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Tactile sensory substitution: Models for enaction in HCI

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ABSTRACT

To apply enactive principles within human–computer interaction poses interesting challenges to the way that we design and evaluate interfaces, particularly those that possess a strong sensorimotor character. This article surveys the field of tactile sensory substitution, an area of science and engineering that lies at the intersection of such research domains as neuroscience, haptics, and sensory prosthetics. It is argued that this area of research is of high relevance to the design and understanding of enactive interfaces that make use of touch, and is also a fertile arena for revealing fundamental issues at stake in the design and implementation of enactive interfaces, ranging from engineering, to human sensory physiology, and the function and plasticity of perception. A survey of these questions is provided, alongside a range of current and historical examples.

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1. Introduction

In tandem with contemporary advances in information technologies, there has been considerable interest in enriching interactive computing systems so as to make more effective use of the perceptual and motor capabilities of their users. Applications of current interest include robotic microsurgery devices, immersive virtual environment (VE) simulations, tangible information systems and gesturally controlled video games. The many interfaces and interactions exemplified within the state-of-the-art depend in turn upon a wide range of continuous input technologies. The scope of this design space serves to highlight the broad importance of enactive considerations for HCI design today. As other contributors to this issue have noted, the enactive viewpoint emphasizes the strong supportive roles that can be played by the coordinated affordance of action and perception in interactive systems, and by the good use of existing sensorimotor abilities on the part of users. Such considerations may be crucial for ensuring that continuous, movement-based control affordances attain the degree of usability and intuitiveness that they are capable of. Sensory substitution devices (introduced below) provide a minimal yet highly illustrative class of examples for the diverse technological and human factors considerations that must be accounted for when designing for such interactions. The purpose of this article is to review these considerations in the context of tactile sensory substitution.

1.1. Tactile feedback in enactive interfaces

An emphasis on tactile feedback in interaction lends context to the present review, and exemplifies a compelling parallel thread of developments in HCI, centered on touch-based interfaces. Tactile information channels play a significant role in diverse everyday interactions. Since most human–computer interaction is mediated through touch, the tactile sense should be positioned to play a richer role in such interactions than it does at present. However, guidelines for the design of non-visual displays remain significantly less developed than in the visual case, and case studies are fewer. Consequently, added attention to this area is warranted. Because of the knowledge gap that exists relative to visual (and to some extent auditory) display design, tactile display is arguably under used. Moreover, tactile display possesses distinct advantages relative to other modalities, while also posing unique challenges to the interface engineer and designer. These issues are reviewed beginning in Section 2. As noted above, many of them are of broader significance to enactive interaction design.

1.2. Sensory substitution

Sensory substitution refers to the translation of sensory information that is normally available via one sense to another. Occasionally, the term is also used to refer to plasticity in the intrinsic senses, i.e. to cases in which an intrinsic sensory capacity is used for a purpose normally tied to another such capacity. The best studied example is the phenomenon of "blindsight" by visually impaired people, in which heightened use of auditory channels enables individuals using it to discern objects, obstacles or

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structures in front of them (Weiskrantz, 1998). However, more commonly, and in the sense intended in the current article, the term is invoked to describe a technological intervention via a system capable of performing such a translation for its user. In such cases, the electronic sensing capabilities of the device are used to perform the requisite capture and translation of signals. As early as 1897, Noiszewski created a device called the Elektroftalm, consisting of an ambient light sensitive selenium cell connected to a sound-producing circuit, designed to aid visually impaired people in distinguishing light and dark spaces (Spirkovska, 2005; Capp and Picton, 2000). Later versions of the device were designed to utilize 80-sensor arrays and tactile, rather than auditory, feedback (Starkiewicz and Kuliszewski, 1963). Sensory substitution systems were subsequently proposed for teleoperation settings, in order to assist humans in the remote operation of a robotic manipulator, where the operator was thought likely to benefit from additional sensory information. Such feedback has been proposed in the form of tactile or auditory display of contact information to supplement a video display. As discussed below, sensory substitution devices have also been developed to test fundamental scientific ideas about perceptual plasticity, or sensorimotor theories of perception.

1.2.1. Relevance to human computer interaction

Human–computer interaction can be regarded as the design of systems that enable their users to interact with digital information, accessed via computers, that would not otherwise be accessible. That information might be organized by a desktop metaphor, virtual reality simulation, or the abstract space of a dataset to be explored. The interface operates by extending the user's perceptual-motor capabilities "into" these virtual environments, in some sense. Without this sensory feedback, users are impaired in acting within the virtual environment. From such a standpoint, sensory substitution can be seen as an organizing perspective for human–computer interaction, most relevant to continuous (as opposed to symbolic) methods of interaction. This viewpoint has practical value to the extent that research on sensory substitution is able to inform the design of new interfaces.

1.2.2. Systems for sensory substitution

A sensory substitution system can be thought of as composed of a number of components of the kind illustrated in Fig. 1. Information about the environment is typically acquired from sensors corresponding to modality A, and the information is transduced into a set of signals $\mathbf{x}(t)$ that are subsequently digitized. The sensors can be physical devices or they may correspond to measurements in a virtual environment. A coupling device maps the sensed data $\mathbf{x}$ onto a set of signals $\mathbf{y}(t)$ for driving the actuators of the display. The actuated display presents the information to a human sensory modality B, which is eventually transduced and processed by the intrinsic sensory system of the body. In the systems of most interest to this article, B will represent a tactile sensory channel or channels.

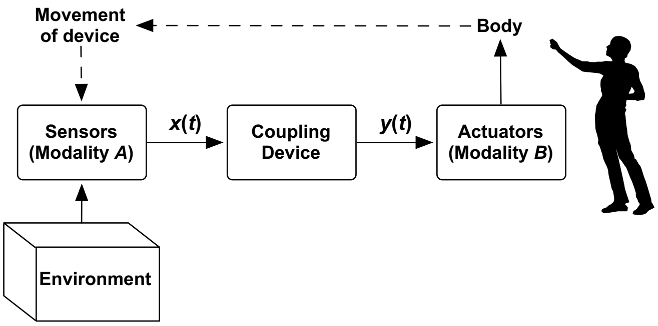

Fig. 1. Structure of a sensory substitution system.

One feature (discussed in Section 5.6) that many have argued is crucial to the effectiveness of such systems is that the interaction loop is closed, through the affordance of user control over the position and orientation of the sensors, represented by the dashed lines in the figure.

1.2.3. Definitions

As suggested in the loose typology alluded to above, authors writing about the subject have differed in the level of significance they have attached to both the term itself and to the phenomenology that can be ascribed to the interventions it labels.

1.2.3.1. Operational definitions. In the narrowest sense, sensory substitution has been taken to refer to the act of translating signals that are normally associated with sensory modality A to signals that can be detected via modality B. For example, ambient light intensity may be translated to the vibration of an object attached to the fingertip, without any pretense of the result constituting a visual or informational aid. Such an operational description avoids any claim as to the utility of the translated information for a particular task, function, or capacity.

1.2.3.2. Functional characterizations. Various authors have applied the term to imply the provision of additional sensory information through a device in such a way as to aid users in performing some task. More specifically, some have identified sensory substitution as the provision of information *to assist people with sensory impairments*. For example, several systems have been designed to enable their users to read printed text, other devices have been created as navigational aids for visually impaired people, and a number of systems have been developed to improve teleoperated control over a remote robot. Examples from each of these categories are reviewed in the sections below.

1.2.3.3. Perceptual claims. Several authors have described sensory substitution systems as enabling a form of artificial perception via the newly provided sensory information (after an initial period of adaptation). In such cases the intervention may be motivated as a *sensory replacement* for individuals with visual or auditory impairments. When such interventions are claimed to be successful, perception is sometimes hypothesized to occur in a cross-modal sense, in which intrinsic perceptual faculties are recruited to utilize the substituted information. As discussed below, support for these ideas has come from behavioral evidence gathered from experiments with users of the systems, from neurological data about activity in the brain, and from qualitative feedback provided by users. Ultimately, the available evidence may support diverging models of what it could mean to acquire artificial perception through a sensory substitution device. The scope of the discussion regarding cross-modal perception somewhat exceeds the domain of the present article, but some of the most significant issues are discussed in Section 5.3 below.

1.3. Tactile sensory substitution

At an operational level, tactile sensory substitution can be described as the display of phenomena typically associated with one human sense by means of the tactile sense.[1] It poses engineering problems associated with electronic sensing, the coupling of sensing to tactile display methods, to the design of the displays

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[1] The author explicitly allows for the possibility of tactile-to-tactile sensory substitution, examples of which will be discussed later in this article.

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themselves, and the presentation of information so as to best take advantage of the intrinsic human tactile information processing pathways. It is specially linked to fundamental questions concerning the plasticity of human perception and to the ways in which perception is intertwined with physical embodiment, the structure of the environment and the means of action. Consideration of these issues is indispensable to a discussion of how tactile sensory substitution (TSS) devices may be successfully realized. Many applications of such devices have been proposed, ranging from sensory replacement in the case of specific sensory deficits (such as blindness), to the rehabilitation of motor function, and the display of task salient channels of ecological information during human interaction with virtual environments. These topics are reviewed in the sections that follow, with reference to the relevant literature.

1.3.1. Tactile vision sensory substitution

An early example of tactile sensory substitution is provided by the Tactile Vision Sensory Substitution (TVSS) system, created by Bach-y-Rita and his collaborators. This research is overviewed in a recent article (Bach-y-Rita, 2004). The name TVSS refers to a family of devices developed beginning in the early 1960s for the purpose of lending sight to visually impaired people (Bach-y-Rita, 2003). Photographs of two of the systems are shown in Fig. 2. The systems captured video of their user's surroundings via a camera, and supply a tactile display of a representation of the video information. Several tactile displays were investigated, consisting of two-dimensional arrays of vibrotactile or low-frequency displacement actuators applied to the skin of the back, forehead, thigh, abdomen, or finger (Bach-y-Rita, 2004). The size of the array has varied from 64 to about 1000 elements. The TVSS has been the subject of an unusual number of studies, over several decades, and has previously been marketed commercially under the VideoTact name, beginning in the 1990s. TVSS researchers have reported that users of these systems are able to learn to discriminate simple tactile stimuli, such as oriented lines. Granted further experience with the device, and, in most cases, the ability to move the camera, users are said to begin to recognize shapes of simple, familiar objects via the tactile display. After a period of about 15 h, Bach-y-Rita and his colleagues state that users' awareness of the proximal tactile sensation fades, and that users begin to "perceive" stable three-dimensional objects *in space* (Bach-y-Rita, 2004). This progression is said to occur without conscious processing.

The authors report that users with sensory impairments have learned to perform tasks including batting a ball, industrial assembly line work, and navigation on foot (Bach-y-Rita, 2004). The authors emphasize the insensitivity of their results to sensor and actuator location (discussed below). They have broadly attributed their results with the TVSS to the plasticity of the human perceptual capacity in adapting to the information supplied by the substitution device, and have emphasized the relation to prior results on neural plasticity (some of which are reviewed in Section 5.3, below). It is suggested that the cross-modal processing capabilities of the brain are critical in enabling such substitutions, particularly in visually impaired people.

2. Tactile display design

The tactile information display is a key component of a tactile sensory substitution (TSS) device. The research and development of such displays is a large subject in its own right, ranging in focus from the engineering of actuators to the study of tactile psychophysics. In this section, key issues in tactile display are surveyed from the viewpoint of sensory substitution.

2.1. Advantages of tactile feedback

Interest in tactile displays has undoubtedly been amplified in recent years for the same reasons that interest in electronic display modalities for all of the senses has grown. Although the most common methods for tactile display have been in use for many years, technological advances in manufacturing, microprocessor and sensor technology during the last decades have made the active components of certain of these systems smaller and less costly. New tactile displays can be made smaller and higher resolution than has been possible in the past, and such devices are now easier to engineer. This, in turn, has opened a larger range of potential applications for enrichment by a wider array of technologies that can be applied to them. A number of recent reviews exist to guide the application developer in the use of tactile display technologies in human computer interaction (Jones and Sarter, 2008; Wall and Brewster, 2006; Benali-Khoudja et al., 2004; Chouvardas et al., 2005; Hafez, 2007).

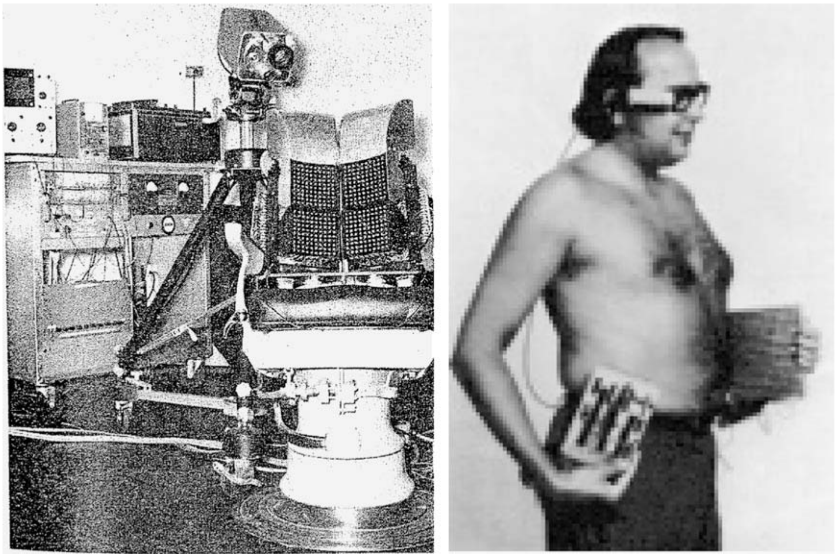

Fig. 2. *Left:* This version of the Tactile Vision Sensory Substitution system of Bach-y-Rita and his colleagues (image reproduced from (Bach-y-Rita et al., 1969) consisted of a 20 by 20 element vibrotactile pin array that was applied to the back, by means of the dental chair shown, and was used for displaying imagery from the video camera. *Right:* A later version of the TVSS utilized a pin array worn on the abdomen and a video camera worn on the head.

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Tactile feedback possesses qualities that make it more suitable under many conditions than other display methods. The actuators involved are cheap and are available in many different forms, including solenoids, eccentric inertial motors, voice coils, piezoelectric transducers, pneumatic components, and others; see Section 2.3 below. They can be made small enough to match the receptive field sizes of the mechanoreceptors in the most sensitive parts of the body, and powerful enough to saturate the activation levels of the same receptors. In this respect, they are well suited even to applications involving inexpensive everyday or portable devices, where they are already seeing widespread use in mobile phones and video games.

Tactile display requires little power, and is readily made portable. By contrast, traditional force-based haptic displays, which provide tactile information as well as kinesthetic information associated with the change in forces over distances of more than a few millimeters, require much more space and power to operate. Furthermore, tactile displays do not possess the instabilities that force-based haptic interfaces must be carefully designed to avoid (Adams and Hannaford, 1999). Thus, tactile displays are easier and more cost-effective to produce than haptic displays. These benefits of tactile display have led several research teams to integrate separate tactile display channels with traditional force feedback haptic interfaces (examples Kontarinis and Howe, 1995; Massimino, 1991; Massimino, 1995 are reviewed in the sections that follow). Such integrated devices may prove relevant to situations, such as robotic surgery, in which haptic feedback may not be an option (Kitagawa et al., 2005; Akinbiyi et al., 2006). Many sources of environmental information are multisensory in nature, and where physical contact is involved, tactile sensation can play an important role, as in the case of the perception of surface texture in real or virtual environments.

Tactile display is well suited to presenting fine textural information to the skin, such as is encountered during manual exploration of a virtual textile or other surface texture. Touch alone is enough to allow us to discriminate between surface textures that differ only microscopically. In the experiments of LaMotte and Whitehouse, for example, the detection thresholds of the fingerpad of macaque monkeys to microdots just a few microns high on an otherwise smooth surface were charted (LaMotte and Whitehouse, 1986).

Tactile feedback plays a special role in skilled manipulation tasks, which normally require touch. Touch is most acute at the interface between the body and the artifacts that are involved in such tasks, and it conveys significant information about contacts between the artifacts concerned. This information is complementary to that which is obtained about kinematic constraints via kinesthetic channels (forces, extensions and joint angles).

Equally significantly, interest in informational display devices has grown due to the proliferation of digital information, whether pertaining to virtual environments or to the state of the real world. As noted in the introduction, when interacting with virtual environments, all users are confronted with a sensory deficit that must be overcome through the design of sensory displays.

From a cognitive standpoint, touch is often thought of as providing a ground truth to experience – which is why we have expressions like "hands-on demonstration" and "hands-on activity". Hearing is, by comparison, notoriously susceptible to confusion (for example, spatial direction and identity can be confused depending on the stimulus properties and direction). Similarly, we become aware of the possibility of visual illusions from a young age. While comparable tactile illusions exist, we rely on touch to reassure ourselves of the reality and validity (or otherwise) of what we are experiencing.

Applications of human computer interaction that are well suited for tactile sensory display are diverse. Moreover, tactile feedback may have a special role to play in motor learning. For example, light (non-force supplying) touch has been shown to facilitate postural correction in dynamic balance (Jeka and Lackner, 1994), providing an additional feedback channel to assist the vestibular system. In addition, several systems have been developed to aid motor learning of dynamic gestural tasks involving control of the body, through the use of vibrotactile feedback (a wearable sleeve developed by Lieberman (Lieberman and Breazeal, 2007) is a recent example).

2.2. Human tactile sensation

Human skin facilitates sensation through touch via the mechanical properties of its tissues, which are responsible for conveying tactile stimuli to the dermal and subdermal receptor sites at which they are transduced into neural signals, and through the tactile receptors that perform the transduction. Human skin can be categorized as hairy (skin on most parts of the body), glabrous (the non-hairy skin on the front of the hands and bottom of the feet), or mucous (the moist skin of the mouth and other bodily openings). The skin contains a range of receptors for pain (nociceptors), temperature (thermoreceptors), chemical stimuli (chemoreceptors), limb joint and muscular states (proprioceptors), and six kinds of tactile force-, or mechanoreceptors (Kandel et al., 2000). Details concerning the nature, distribution, and properties of such receptors are still open issues. Properties of five types of mechanoreceptors present in the cutaneous and subcutaneous layers of the skin, and associated connective tissue, are summarized in Table 1. Detailed descriptions of the anatomy and physiology of receptor populations in the hands are available, and summarized in standard references on neuroscience (Kandel et al., 2000). The literature on properties of tactile receptor populations in skin on other parts of the body is less expansive.

In addition, many relevant psychophysical properties are known. These include the relevant ranges of frequency sensitivity, receptive field sizes, receptor densities, and sensory correlates, all quantities that are highly salient to the low-level design of tactile displays. Spatial tactile resolution is among the most extensively studied features. The most frequently cited measure is the two-

Table 1

An understanding of skin tactile mechanoreceptor properties is a necessary prerequisite for the design of effective tactile displays (table adapted and modified from Kaczmarek et al. (Kaczmarek et al., 1991)

Receptor	Class, type	Receptive field (mm^2) (Median)	Skin type	Frequency range (most sensitive)	Threshold skin deform on hand (median)	Probable sensory correlate	Receptors/cm^2 fingertip (palm)
Pacinian corpuscle	FA, II	10–1000 (101)	G, H	40–800 Hz (200–300 Hz)	3–20 μm (9.2 μm)	Vibration tickle	21 (9)
Meissner's corpuscle	FA, I	1–100 (12.6)	G	10–200 Hz (20–40 Hz)	4–500 μm (13.8 μm)	Touch tickle motion Vibr flutter tap	140 (25)
Merkel's cells	SA, I	2–100 (11.0)	G	0.4–100 Hz (7 Hz)	7–500 μm (56.5 μm)	Edge pressure	70 (8)
Ruffini corpuscle	SA, II	10–500 (59)	C	7 Hz	40–1500 μm (33 μm)	Stretch shear tension	9 (15)[a]
Hair follicle receptor	FA	–	H	?	–	Touch vibration proximity	–

FA, fast acting; SA, slow acting; G, glabrous; H, hairy; C, connective tissue.

[a] Kaczmarek et al. originall cited figures of 9 and 15 cm^2 for the density of Ruffini corpuscles in the fingerpad and palm, but later work by Paré et al. (2003), Paré et al. (2002) indicates that Ruffini cells are missing from the finger pads, and insteadare confined to connective tissues, such as the collagen bundles at the base of the fingernails.

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point threshold, which is the minimum distance between two point-like indentations applied to the skin below which only a single point of contact is discerned. This value varies from 2.5 mm in the fingers, up to as much as 50 mm for other body regions (Fig. 3). More recent authors have focused on inadequacies of the two-point threshold as a measure of tactile acuity (Craig and Johnson, 2000). Much finer features on surfaces can be detected through dynamic touch, as in the study of LaMotte and Whitehouse mentioned above (LaMotte and Whitehouse, 1986). Tactile acuity exhibits high inter-individual differences (Craig and Johnson, 2000), and depends very much on the nature of the stimulus that is used (see the next section for a typology of tactile display methods), and properties of the stimulus, such as frequency, duration, and amplitude (Cholewiak and Collins, 2000). For example, Hayashi and Nijouji reported measurements of two-point thresholds due to electrode stimulation of the fingertip at various frequencies (Hayashi, 2004). A highly salient review of tactile display by Jones and Sarter summarizes the available psychophysical data on tactile sensitivity to vibrotactile stimulation on various body parts (Jones and Sarter, 2008).

Psychophysical thresholds for a particular type of stimulation indicate the minimum noticable intensity of stimulation $I_{\min}$, with stimulus properties (other than amplitude) held constant. Maximum stimulus instensity $I_{\max}$ is typically taken to be the threshold for pain perception. These values are significant for display engineering, as they determine the maximum dynamic range R attainable by stimulation with a particular stimulus type, which may be expressed in decibels via

$$R(\mathrm{dB}) = 10\log_{10}(I_{\max}/I_{\min}) \qquad (1)$$

In general, the maximum dynamic range will be a function of stimulus type, frequency of stimulation, location on the body, etc.

Sensory transduction is not a linear, temporally or spatially independent process, and complex sensory phenomena result from this. Processes such as temporal and spatial integration create dependencies between the influence of stimuli located near each other in time or spatial position. Locally, sensory thresholds rise under sustained stimulation. Among other things, this makes it possible to ignore low-level tactile stimulation, such as the sensation of an object held against the skin. Adaptation is important to account for in tactile interaction design, and for sensory substitution, because such interventions may involve a continuous coupling between the user of the system and the stimulating device over an extended period of time. Tactile sensory thresholds rise by a few dB in response to only a few seconds of sustained vibrotactile stimulation, and do not attain a maximum until approximately 25 min of stimulation have passed. Full recovery requires on the order of 2 min (Kaczmarek et al., 1991).

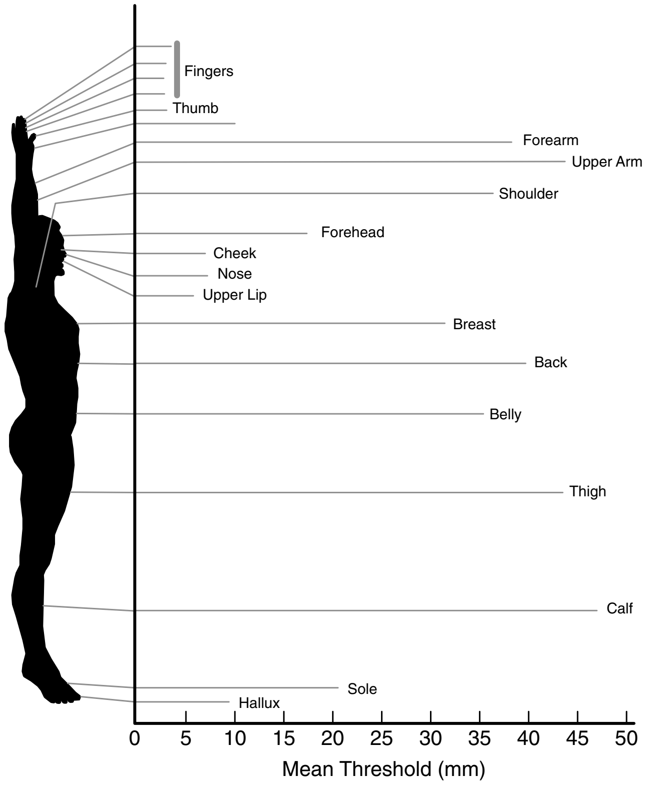

Fig. 3. Average two-point tactile discrimination thresholds for various bodily regions (adapted from Kandel et al. Kandel et al., 2000).

As is familiar from everyday experience, qualitative tactile sensations are wide-ranging and heterogeneous. They include pressure, texture, puncture, thermal properties, softness, wetness, friction (slip, adhesion, microfailures), dynamic events (contact, release), pain, object features like shape, edges, embossings, recessed features, and vibrotactile sensations, such as tickling, itch, vibration, and buzz (Hayward et al., 2004). Many of these sensations can be associated with different types of tactile stimulation, several of which are reviewed in the next section.

2.3. Tactile display methods

It is necessary to distinguish tactile display methods from the sensations that they produce and the actuators required to produce them. Such display methods can be primarily characterized by the format in which energy is transmitted to the skin, and thereby to the tactile receptors in it. A brief and non-exhaustive summary of such methods follows.

Low frequency, low amplitude mechanical deformation

Bumps or objects are raised against the skin or other body part, or are used to render a relief that can be explored by touch. One can distinguish between continuous contact with an object, and "make-and-break" contact, in which an object is brought in and out of contact with the body part. The skin possesses an especially high sensitivity to the latter (Kaczmarek et al., 1991).

Vibrotactile stimulation

Consists of objects vibrating against the skin or other body surface (for example, the teeth). Typical frequencies are chosen to maximize Pacinian FA II receptor sensitivity (highest near 250 Hz). Vibrations may be effectively transmitted through an air gap, again due to the high make-and-break contact sensitivity. This effect has been exploited through vibrotactile pin array based devices, such as the Optacon (described below).

Electrotactile stimulation

Currents are passed through the skin via a source. These currents excite the afferent nerves directly rather than the tactile receptors themselves. Current may be supplied by electrodes of different types, or by fine wires inserted into the skin. Different afferent types can be excited differentially through the design of the drive signal and electrical contacts.

Force feedback displays

Force feedback displays are by nature meant to access primarily the kinesthetic haptic channel. However, they interact with the cutaneous tactile sense when friction phenomena, vibration, or contact transients are inevitably generated.

Thermal displays

Heat is directed toward or away from the skin. The mechanisms of heat transfer can include contact conduction via a medium, convection, or radiation. Ultimately, the method

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of transfer to heat-sensitive receptors in the body is conduction through bodily tissues. Thermal displays may be readily implemented using Peltier cells, which can be electronically controlled to pump heat toward or away from an area of skin that is in contact with it.

Air or liquid jets or currents

Such currents can stimulate SA mechanoreceptors by supplying forces, FA mechanoreceptors by vibrating skin (Collins, 1970), or hair follicle receptors by moving hairs. They may supply a regularly varying or dynamic, noisy stimulus. Thermal effects can also come into play through heat transfer mechanisms noted above. Focused ultrasonic vibrations in air, modulated at lower frequencies, have been used for spatially localized in-air tactile display (Iwamoto et al., 2001).

In order to implement any of these methods for tactile display, a more detailed accounting is needed of various factors, foremost among which is the availability and suitability of different actuator technologies. Moreover, higher-level properties of and structure in the stimulus signals must be considered, such as:

- The total number of actuation sites on the body, and the density of sites per unit area. The density may be weighed relative to spatial tactile discrimination thresholds of the kind described above.
- The size, location on the body, spatial layout and other features of the area to be actuated.
- Temporal qualities of the stimulus, such as its frequency, and pattern in time. The temporal dependence of tactile thresholds provide highly salient design considerations (display gain may need to adapt over time to achieve a constant percept).
- The dynamic range and absolute maximum amplitude of the stimulus. This may be considered relative to the amplitude threshold and saturation amplitude of the receptors.
- Frequency bandwidth and dynamic range of the device. Again, these may be measured relative to receptor characteristics.
- Local features of the interface with the skin at the site of actuation. Examples include: moistness of the skin, skin biomechanics, such as stretching and compliance, any oils on the surface of the skin, etc.
- Constancy and reliability of the display; drift.
- Stability of the display in interaction (mainly relevant for force feedback displays).
- Device accuracy and precision (relative to those of the tactile channels).
- Safety issues: risks of pain and damage to the user; long-term ergonomics.
- Size, weight, power requirements, portability, and durability.

Another key detail concerns whether the display targets what is sometimes called passive touch, in which case the transducer is applied to a fixed location on the skin, or whether it involves active touch, in which the area of the display contacted by the skin changes dynamically as the former is explored.

2.3.1. Vibrotactile stimulation

Vibrotactile stimulation may be the most popular method for tactile display. It involves an object or objects that are made to vibrate against the skin or other body surface for the display of information. The most common method of information coding by a single actuator is amplitude modulation. If it is desired to transmit a signal $u(t)$, then the actuator is typically driven by a signal $y(t)$ given by

$$y(t) = [A + u(t)]\sin(2\pi f_c t), \quad f_c \approx 250\ \text{Hz} \tag{2}$$

As noted above, the carrier frequency is most commonly selected in this way to best address the FA II (Pacinian) mechanoreceptors in the skin. The resulting stimulus elicits a sensation that is felt as a bump, a vibration (possibly one possessing the signature of a physical process, such as rolling or sliding), a texture or perhaps a material quality.

Cross-modal sensations and illusions can also be elicited through vibrotactile stimulation. An appropriately chosen stimulus, applied to the muscle and tendonal mechanoreceptors, can make the limbs seem to move in a manner that can be controlled. Roll and Gilhodes (Roll and Gilhodes, 1995) studied the organization of illusory vibrotactile proprioceptive sensation in movement trajectory perception. Their system has elicited the feeling of self-generated drawing movements in subjects by applying vibrotactile patterns to their wrist muscles. Such illusions have been exploited for the purpose of generating whole arm and upper body movement illusions via vibrational feedback in subsequent work by the same authors.

2.3.2. Electrotactile stimulation

Electrotactile information displays have been investigated at least since the early 1970s (Triggs et al., 1973). Electrotactile stimulation involves a current passed through the skin via a current source. The current elicits a sensation by exciting afferent nerves directly. Secondary electrotactile effects can result in cases in which a small current modifies the frictional properties of a surface. Electrotactile stimulation can evoke a wide range of sensations, including, itching, tingling, vibration, buzzing, touch, pressure, pinch, or pain. Currents may be supplied by an electrode on the skin or by a fine wire or other structure inserted into or beneath the skin (Kaczmarek et al., 1991). In sensory studies, single afferent fibers are stimulated with microelectrodes to reveal the sensations associated with activation of different fiber types (Torebjork et al., 1984, as related in Kaczmarek et al., 1991). Newer methods of electrotactile stimulation attempt to differentially evoke desired sensations by controlling the mode of stimulation.

Several difficulties must be overcome for electrotactile stimulation to be practical (Kaczmarek et al., 1991). First, the electrode type and material are significant, as are the skin-electrode coupling, including contact force, skin location, skin hydration and oiliness. Hairy and glabrous skin pose challenges due to the fact that the skin conductivity can change rapidly as pores open or close or as sweat accumulates on or under the top layers of the skin. In the absence of careful current control, such changes can lead to painful shocks. Mucous skin like that of the mouth has benefits for electrotactile stimulation, as discussed below, because tactile receptors are closer to the surface and the tissue is kept moist.

2.3.3. Selective electrostimulation of tactile mechanoreceptors

Work by Tachi and his colleagues (Kajimoto et al., 2004) has focused on the development of electrotactile displays for the glabrous skin that are capable of differentially activating mechanoreceptors – a phenomenon they have described as “tactile color” (see Fig. 4. Their work is based on a study of the electrical physics of the skin in relation to the geometry and composition of afferent neurons in the skin. The main points are as follows. The axons of the primary mechanoreceptors turn out to be of larger diameter than others present in the skin (i.e. those corresponding to the nociceptors, themoreceptors, and so on). This translates into a lower activation potential for the mechanoreceptors, so that they are activated first as current is increased. The Meissner corpuscles (FA I) possess vertically oriented afferent nerves, while that of the Merkel receptors (SA I) is horizontally oriented. When stimulated by a coaxial electrode pair, the vertically oriented afferent of the

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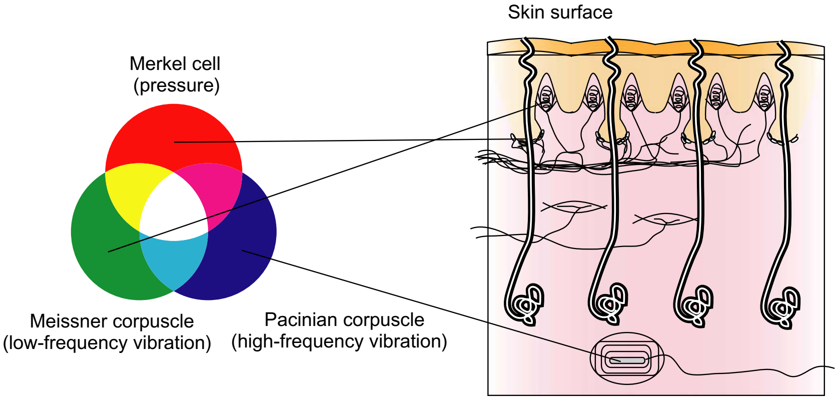

Fig. 4. The Smart Touch project the Tachi Laboratory, The University of Tokyo (Kajimoto et al., 2003, 2004) aims at enabling the composition of tactile sensations by means of selective electrical stimulation of tactile mechanoreceptors (image courtesy of Tachi Laboratory, University of Tokyo).

Meissner corpuscle is more susceptible to activation when the central electrode of the pair is a cathode. When stimulation is supplied in this way, a vibratory sensation is said to be felt. Conversely, the horizontally oriented afferent of the Merkel corpuscle is more susceptible to activation when the central electrode is an anode, and consequently under this mode of stimulation, pressure sensations are said to be felt.

The Pacinian corpuscles lie deeper within the skin, and a larger electrode current is required to activate them for this reason. Further work by Tachi and his colleagues has aimed at selectively stimulating these receptors through the use of arrays of electrodes.

2.3.4. The Tongue Display Unit system

The Tongue Display Unit (TDU) is an electrotactile sensory substitution device developed by Bach-y-Rita and his colleagues (Bach-y-Rita et al., 1998). The device (Fig. 5) consists of an input sensor coupled to a two-dimensional electrotactile array placed on the tongue. A significant advantage of tongue-based electrotactile display is that the tongue provides a surface that is consistently moist with saliva, ensuring good electrical contact. In addition, the sensory receptors lie closer to the surface of the tongue than they do in most of the body, including the fingers, so lower voltage and current can be used for stimulation – about 5–15 V and 0.4–2.0 mA (Bach-y-Rita et al., 1998). Compared with the glabrous or hairy skin, electrotactile stimulation of the tongue is safer (due to the lower power), poses fewer engineering problems and is more consistent (due to the favorable electrical conditions).

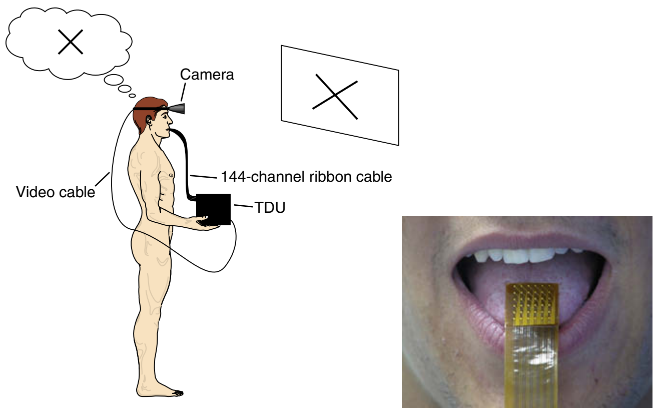

Fig. 5. The Tongue Display Unit (TDU) of Bach-y-Rita and his colleagues (Bach-y-Rita and Kercel, 2003), showing a configuration designed for visual to tactile substitution Right: TDU display of Vuillerme et al. (2007a).

Later versions of the TDU have been designed to be fitted to a custom denture which is worn in the mouth, including wireless transmission from a portable base unit. The device has been used for visual to tactile substitution (Fig. 5) and for vestibular to tactile substitution (Section 3 below), in which case it is coupled, respectively, to a video camera or to an inertial sensing device.

3. Electronic sensing for sensory substitution

Electronic sensors of some form are required to capture the information associated with the substituted modality that is to be displayed through touch. Table 2 provides an incomplete list of sensing methods for sensory substitution. Methods can be characterized according to the sense being substituted, the main sensor device types that are used, the type of environmental information the sensor captures, and the range of applications for which they are useful.

A number of other features of the sensing apparatus and its integration in the substitution device must also be addressed. These include:

- The range and field of view to be displayed, which has been found to affect recognition of familiar symbols in ways that are difficult to predict (Wall and Brewster, 2006).
- The sensor location, whether on the body or mounted elsewhere, which determines the perceptual coordinate inversion that must be solved if the information is to be used in some motor task.
- The mode of user control over the sensor, typically via motor behavior of some form.
- The spatial and temporal resolution, bandwidth, and other characteristics of the sensor.
- The relation of the sensing method to the context and task – for example, the environment of the home vs an assembly line production.

Such questions tend to depend on the type of sensing method used, and choices may be influenced by the application, display method and coupling possibilities.

3.1. Example: electrotactile displays for vestibular disorders and proprioception

The Tongue Display Unit (TDU) of Bach-y-Rita and his colleagues (Bach-y-Rita, 2004) has been used as a balance prosthesis in work by Vuillerme et al. (Vuillerme et al., 2007a)

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(Fig. 6). Their system consists of a pair of force sensing shoe soles that are used to determine the position of the center of pressure applied by the individual to the ground. This position provides an indication of the direction and amount of postural sway (but furnishes limited information about dynamic sway in the upper body). The sway is displayed through the TDU by means of a discrete signal indicating when the center of pressure exceeds a bound in the medial–lateral or anterior–posterior directions. As is the case in many biofeedback systems designed for rehabilitation, the information supplied by the feedback channel is reduced from a complex set of variables (in this case, postural) to a small number of discrete indicators. In separate work (Vuillerme et al., 2006), Vuillerme et al. applied the same TDU device to the display of joint angle position information in a task requiring the matching of ankle joint angle configuration by healthy subjects. The display consisted of a six-by-six electrotactile array applied to the tongue. The encoding consisted of discrete cues to indicate when the subject has positioned the angle in an overly plantarflexed position relative to the reference (opposite) ankle, or in an insufficiently plantarflexed position. The cues themselves consist of stimulating the tongue at 12 out of the 36 sites, either in the posterior or anterior end of the electrotactile array. Feedback was found to aid the ability of subjects to correctly match the ankle joint angle in this task. No comparison was made between the discrete electrotactile cues that are provided and any other form of feedback. The authors suggest that some specific mechanism may be at work, whereby the CNS combines the electrotactile information with proprioception to complete the task. It is difficult to evaluate such a claim, due, not least, to the rather simple nature of the stimulus as an error indicator. One could also argue that the correct behavioral response can be learned via classical conditioning, which may not depend on any special sensory integration mechanism.

4. Coupling sensing to actuation

In addition to display and sensing devices, a coupling method mapping the second to the first is required to complete the interaction loop of the substitution apparatus, as shown in Fig. 7. The coupling maps information $\mathbf{x}t$ transduced by the sensors into signals $\mathbf{y}t$ suitable for driving the actuators of the display. In interesting examples, it need not be a static (memoryless) function, nor a linear map.

Requirements for coupling vary considerably by application. Some considerations include the domain of the electronically transduced sensory signals, and that of the target actuator signals. Properties of intrinsic human sensory pathways and information processing capabilities associated to the display modality are significant. Finally, human sensory information processing capabilities nominally associated with the electronic sensing modality (for example, human vision, in the case of video-based sensing) may be important, if those sensory processing pathways are conjectured to be able to be recruited for processing the displayed information.

Sensor and actuator configurations can be characterized, in part, by their spatial and temporal domains. Examples include one- or two- dimensional spatial arrays (also dependent on time), as in video data; non-spatially arranged vectors, such as those from kinematic or force data. A single point transducer may vary in a more or less complex way over time. This variation may be profitably thought of in terms of its time-varying spectral contents, as for

Table 2
Selected sensing methods used in tactile sensory substitution

Modality	Sensor type	Information captured	Application/examples
Vision	Video cameras or light sensors	Visual appearance of environment	*TVSS* Epstein et al. (1986)
Audition	Microphones	Acoustics (ambient, interactions)	Hearing aid/*Tactaid* Reed and Delhorne (1995)
Distance sensing (sonar)	Ultrasonic; IR ranger; other distance sensor; arrays	Distance to nearest object structure of environment	*Mowat* electronic travel aid
Vibration, friction (touch)	Piezoelectric elements or other vibration transducers	Contact interactions, vibrations	Teleoperation display Massimino (1991)
Force (cutaneous)	Strain gauges, other force sensors	Force	Haptic teleoperation (Debus et al. (2001)
Proprioception	Position or rotation encoders; inertial sensors; motion capture	Sense position of & forces in the body; joint position, posture	Biofeedback – e.g. *TIKL* Lieberman and Breazeal (2007)
Vestibular	Inertial sensing; compass; motion capture	Sense balance related information	Vestibular aid *TDU* (Bach-y-Rita et al.)

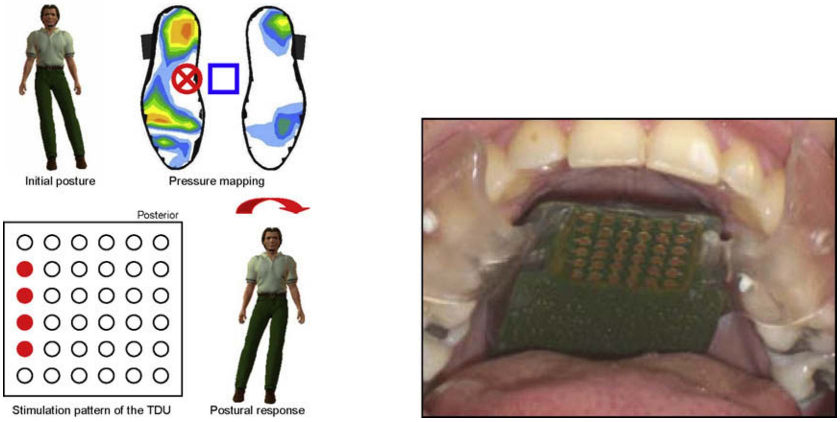

Fig. 6. The TDU-based balance prosthesis of Vuillerme et al. (Vuillerme et al., 2007a). *Left:* The pressure mapping and corresponding stimulation pattern for the TDU given the shown body posture (Vuillerme et al., 2007b). *Right:* The wireless version of the TDU, a 6 × 6 electrotactile matrix fitted to a custom denture with an embedded radio-frequency receiver in the mouth of the subject.

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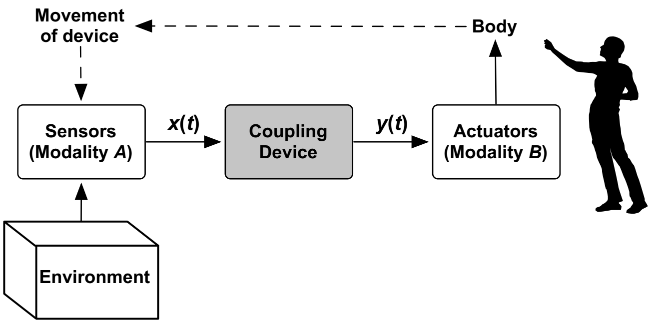

Fig. 7. The coupling component in a sensory substitution system, shaded in grey.

example with audio data captured from a microphone, or it might be better characterized according to its temporal structure (e.g. roughness or rhythmic pattern).

4.1. Information coding in sensory substitution

On the surface, information coding refers to way in which information that is acquired through the sensing apparatus is presented to the display. This presentation should be performed in such a way that the displayed information is useful for the human sensory apparatus that is involved. At the most basic level the relevant sensory and psychophysical properties surveyed in Section 2 must be respected. Equally importantly, the information should be displayed so as to be useful for processing in the central nervous system. Such tactile information processing capacities have been the subject of considerable attention in the literature on tactile display and perception (Gallace et al., 2007). Due to the cross-modal nature of sensory substitution devices, this raises many complex questions. For example, it is not a priori clear that human sensory processing resources for tactile information would have any success at extracting information from video data, given the relatively specialized neural pathways devoted to visual processing. As noted below, however, some have seen promise in results of several studies on cross-modal processing in the brain.

4.1.1. Tactile display encodings

Consideration as to the manner in which the input signal will be coded for presentation by the display device is needed. The simplest encodings employ a one to one mapping from the domain of the sensor to the actuator array, when the two are homeomorphic. If there is a mismatch in the number of elements in the displays, simple resampling methods may be used.

A mapping of temporal or frequency features to spatial features is sometimes employed – for example, in auditory to tactile substitution. The Tactaid VII device (Section 5.1.0.2) is such an example. In such cases, the level of activation of each actuator in a linear array can be chosen to correspond to the amplitude of the sensed signal in a given frequency band.

Position coding is frequently used to display a continuous, scalar value by means of a one-dimensional array; typical encodings include “1-hot”, where a single actuator element is excited along the array at a position corresponding to the value, or thermometer encoding, where all actuators up to the given position are turned on. Similar two-dimensional positional encodings have also found use. The vestibular substitution of Vuillerme et al. is a simple example (Vuillerme et al., 2007a).

Van Erp and his colleagues have made extensive use of vibrotactile displays worn on the torso as directional or position cues. The authors have conducted psychophysical studies of the localization of vibrotactile stimuli on the torso, the dependence of localization on stimulus parameters, and the indication of spatial directions using these stimuli (van Erp, 2005,). Applications from their work have included the display of orientation information via a wearable tactile vest (Fig. 8) for astronauts in zero gravity (van Erp and van Veen,2003, 2006), and the display of directional information for pedestrian wayfinding (van Erp et al., 2005) and in-vehicle navigation (van Erp, 2004). Others have similarly used position encoding within a vibrotactile array to indicate a directional vector, with or without magnitude display. Hein and Brell (Hein, 2007) presented a vibrotactile glove with several embedded tactors for the display of positioning information to a surgeon during computer assisted surgery.

A tactile illusion called *sensory saltation* has been used by Tan and others to display a position on the skin via vibrotactile feedback (Tan and Pentland, 1997). The illusion creates the sensation that the point of actuation is located within an area of finer spatial resolution than the physical actuator array layout.

Ecological encodings can be used to exploit innate human abilities to perceive dynamical properties of physical systems from their vibrational signatures, such as the sound or feel of a rolling ball (Yao and Hayward, 2006; Rath and Rocchesso, 2005).

4.2. Evaluating coupling methods

The choice that is involved in constructing a coupling from sensing to actuation is frequently overlooked in the literature. In some cases, it is possible to independently evaluate the coupling method, comparing candidate choices of coupling map. Perceptual evaluations can be designed to measure information transfer to the users through the channel, based on users' ability to identify the stimuli with which they are presented (Tan et al., 1999). Or evaluations be task-based, asking users to complete tracking (van Erp and Verschoor, 2004) or control (Kadkade et al., 2003) tasks. The degree to which users of such a device may be able to adapt to a particular choice of coupling map over time remains somewhat underexplored.

Kadkade and his colleagues (Kadkade et al., 2003) evaluated different methods of vibrotactile coding using an unstable, one-dimensional manual control task. Their display consisted of

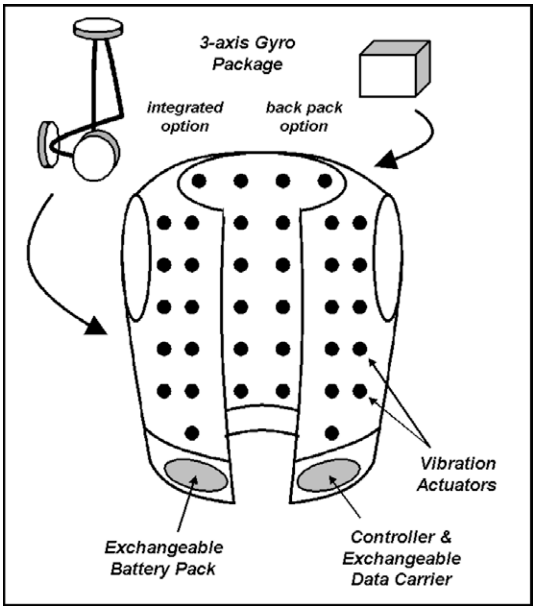

Fig. 8. A vibrotactile vest, presented in (van Erp and van Veen, 2003), used for the display of orientation information for astronauts in zero gravity (figure reproduced from van Erp and van Veen, 2003). Direction of a reference position is displayed by activating a single tactor of the vest (an example of “1-hot” encoding).

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Fig. 9. Pictorial collage of sensory aid devices. *Left to right:* The Braille alphabet, the long white cane, the VTPlayer mouse (a mouse with integrated tactile pin array), an electronic Braille reader, and the Optacon.

a linear array of tactile vibrators applied to the back. Several candidate codings were evaluated, including 1-hot position encoding, with a single active tactile vibrator, or tactor, providing position feedback. The authors also evaluated a spatially discrete display consisting of one tactor on the right and another on the left side, excited at intervals. In this configuration, the rate of excitation encoding the amount of error, and the side encoded direction. The position based encoding scheme was found to provide better performance on the manual control task.

5. Perspectives and conceptual models

Accounts of the creation, engineering and assessment of sensory substitution devices throughout the past century have been strongly influenced by the prior conceptions that have motivated groups researching the devices. Conceptual viewpoints have variously been guided by ideas about the creation of sensory prosthetics, the provision of unseen environmental information, studies of the adaptability of human perception and cross-modality, and long-standing questions about the phenomenology of perception. These notions are or broader significance for enaction and enactive interfaces, and have frequently arisen in discourses on these subjects. To do justice to all of the ideas involved would exceed the scope of this review. The theoretical issues related to perception, while fundamental to the design and understanding of tactile sensory substitution systems, are both wide in scope and, at times, controversial.[2] Nonetheless, this section collects some of the relevant ideas.

5.1. *Sensory assistance*

As noted in the introduction, sensory substitution has at times been equated to the provision of devices to aid people who experience sensory deficits such as blindness or deafness. The development of the TVSS and other systems like it were motivated in this way (Bach-y-Rita and Kercel, 2003). A wide range of sensory aid devices has been developed to date. Two important categories are communication aids and travel aids – devices, in other words, that help people with sensory deficits to understand communication, or that aid perception for locomotion and transit. Among the earliest communication aids are Braille, the system of text display for visually impaired people that was developed by Louis Braille in the 1840s; and sign language, a gesture-based substitution for spoken language for use by deaf people, with its roots in 18th century France. Braille and sign language were designed to convey symbolic information in ways that circumvent the impaired sensory channel, albeit at different levels of abstraction (Braille's symbols are characters, while those of sign language are linguistic elements – words or phrases). Braille reading is a task requiring a high level of tactile information processing, needed to translate the patterns of raised dots into characters (Foulke, 1982). It has also been the subject of a number of studies on the difference in tactile performance between sighted and blind people.

Standing in contrast with the symbolic nature of these communication aids is the long cane, a travel aid that is now commonly used by visually impaired pedestrians. The cane conveys information about the structure of the environment in a continuous way, through the haptic transmission of contact between the far end of the stick and ground, and through the sound that is produced through contact such as tapping. The long cane is a commonly cited example of the phenomenon of *distal perception* (Merleau-Ponty, 1945; Kreuger, 1970; Gibson, 1962), which refers to the fact that, that when employing it, users do not attend to the proximal haptic signal at the interface of their hand with the cane. Rather their tactile perception is focused upon the distal stimulus, at the locus of contact between the cane and the ground. Fig. 9 shows several examples of sensory aids (see Fig. 10)

5.1.0.1. *Example: the Optacon*

The Optacon is a tactile sensory substitution device developed by Bliss and his collaborators beginning in the early 1960s. The Optacon was designed as a reading aid, and later adapted to supply visual environmental information via touch, through the addition of a lens with a more distant focal plane (Bliss et al., 1970). It possesses a tactile display consisting of a 6 × 24 pin array designed for the finger pad. A version of the Optacon was available for sale from a company called TeleSensory until the device went out of production in the mid 1990s (Wall and Brewster, 2006). The decline in popularity of the Optacon coincided with a growth in interest by visually impaired readers in page scanners based on optical character recognition (OCR), and eventually in computer-based screen

Fig. 10. The optacon device is used both for reading printed text and for viewing an environment, both through its 6 × 24 pin tactile display. As noted in the original caption of this figure, reproduced from Bach-y-Rita et al. (Bach-y-Rita and Kercel, 2003), the child is able to mimic the hand posture of the teacher using feedback acquired via the device.

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[2] A wide range of opinions on the ideas noted in Section 5.6 are represented in the commentaries accompanying the seminal 2001 article on sensorimotor behavior in visual consciousness by O'Regan and Noë (O'Regan and Noë, 2001).

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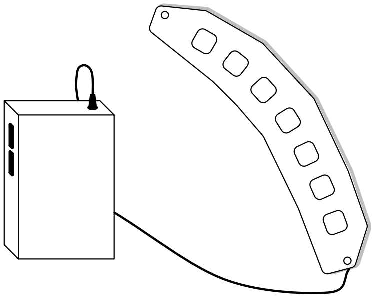

Fig. 11. The Tactaid auditory-tactile substitution device.

readers, both of which require much less training to use than the Optacon. In addition to aiding individuals with visual deficits, the Optacon has been used in fundamental studies on sensory substitution and tactile perception.

5.1.0.2. Example: the Tactaid

The Tactaid VII is an auditory-tactile substitution device that has been made commercially available to aid hearing impaired people.[3] The device is shown in Fig. 11. It is worn on the forearm or on another body part. Ambient acoustic signals are captured by the microphone, and their intensity is measured in seven frequency bands. The resulting amplitudes are mapped to the vibration amplitudes of seven actuators on the device, spaced in a linear array, using the frequency band coding described above. The device has been found to improve speech sentence understanding by about 10% after training (Reed and Delhorne, 1995).

5.1.1. Sensory substitution as rehabilitation

The term *rehabilitation* is commonly applied to describe a process whereby a patient afflicted with some physical or cognitive disorder is assisted in recovery. It is interesting that the label is also applied to sensory substitution, because the sensory deficit is not normally healed by means of the substitution, but is instead circumvented through the intervention of the device. The Oxford American Dictionary offers the following definition.

Rehabilitate (verb)

(i) Restore to health or normal life by training and therapy after [...] illness.
(ii) Restore (someone) to former privileges or reputation after a period of critical or official disfavor.
(iii) Return to its former condition (applied to environmental state).

In English the word originates in the late 16th century, and refers to the “Restoration to former privileges”, such as those conferred by a title. This usage in turn comes from the medieval latin verb *habilitare*, which means “To clothe or equip” and “To make able to”.

The description of tactile sensory substitution as “rehabilitation” seems, from the etymological standpoint, apt. First, because the substitution confers an ability or privilege (that of sight, for example), and is aimed at a restoration of ability after it has been lost. Second, because it evokes the idea of a surrogate sensory channel as re-clothing the individual with the sensory layer that it has lost, a notion that specifically resonates with the idea of touch.

5.2. TSS as the display of hidden features of an environment

Tactile sensory substitution has been viewed by various researchers as the attempt to replace sensory deficits through touch. This idea can be extended to include the display of sensory information associated with an environment (Kaczmarek et al., 1991; Lenay et al., 1997; Lenay et al., 2003), even if this information was not lost, but is merely hidden, i.e. unavailable to an individual acting in that environment. Such a characterization would include sensory replacement devices, as well as the provision of super-normal sensory capabilities. The environment about which the user receives this information could be the real space occupied by the user, or one in which the user acquires information about a different space, such as a virtual environment, a simulation, or the surroundings of a slave robot controlled via teleoperation in a remote environment. When it is not the user’s immediate environment that is being portrayed, the sensory substitution may constitute the entire experience of the space, which may be otherwise fully disconnected from the user’s sensory capabilities.

5.2.1. Vibrotactile (VT) feedback in teleoperation or VR

Vibrotactile (VT) feedback has been used in several ways in teleoperation and virtual reality. Information displayed by such a system may include:

- Surface textures and friction with surfaces in the remote environment or simulation (Minsky et al., 1990, Fujimoto et al., 2004).
- Contact events (Massimino, 1991).
- Shape related features (Cohn et al., 1833; Hasser, 1993; Kontarinis and Howe, 1995).
- Dynamic physical processes, such as rolling (Yao and Hayward, 2006) or breaking.
- Force magnitude and/or direction, specifically arising from contact forces (Massimino, 1991; Debus et al., 2001, 2002).

In addition to fulfilling the essential requirement of revealing a remote environment to an operator, VT sensory feedback offers several advantages in such settings. It can be implemented in ways that are cheap, compact, low power, and simple. It is well suited to displaying information for skilled manipulation and fine motor control. The ability to perceive elements of a remote environment can enhance presence, or the sense of being there. It can also improve users’ understanding of the forces involved in interaction, reducing overexertion in cases in which the preexisting force data is not clear (for example, during the use of a space suit). Vibrotactile feedback may be used as a substitute for force display, which can be beneficial because VT feedback does not destabilize interaction loops in the way that force feedback is capable of doing. VT feedback has also been used in combination with force feedback, where it seems to be most efficient for display of frequency components above the lowest resonant frequency of the force feedback interface (Kontarinis and Howe, 1995). The added vibrotactile information may be supplied through the motors of the haptic interface, or via dedicated vibrotactile actuators.

Evaluations of the effectiveness of augmenting teleoperation or VR tasks with VT feedback have been decidedly mixed (Browse and McDonald, 1992). In situations where other modalities provide clear information about the environment’s state relative to the task (for example, clear visual feedback in the case of an assembly task), VT feedback does not seem to improve performance (Massimino, 1991; Debus et al., 2001). Common performance measures include the time to complete a task, the amount of energy required to complete it, the peak force or excess force used in carrying it out. Subjective improvements can be assessed via qualitative tools, such as the Nasa Task Load Index (Hart and Staveland, 1988).

5.2.1.1. Example. VT augmentation of a haptic manipulandum (Debus et al., 2002) Debus and his colleagues studied VT enhancement of a PHANTOM haptic interface for the display of

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[3] It is currently sold through the following website: http://www.tactaid.com.

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forces at the peg-like end effector of a slave robot (Debus et al., 2002). The device they created is a VT enhanced manipulandum handle that displays force magnitude and direction during interaction with a virtual environment (Fig. 12). The handle contains four vibrotactile actuators arranged around the circumference of the handle, each of which is coupled to the skin via a pin array. The vibration amplitude of each actuator is designed to be proportional to the component of a force in the plane orthogonal to the principal axis of the peg at the end of the slave robot. As suggested above, performance improvements accompanying this augmentation were limited. In a peg-in-hole task, subjects tended to use 10% less force for task completion as compared with the case of visual only feedback. No improvement in mean task completion time was found.

5.3. Cross-modal plasticity

Many authors have discussed cross-modal plasticity in the brain as an explanatory mechanism for sensory substitution. Plasticity in neuroscience refers to the nervous system's ability to change structure and function in response to experience or change in operating conditions (Kolb and Whishaw, 1998). Changes, which may affect perception or other functions, can be continuous (due to modifications of the environment, developmental experience, or perturbations to the perceptual system (Clifford, 2002; Goldstone, 1998) or discontinuous (as in the case of brain lesions due to stroke, accidental blindness, etc). Subjected to discontinuous changes, the brain is capable of both restoration of function in damaged pathways and of reorganization, in which functions associated to one brain region are instead directed to another (Bach-y-Rita, 2001). Pascual-Leone et al. argue that plasticity is an intrinsic property of the nervous system, part of its normal ongoing state throughout the life span (Pascual-Leone et al., 2005). They suggest that it is not possible to understand normal psychological function or disease without invoking it.

Cross-modal perceptual reorganization has been hypothesized to be salient to sensory substitution, because it has been supposed that neural resources associated to the substituted modality can be recruited to process the same information as displayed through another sensory input. Such a reorganization, if possible, could allow users of a sensory substitution device to take advantage of existing neural circuitry associated to the substituted modality. For example, it has been suggested that areas of the brain normally used for processing visual information could be employed to process information displayed to the skin via a tactile vision substitution device (Bach-y-Rita and Kercel, 2003,).

Bavelier and Neville review recent knowledge on cross-modal plasticity, citing evidence from healthy animals and people, those with hereditary sensory deficits, and those that have experienced deficits due to lesions of some form (Bavelier and Nevile, 2002). Théoret, Merabet, and Pascual-Leone discuss evidence of neural-reorganization in adjustment to blindness. They cite findings of enlargement in the somatosensory cortical representation of body parts involved in increased tactile experience (such as Braille reading (Pascual-Leone and Torres, 1993; Hamilton and Pacual-Leone, 1998), and recruitment of visual areas of the brain for tactile and auditory processing in early blind individuals (Théoret et al., 2004; Pascual-Leone, 2001). Théoret et al. note that the correspondence between behavioral studies and evidence of neural reorganization within the brain have not generally been clear. For example, while there have been conflicting results on changes in performance within the remaining senses after blindness, evidence of neural reorganization has been less ambiguous (e.g., Amedi et al., 2007). However, the relevance of the latter to perception and behavior is more difficult to assess. The idea of plasticity, as introduced by William James in the 1890s, was advocated later by Ramón-y-Cajal as an explanatory mechanism for behavioral modifiability in terms of changes in brain anatomy. Yet as various authors have noted (Pascual-Leone et al., 2005; Clifford, 2002), the mapping between the two is far from being one to one. This ambiguity complicates the picture of neural plasticity as a mechanism in sensory substitution. Consequently, it remains difficult to draw firm conclusions about sensory substitution from the many recent brain imaging studies that have found evidence of cross-modality. Poirier et al. provide some further analysis and evidence in support of neural cross-modal plasticity as a mechanism specifically enabling sensory substitution (Poiriera et al., 2007).

5.3.1. Corrolaries to plasticity

The conceptual implications of plasticity in sensory substitution are intriguing. First, plasticity highlights the way in which perception may adapt to utilize different information sources, and by consequence, perhaps, different display modalities. Bach-y-Rita argues, "we see with the brain" (Bach-y-Rita, 2003), not with the sensory organ. In studies with the TVSS, researchers noted that if the display is moved to a different area of skin – say, from the skin on the back to that on the forehead – functional use of the device is recovered almost immediately relative to the time that was required to first learn to use it (Bach-y-Rita and Kercel, 2003). Similar rapid adaptation has been reported if the sensor is moved from one location to another – for example, if the video camera is moved from the head to the hand. Perceptual plasticity has been proposed as an exploration for this form of site-independence.

Many open issues exist surrounding the degree to which neural plasticity may be involved in the use of sensory substitution devices, or in substitution through intrinsic perceptual channels.

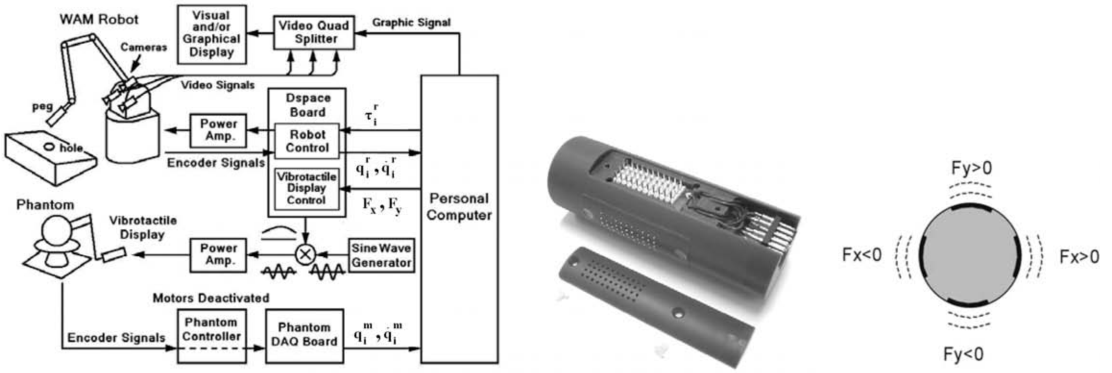

Fig. 12. The VT enhanced PHANTOM manipulandum of Debus and his colleagues (Debus et al., 2004). *Left:* A diagram of the master (PHANTOM) – slave (robot) system configuration. *Center:* The VT augmented manipulandum handle. *Right:* The actuated handle, as seen in 2D projection.

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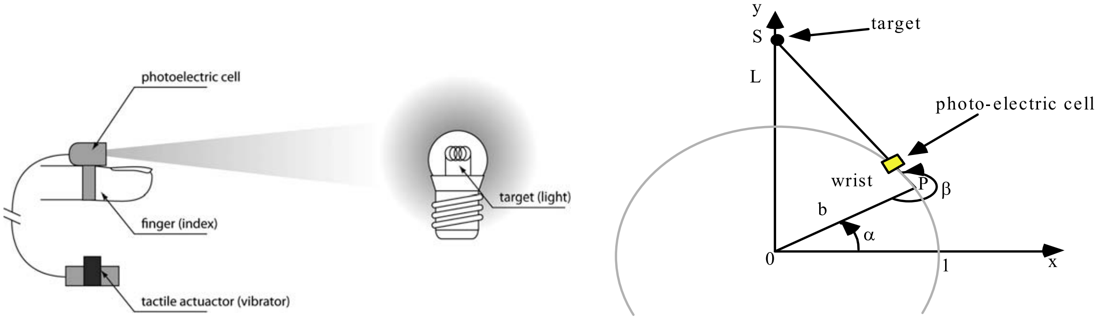

Fig. 13. The minimal sensory substitution experiment of Lenay and his colleagues (figures reproduced from (Lenay et al., 1997).

Among the earliest to pose the question explicitly was William Molyneux (whose spouse was blind). Posing what is now known as "Molyneux's Question", he wrote to John Locke in 1688, asking whether a person blind from birth who had learned to distinguish by touch between a sphere and cube would, upon suddenly gaining sight, be able to distinguish the two forms visually (recounted by Morgan (Morgan, 1977) and later discussed by Bach-y-Rita and Kercel (Bach-y-Rita and Kercel, 2003). Molyneaux's question evokes the idea of cross-modal transfer of knowledge, the question of equivalence between two senses, and the role of behavior in reflecting perception (Degenaar and Lokhorst, 2005). Morgan boldly asserts that "There is not the slightest reason to think that if two sensory messages give the animal exactly the same information, and lead to exactly the same behavior, they will be perceived differently – even if they come over completely different pathways" (Morgan, 1977).

5.4. Distal perception

Distal perception refers to the notion that stimuli received on the skin by means of the TSS device may become associated with a distant location in the environment, or even perceived as having an origin there. The location would correspond to the end of a stick (in the case of exploration of the environment with a cane) or a point attended to by a camera in a TVSS system. It can be deduced according to the laws that govern the change in stimulation received as the sensory device's orientation and position are changed. Several authors have emphasized the notion that sensations can be externalized (attributed to environmental sources outside the self) only when this afferent stimulation depends on ones actions (Loomis, 1992; White, 1970; Epstein et al., 1986).[4] In tactile perception, Gibson, among others, noted the difference between being touched, as a sensation arising from the stimulation of ones skin, as compared to actively touching, in which the sensation is associated to properties of the external object (Gibson, 1962; Kreuger, 1982).

The potential for distal attribution in tactile sensory substitution offers another perspective on studies that have found stimulation site invariance (cited in the preceding Section (Bach-y-Rita and Kercel, 2003). The idea is that the source of the stimulation comes to be attributed not to something on the skin, but to the location in space that is consistent with the stimulation that is received as the orientation and position of the sensor vary. Environmental attribution, if accurate, suggests that the experienced phenomenon may be largely invariant upon displacement of the display to a different area of the body because the stimulus refers to a determinate location in the surrounding space.

5.5. Sensorimotor behavior and externalization

Some authors have gone further, and emphasized the role of sensorimotor invariants as a fundamental feature of perception, to be studied through TSS devices (Lenay et al., 1997, 2001, 2003; Auvray et al., 2005) and simulations (Philipona et al., 2003, 2005). Lenay and his colleagues conducted a set of experiments to investigate the role of sensorimotor behavior in externalization (Lenay et al., 1997). They created a device worn on the finger consisting of a single photoreceptor with an angle of sensitivity of approximately 30° coupled to a single vibrotactile actuator with a simple on/off capability. The environment used in their experiments consisted of a single point light source in an otherwise dark space. In the absence of motor control over the device, its user cannot "see", because all that can be inferred is whether the light source stands in front of it or not. Granted control, over the orientation of the sensor (via the direction the finger points to) and its position, a user of the device can infer the direction to the light source, and by changing its position, can infer the position, through parallax. One way to explain this is that through interaction, the user infers the invariant relation:

$$L = b(\sin\alpha - \cos\alpha\tan(\alpha + \beta)) \tag{3}$$

Here, L is the distance to the light source, b is the length of the arm, α and β are the arm and wrist angles, respectively, as depicted in Fig. 13. The stimulus' origin can be readily distinguished using this formula.

Current commercially available electronic travel aids for visually impaired people function in a fashion that is somewhat analogous to the device of Lenay et al. Handheld sonar devices such as the Miniguide[5] or the Mowat[6] vibrate to indicate the distance to the nearest object in their line of sight. The Miniguide costs approximately US$380. Several related electronic travel aids are reviewed in a survey on tactile sensory aids by Levesque (Lévesque, 2005).

5.5.1. Cognitive information in externalization

While many studies on sensory substitution have found evidence that subjects were able to externalize the sensations they felt, in most of these experiments, including that of Lenay et al., subjects are made aware of the fact that the sensory objects they experience are the result of physical objects in their surroundings (the light source, in the case of (Lenay et al., 1997). Comparatively few studies have assessed externalization in the absence of such cognitive information (Auvray, 2004). Epstein et al. designed a vibrotactile sensory substitution system based on the stimulation of the index fingertips of blindfolded individuals, who were allowed to experience transformations of the stimulation that were

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[4] When afference is independent of ones actions, it has the same character as such internal experiences as hearing ones heartbeat, or feeling a tingling in the extremities.

[5] The Miniguide ultrasonic mobility aid. http://www.gdp-research.com.au/ultra.htm.

[6] The Mowat sensor. http://www.as.wvu.edu/scidis/terms/mowat.html.

correlated with self-movement (Epstein et al., 1986). These subjects were found to have developed an awareness of the sensorimotor contingencies between their actions and the tactile stimuli they received. However, subjects were reported largely to have failed to externalize these stimuli.

5.6. Sensory substitution as sensorimotor augmentation

As illustrated by the experiments of Lenay and his colleagues, purely sensory substitution, without motor affordances to close the perceptual interaction loop, may of limited use, since a user of the system may not have sufficient information to associate the sensation received to events in his or her surroundings. In tactile sensory substitution, this observation is supported by the poor performance exhibited by users of tactile displays in the recognition of static forms, despite learning (Sampaio et al., 2001). By contrast, studies with closed-loop systems like the TVSS have demonstrated that users are able to learn to improve their performance in object identification tasks as they acquire sensorimotor experience with the device (Bach-y-Rita and Kercel, 2003). However, the mechanism of this improvement (and of impairment where static forms are concerned) is not altogether clear.

Motor control over sensory input allows to infer where the information is coming from, and to construct the space of the environment and events in it. Authors researching this subject have claimed that this information is encoded in sensorimotor contingencies that link sensation and control over the device (Lenay et al., 1997; O'Regan and Noë, 2001). Moreover, it enables the individual to sense more accurately, in the sense of spatial resolution, than is possible with a static display. An extreme version of this "hyperacuity" (Lenay et al., 2003) is exhibited by the system of Lenay and his colleagues, but it also applies to cases in which the sensor has a significant resolution of its own.

The role of action in perception is a theme of current interest in perceptual psychology. It is related to active vision, exploratory touch, and (to some degree) attentional listening. Eye movements in vision provide a ready example. The sensitive foveal region of the retina constantly pans across the visual scene in order to gather knowledge about the regions of the environment that are most salient to whatever the user is doing. The work of Held and Hein illustrated the importance of sensorimotor coordination to the development of an organisms intrinsic senses. Their famous experiments with early visually deprived kittens revealed that from a pair of such kittens, one that was granted the same visual input as the second, but deprived of the ability to exert motor control over what it saw, failed to develop the visual capacity that the self-moving kitten developed (O'Regan and Noë, 2001).

O'Regan and Noë have most prominently argued the case for a sensorimotor basis of perception. They suggest that meaning in sensation arises primarily from sensorimotor contingencies, such as those cited above (O'Regan and Noë, 2001; Noë, 2005; Hurley and Nöe, 2003). Noë writes: "Perception is not something that happens to us, or in us. It is something that we do." The strong version of this sensorimotor hypothesis can be said to hold more specifically that "sameness of perceptual experience" requires an identical sensorimotor profile (Clark, 2006).

6. Evaluation, caveats, and open questions

The evaluation of sensory substitution devices is made more difficult, because the most interesting questions facing both scientists and device designers do not merely concern whether users of the devices are able to better perform tasks, but how a given level of performance is achieved in relation to device design parameters and the capacities of the user. Indications of performance are available through behavioral or neurological data. For example, Ptito and Kupers discuss differential activation of visual areas of the brain in blind human subjects trained to perform an orientation discrimination task via an electrotactile device applied to the tongue, where normally sighted subjects showed only activation in the somatosensory cortex representing the tongue (Ptito et al., 2005). Psychoacoustic studies have evaluated users' perceptual abilities via visual depth perception tasks (Siegle and Warren, 2007), object recognition, or using ophthalmological tests based on character discrimination (Sampaio et al., 2001). Functional evaluations have sought to demonstrate that tasks such as assembly using a teleoperated robot are performed more efficiently (Debus et al., 2001), or that lipreading is improved (in both cases, with limited results).

6.1. Substitution – no substitute

Several authors have argued that, such evaluations aside, "sensory substitution" may not be appropriate as a description of the *experiences* that such devices produce (Lenay et al., 2003). These experiences fail to match those provided by intrinsic perceptual channels in several respects. Visual to tactile substitution devices might allow their users to recognize the forms, locations, or contours of familiar objects, but, to date, such interfaces do not convey the color, level of resolution, or depth of gradations of contrast that are conveyed by vision through the eyes. The devices fail, therefore, to convey a large proportion of what one would normally associate with the visual experience, and they do not capture the beauty of the world. Their users are said to fail to respond emotionally to evocative images, such as those of loved ones, when they are perceived through the devices. From this standpoint, sensory substitution devices might be better viewed as supplements to an individual's perceptual apparatus, rather than as replacements. They allow their users to obtain more knowledge about the environment, which is not equivalent to that provided by intrinsic and intact perceptual channels.

6.2. From tactile sensory substitution to enactive interfaces

If sensory substitution devices are to one day enable experiences comparable to what intrinsic perception affords, significant advances will be required. Electronic sensing and display components must become higher in fidelity, and equally importantly, they must be closely matched to the intrinsic sensory apparatus that is linked to the display. In the case of tactile-visual sensory substitution, which seems to have been the subject of more studies than other kinds of tactile sensory substitution has, there seem to be serious questions as to the level of veridicality that can be achieved, given the limited spatial and temporal information transmission rates that are possible via the surface of the skin. For cases in which the peripheral sensory organ is damaged, sensory prosthetics, including cochlear and retinal implants, appear to more promise. Nonetheless, an understanding of the fundamental mechanisms involved would be of potential benefit to the engineering of sensory substitution devices and sensory prosthetics.

Indications are, moreover, that the range of applications of sensory substitution systems in areas other than sensory aids will continue to grow. This article has provided numerous examples. They already display the most important features of enactive interfaces, including the timely delivery of sensory information, the central role played by continuous action or movement, and the strong interplay of perception and action. In addition, they illustrate specific features associated to tangibility and tactile feedback, and to sensing of environmental information, that are relevant for emerging classes of human computer interfaces. Finally, they raise distinct questions related to the possibility of designing for cross-modal perception. A better understanding of the concepts and design considerations relevant for tactile sensory substitution systems, as summarized here, might therefore aid the creation and investigation of current enactive interfaces, and influence the design of future human computer interactions that have not yet been conceived.

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