Vestibular sensory substitution using tongue electrotactile display

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Sensory substitution

Sensory substitution systems provide their users with environmental information through a human sensory channel different from that normally used. For example, a person who is blind may use a long cane to detect obstacles while walking and Braille or raised-line graphics to read information normally received visually. A person who is deaf may read lips to understand speech. A person without vision or hearing may use a method called Tadoma, placing his or her hands over the face and neck of a speaker to understand speech [1]. Persons with an impaired vestibular (balance) system use their hands, not primarily for mechanical support, but to sense how they move relative to their environment. Electronic sensors and tactile (touch) displays enable more sophisticated applications for sensory substitution. In this chapter we will briefly review visual and auditory sensory substitution, as well as tactile feedback in robotic systems, followed by an extended discussion of vestibular sensory substitution. A more detailed discussion of vision substitution is provided in the chapter by Ptito in this book.

For the brain to correctly interpret information from a sensory substitution device, it is not necessary for the information to be presented in the same form as the natural sensory system. One needs only to accurately code action potentials in an alternate information channel. With training, the brain learns to appropriately interpret that information and utilize it to function as it would with data from the normal natural sense.

Reported attempts to present spatial visual information *via* tactile displays date from at least the early 1900s, with serious scientific study starting in the 1960s [2–4]. These systems operate by using an electronic camera or matrix of light sensors to control the stimulation intensity on a spatially-corresponding matrix of electrical or mechanical tactile stimulators on the surface of the skin. The user perceives tactile shapes on the skin having the same shape as the visual image recorded by the camera. Blind and blindfolded users are then able to identify simple objects in a high-contrast environment, and have reported visual concepts such as distal attribution (i.e., perceptually localizing the target object out in front of the camera, rather than on the tactile display proper) [5], looming, and perspective [6], and also optic flow phenomena [7]. A vision substitution device using a forehead tactile display is being commercialized (http://www.eyeplus2.com).

Electrotactile stimulation (inducing touch sensations using carefully-controlled electric current pulses delivered *via* electrodes on the surface of the skin) has been studied extensively in many laboratories [8, 9], including ours at the University of Wisconsin-Madison. Electrotactile displays have been used to deliver tactile graphics to the fingertips [10], abdomen [7], or tongue [11]. Vision substitution research using the tongue-based tactile display developed in our lab [12] has demonstrated that the visual cortex is active in processing visual data presented to the tongue [13, 14]. This is an example of brain plasticity, the ability of the brain to reorganize its function for optimal processing of information following injury, loss of 'normal' sensory information, or other challenge [15, 16].

Auditory prostheses using electrotactile stimulation typically use the stimulation intensity on each electrode in a linear [17, 18] or two-dimensional [19] matrix to represent the sound intensity in a particular frequency range of sounds recorded by a microphone. Results have generally included increased awareness of sounds and improved lip reading ability [20, 21]. At least two devices (made by Tacticon Corporation and Sevrain-Tech, Inc.) were commercially available in the 1970s–1980s. Based on our tongue-based tactile display system, Wicab, Inc. (http://www.wicab.com) is commercializing auditory, visual, and vestibular (see below) sensory substitution systems.

The telerobotic-manipulation community has long recognized the inadequacy of strictly visual feedback, and the particular need for haptic information such as contact, grasp force, shear, and slip, which convey critical information about the state of the hand-object interaction [22]. Operators with normal motor control could incorporate hand feedback and tongue tactile stimulations from a sensate robotic gripper to create an additional haptic channel [23]. The technical term for human touch is haptic or tactual perception, which combines tactile (spatial pressure profile) and kinesthetic (joint position and torque) information [24]. Haptic human-machine interfaces are an active area of research [25].

One of the recent and successful discoveries in sensory substitution approach for clinical rehabilitation purposes is electrotactile vestibular substitution [26]. The tactile sensory channel of the skin was used to substitute missing or damaged sensation from the one of the most sophisticated natural sensory devices – vestibular sensory organs. The remainder of this chapter is an in-depth case study of electrotactile vestibular substitution.

Vestibular sensory system

To navigate correctly in three dimensional space, we should use sophisticated guidance systems that register every acceleration along three spatial axis and rotation around them. To do that technically we are using highly sophisticated systems, including 3-D accelerometers and gyroscopes under computer control to provide precise information in many areas of industry, robot technology, space and military applications. Vertebrates, including primates and humans, are using a naturally designed navigational system – vestibular.

The sensory receptors that allow us to maintain our equilibrium and balance are located in the vestibular apparatus, which consists (on each side of the head) of two otolithic organs, the utricle and the saccule and three semicircular canals. The semicircular canals, hoop-like tubular membranous structures, sense rotary acceleration and motion.

The sensory structures in these organs, called maculae, also employ hair cells, similar to those of the auditory sensory system. The 'hairs' of these cells, which consist of numerous microvilli, called stereocilia, and one cilium, called a kinocilium, are embedded in a gelatinous mass weighted by the presence of otoliths composed of protein and calcium carbonate. The gelatinous mass moves in response to gravity, bending the hair cells and initiating action potentials in the associated neurons.

Gravity pulls on the otoliths and bends the hair cells as the position of the head changes. The body responds by making subtle tone adjustments in muscles of the back and neck, which are intended to restore the head to its proper neutral, balanced position. The maculae also respond proportionally to linear acceleration and activate your awareness during acceleration or deceleration in the car or speeding lift.

The impulses generated by these hair cells are carried by the vestibular portion of the 8th cranial nerve to the cerebellum, the midbrain, and the temporal lobes of the cerebrum. The cerebellum and midbrain use this information to maintain equilibrium at a subconscious level.

The three semicircular canals are fluid-filled membranous ovals located on each side, and lie in three mutually perpendicular planes. Near its