34(2-3):102–254, 1911.

[16] M. Hollins, M. H. Buonocore, and G. R. Mangun. The neural mechanisms of top-down attentional control. *Nature Neuroscience*, 3(3):284–291, 2002.

[17] C.-M. Huang and B. Mutlu. The repertoire of robot behavior: Enabling robots to achieve interaction goals through social behavior. *Journal of Human-Robot Interaction*, 2(2), 2013.

[18] A. Iriki, M. Tanaka, and Y. Iwamura. Coding of modified body schema during tool use by macaque postcentral neurones. *Neuroreport*, 7(14):2325–2330, 1996.

[19] M. Izzetoglu, K. Izzetoglu, S. Bunce, H. Ayaz, A. Devaraj, B. Onaral, and K. Pourrazaei. Functional near-infrared neuroimaging. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 13(2):153–159, 2005.

[20] D. L. Jones, S. Dechmerowski, R. Oden, V. Lugo, J. Wang-Costello, and W. Pike. Olfactory interfaces. In K. S. Hale and K. M. Stanney, editors, *Handbook of Virtual Environments, 2nd Edition*, pages 131–161. CRC Press, Boca Raton, FL, 2015.

[21] N. P. Jouppi and S. Thomas. Telepresence systems with automatic preservation of user head height, local rotation, and remote translation. In *Proc. IEEE International Conference on Robotics and Automation*, pages 62–68, 2005.

[22] D. Katz. Der aufbau der tastwelt. *Zeitschrift für Psychologie*, Ergänzungsband 11, 1925.

[23] B. Keshavarz, D. Stelzmann, A. Paillard, and H. Hecht. Visually induced motion sickness can be alleviated by pleasant odors. *Experimental Brain Research*, 233:1353–1364, 2015.

[24] S. M. LaValle. *Planning Algorithms*. Cambridge University Press, Cambridge, U.K., 2006. Available at http://planning.cs.uiuc.edu/.

[25] D. Lazewatsky and W. Smart. An inexpensive robot platform for teleoperation and experimentation. In *Proc. IEEE International Conference on Robotics and Automation*, pages 1211–1216, 2011.

[26] M. A. Lebedev and M. A. L. Nicolelis. Brain-machine interfaces: Past, present, and future. *TRENDS in Neurosciences*, 29(9):536–546, 2006.

[27] A. Lecuyer, L. George, and M. Marchal. Toward adaptive vr simulators combining visual, haptic, and brain-computer interfaces. In *IEEE Computer Graphics and Applications*, pages 3318–3323, 2013.

[28] A. Lécuyer, F. Lotte, R. B. Reilly, R. Leeb, M. Hirose, and N. Slater. Brain-computer interfaces, virtual reality, and videogames. *IEEE Computer*, 41(10):66–72, 2008.

[29] F. Lotte, J. Faller, C. Guger, Y. Renard, G. Pfurtscheller, A. L'ecuyer, and R. Leeb. Combining BCI with virtual reality: Towards new applications and improved BCI. In B. Z. Allison, S. Dunne, R. Leeb, J. Del R. Millán, and A. Nijholt, editors, *Towards Practical Brain-Computer Interfaces*, pages 197–220. Springer-Verlag, Berlin, 2012.

[30] F. Lotte, A. van Langhenhove, F. Lamarche, T. Ernest, Y. Renard, B. Arnaldi, and A. Lécuyer. Exploring large virtual environments by thoughts using a braincomputer interface based on motor imagery and high-level commands. *Presence: Teleoperators and Virtual Environments*, 19(1):154–170, 2010.

[31] M. J. Lum, J. Rosen, H. King, D. C. Friedman, T. S. Lendvay, A. S. Wright, M. N. Sinanan, and B. Hannaford. Telepresence systems with automatic preservation of user head height, local rotation, and remote translation. In *Proc. IEEE Conference on Engineering in MEdicine and Biology Society*, pages 6860–6863, 2009.

[32] K. Y. Ma, P. Chirarattananon, and R. J. Wood. Design and fabrication of an insect-scale flying robot for control autonomy. In *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 1133–1140, 2012.

[33] G. Mather. *Foundations of Sensation and Perception*. Psychology Press, Hove, UK, 2008.

[34] M. Minsky. Telepresence. *Omni magazine*, pages 44–52, June 1980.

[35] G. Morrison. Input lag: How important is it? *CNET*, June 2013. Posted online at https://www.cnet.com/news/input-lag-how-important-is-it/.

[36] T. Narumi, S. Nishizaka, T. Kajinami, T. Tanikawa, and M. Hirose. Augmented reality flavors: gustatory display based on edible marker and cross-modal interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 93–102, 2011.

[37] N. Naseer and K.-S. Hong. fNIRS-based brain-computer interfaces: a review. *Frontiers in Human Neuroscience*, 9(3), 2015.

[38] G. Nelson, J. Chandrashekar, M. A. Hoon, L. Feng, G. Zhao, N. J. P. Ryba, and C. S. Zuker. An amino-acid taste receptor. *Nature*, 416:199–202, 2002.

[39] L. F. Nicolas-Alonso and J. Gomez-Gil. Brain computer interfaces, a review. *Sensors*, 12(2):1211–1279, 2012.

[40] A. M. Okamura, J. T. Dennerlein, and R. D. Howe. Vibration feedback models for virtual environments. In *Proc. IEEE International Conference on Robotics and Automation*, volume 1, pages 674–679, 1998.

[41] E. Paulos and J. Canny. Prop: Personal roving presence. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 296–303, 1995.

[42] E. Paulos and J. Canny. Social tele-embodiment: Understanding presence. *Autnomous Robots*, 11(1):87–95, 2000.

[43] V. I. Petkova and H. H. Ehrsson. If I Were You: Perceptual Illusion of Body Swapping. *PloS ONE*, 3(12), 2008.

[44] S. Rajangam, P. H. Tseng, A. Yin, G. Lehew, D. Schwarz, M. A. Lebedev, and M. A. Nicolelis. Wireless cortical brain-machine interface for whole-body navigation in primates. *Scientific Reports*, 2016.

[45] N. Ranasinghe, R. Nakatsu, N. Hieaki, and P. Gopalakrishnakone. Tongue mounted interface for digitally actuating the sense of taste. In *Proceedings IEEE International Symposium on Wearable Computers*, pages 80–87, 2012.

[46] K. J. Ritchey. Panoramic image based virtual reality/telepresence audio-visual system and method. US Patent 5495576A, February 1996.

[47] R. Ron-Angevin and A. Diaz-Estrella. Braincomputer interface: Changes in performance using virtual reality techniques. *Neuroscience Letters*, 449(2):123–127, 2009.

[48] K. Ruhland, C. E. Peters, S. Andrist, J. B. Badler, N. I. Badler, M. Gleicher, B. Mutlu, and R. McDonnell. A review of eye gaze in virtual agents, social robotics and hci: Behaviour generation, user interaction and perception. *Computer Graphics Forum*, 34(6):299–326, 2015.

[49] S. Sanei and J. A. Chambers. *EEG Signal Processing*. Wiley, Hoboken, NJ, 2007.

[50] G. M. Shepherd. Discrimination of molecular signals by the olfactory receptor neuron. *Neuron*, 13(4):771–790, 1994.

[51] T. B. Sheridan. Musings on telepresence and virtual presence. *Presence: Teleoperators and Virtual Environments*, 1(1):120–126, 1992.

[52] M. Siedlecka, A. Klumza, M. Lukowska, and M. Wierzchon. Rubber hand illusion reduces discomfort caused by cold stimulus. *PloS ONE*, 9(10), 2014.

[53] M. Slater, B. Spanlang, M. V. Sanchez-Vives, and O. Blanke. Experience of body transfer in virtual reality. *PloS ONE*, 5(5), 2010.

[54] C. U. M. Smith. *Biology of Sensory Systems, 2nd Ed.* Wiley, Hoboken, NJ, 2008.

[55] D. Song, K. Goldberg, and N. Y. Chong. Networked telerobots. In O. Khatib and B. Siciliano, editors, *Springer Handbook of Robotics*, pages 759–771. Springer-Verlag, Berlin, 2008.

[56] J. Steuer. Defining virtual reality: Dimensions determining telepresence. *Journal of Communication*, 42(4):73–93, 1992.

[57] L. Takayama, E. Marder-Eppstein, H. Harris, and J. Beer. Assisted driving of a mobile remote presence system: System design and controlled user evaluation. In *Proc. IEEE International Conference on Robotics and Automation*, pages 1883–1889, 2011.

[58] B. Ullmer and H. Ishii. Emerging frameworks for tangible user interfaces. In J. M. Caroll, editor, *Human-Computer Interaction for Tanglible User Interfaces*, pages 579–601. Addison-Wesley, Boston, MA, 2001.

[59] J. Vidal. Toward direct brain - computer communication. *Annual Review of Biophysics and Bioengineering*, 2:157–180, 1973.

[60] J. J. Vidal. Real-time detection of brain events in EEG. *Proceedings of the IEEE*, 65(5):633–664, 1977.

[61] J. R. Wolpaw, N. Birbaumer, D. J. McFarland, G. Pfurtscheller, and T. M. Vaughan. Braincomputer interfaces for communication and control. *Clinical Neurophysiology*, 113(6):767–791, 2002.

[62] S. Xu, M. Perez, K. Yang, C. Perrenot, J. Felblinger, and J. Hubert. Determination of the latency effects on surgical performance and the acceptable latency levels in telesurgery using the dV-Trainer simulator. *Surgical Endoscopy*, 28(9):2569–2576, 2014.

[63] T. Yamada, S. Yokoyama, T. Tanikawa, K. Hirota, and M. Hirose. Wearable olfactory display: Using odor in outdoor environment. In *Proceedings IEEE Virtual Reality Conference*, pages 199–206, 2006.