**Sensory Substitution (SenSub)** is an approach that allows perceiving environmental information that is normally received via one sense (e.g., vision) via another sense (e.g., touch or audition). A typical SenSub system includes three major components: (a) a sensor that senses information typically received by the substituted modality (e.g., visual), (b) a coupling system that can process the sensor’s output and drive the actuator, and (c) an actuator that activates receptors of the substituting modality (e.g., skin mechanoreceptors or auditory hair cells) (Bach-y-Rita 2002; Bach-y-Rita and Kercel 2003; Lenay et al. 2003; Renier and De Volder 2005; Ziat et al. 2005). Vision, the predominant sense in sighted humans, is typically the substituted modality in SenSub. The substituting modalities are touch and hearing (Renier and De Volder 2005). This chapter focuses on visual-to-touch SenSub (VTSenSub).

**VTSenSub Feasibility**

The ability to use a novel sensory modality, such as that offered by a SenSub, builds on the plasticity and flexibility of the perceptual system (Bach-y-Rita 2004). Yet, as the range of plastic changes is limited, not every SenSub system is feasible. There is an advantage to SenSub that bridges between modalities that operate on similar low-level principles and share high-level classifications. Vision and touch share several major perceptual principles. Both modalities are based on two-dimensional (2D) arrays of receptors that actively scan the environment (Bach-y-Rita 1972; Geldard 1960), encoding its spatial aspects via spatial and temporal cues (Collins and Saunders 1970). In comparison, acoustic signals activate a one-dimensional...
array of cochlear receptors in a relatively passive ear, coding spectral and temporal cues. Furthermore, vision and touch exhibit similar strategies of active sensing (Ahissar and Arieli 2001; Bach-y-Rita 2002). These similarities between vision and touch enable exploitation of existing natural mechanisms in tactile substitutions for vision, an advantage that cannot be applied to hearing. This, together with other disadvantages of hearing as a substituting sense for vision (Hanneton et al. 2010; Kim and Zatorre 2008; Tang and Beebe 1998; Visell 2009), make VTSenSub a natural choice. Indeed, there is evidence for perception in visual terms (e.g., shadow or luminance) while using VTSenSub systems (Bach-y-Rita 1969, 1972, 1987, 1995; Bach-y-Rita et al. 1998; White et al. 1970). Interestingly, attempts to use combined tactile-hearing SenSub did not succeed, possibly due to a cognitive overload (Chekhchoukh et al. 2011; Jansson and Pedersen 2005).

In spite of these similarities between vision and touch, the nature of the qualia perceived via tactile substitution is not yet clear: is it visual-like (Hurley and Noë 2003; Noë 2004; O’Regan and Noë 2001), tactile-like (Block 2003; Prinz 2006) or representing a completely new modality (Lenay et al. 2003). The latter is consistent with the limited resolution of VTSenSub (Bach-y-Rita 2002; Lenay et al. 2003). Yet, VTSenSub experiences had been reported to be rich enough to evoke emotional excitements, for example when being able to watch a moving candle flame (Guarniero 1974) or finding a toy for a blind child (Bach-y-Rita 2002).

Fundamental Limitations of VTSenSub

Most existing VTSenSub devices convert visual space to tactile space and visual luminance to tactile vibrations (Bach-y-Rita et al. 1969; Krishna et al. 2010; Ziat et al. 2005). The idea of conveying information through vibrating array of pins on the skin is known from the 1920s and the first attempt to convey visual information via touch was done in the 60s by Starkiewicz and later by Bach-y-Rita who coined the term sensory substitution (Starkiewicz et al. 1971; Bach-y-Rita 1969). With such active conversion, conveyed to a passive sensory organ, the crucial factor
determining perceptual resolution is the resolution of the actuators array. This poses a significant limitation on VTSenSub as actuators arrays usually contain only tens of actuators, with the densest device containing 1000 actuators (Visell 2009). The amount of information that can be conveyed via such arrays is several orders of magnitude lower than what can be conveyed by an intact retina, which severely limits the functioning of VTSenSub as visual substitute.

Another fundamental limitation of VTSenSub is its competition with other essential functions of the blind person. In order to maximize perceptual resolution a VTSenSub system should be attached to a sensitive skin surface, such as that of the fingertips or the tongue. This of course comes with a cost of losing co-functioning of these organs in other essential functions (Bach-y-Rita 1972). Finally, energy consumption of VTSenSub systems is typically high (Auvray et al. 2007; Lenay et al. 2003).

Active SenSub (ASenSub)

Visual and tactile sensory organs are attached to muscles whose activation enables information acquisition. Although muscle-driven active sensing can be bypassed by flashing stimuli on passive sensory organs, active sensing typically outperforms passive sensing (Gamzu and Ahissar 2001; Heller 1980; Heller and Myers 1983; LaMotte and Whitehouse 1986; Lederman and Klatzky 1993; Loomis and Lederman 1986; Saida and Wake 1982; Saig et al. 2012; Yanagida et al. 2004). With active sensing, motor-sensory relations, and not sensory signals per se, are the relevant cues for the perception of external objects (Held and Hein 1973; O’Regan and Noë 2001; Ahissar and Vaadia 1990, Ahissar and Arieli 2001, Ahissar and Assa 2014; Gibson 1962; Katz 1989; Saig 2012; Bagdasarian et al. 2013).

Active haptic exploration via a SenSub system enables the development of a unique scanning strategy for each participant (Tang and Beebe 1998), which is instrumental for accurate perception (Jansson 1998; Rovira et al. 2010). Sensor movement can facilitate perception even when dissociated from the sensory organ. For example, with head-attached video camera and fingers-attached actuators, recognition and learning improve when participants are allowed to move their heads
This improvement is often associated with “externalization” of the sensed object, i.e., feeling it in a remote location rather than on the skin, a phenomenon crucially dependent on active control over sensor motion (Harman 1990; Lenay et al. 1999; Siegle and Warren 2010).

Bach-y-Rita and others demonstrated that in order to achieve externalization, the user must be trained, the sensor must be placed on one of the user’s motor systems and a motor-sensory control should be obtained (Bach-y-Rita 2002, 2005, Loomis et al. 1992; White et al. 1970; Epstein et al. 1986). Bach-y-Rita also suggested that the sensor movement can be replaced with a virtual movement, which can also result in externalization and assumed that there is no importance to the position of the sensor and actuator (Bach-y-Rita and Kercel 2003). Consistent with this, no significant difference was found between having the actuator on the same hand that moved the sensor or at the other hand, although some participants claimed for disruption at the split-hand condition (Pietrzak et al. 2009). This assumption, however, appears to be contrasted by experiments in humans and animals demonstrating the dependency of active sensing on natural sensory-motor loops (Visell 2009; Saig et al. 2010; Ahissar and Knutsen 2008). Indeed, SenSub devices in which the sensor and actuator are attached to the same organ, show improved performance (Chan et al. 2007; Zilbershtain-Kra et al. 2014).

Having the sensor and actuator on the same organ is not sufficient for driving active sensing. As naturally a perceptual system acquires its sensations by movements, the SenSub device must not induce any active actuation by itself—actuation should result only from sensor motion. Indeed, devices in which no tactile vibrations are used, and actuation depends solely on sensor motion, show improved performance (Chan et al. 2007; Zilbershtain-Kra et al. 2014). Such devices, in which the sensor and actuator are attached to the same organ and sensations are generated only via sensor motion, are termed Active (ASenSub) devices.

**Evaluating the Perceptual Power of VTSenSub Devices**

Evaluation of the relative perceptual power of SenSub systems can be done by comparing behavioral performance in different tasks (Visell 2009). Tasks that has been used for this purpose include: distance measurement (Bach-y-Rita et al. 1969), line orientation detection (Bach-y-Rita et al. 1969; Chekhchoukh et al. 2011; Ziat et al. 2005), shape identification (Bach-y-Rita et al. 1969; Chan et al. 2007; Shinohara et al. 1998; Tang and Beebe 1998; Ziat et al. 2005; Zilbershtain-Kra et al. 2014), object identification (Bach-y-Rita et al. 1969; Shinohara et al. 1998; Zilbershtain-Kra et al. 2014), face recognition (Bach-y-Rita et al. 1969), letter reading (Bliss et al. 1970; Chan et al. 2007; Linvill and Bliss 1966; Loomis 1974; Ziat et al. 2005), movement detection (Chekhchoukh et al. 2011), body movement recognition (Miletic 1988; Jansson 1983; Mandik 1999), hand—“eye” coordination (Guarniero 1974; Miletic 1988), navigation (Segond et al. 2005) and assembling tasks (Bach-y-Rita 1995).
Comparisons across tasks and research groups still lack a common acceptable metrics. Importantly, in most cases performance depends crucially on learning and learning time and effort should be taken into account when comparing different approaches.

**Exploration Strategy with VTSenSub**

Differences in performance levels between subjects in the same task can often be accounted for by differences in motion strategies (Gamzu and Ahissar 2001; Rovira et al. 2010). To date, information about these dependencies is sparse. Existing data are based on both subjective reports and objective measurements of sensor motion. Strategies reported so far include: contour following, orthogonal (horizontal and vertical) scanning, random scanning and feature oriented scanning (Chan et al. 2007; Guarniero 1974; Hsu et al. 2013; Rovira et al. 2010; Ziat et al. 2005; Zilbershtain-Kra et al. 2014).

**Challenges for VTSenSub**

Although the first study with VTSenSub system was done five decades ago, those systems are still not used by the blind community. It seems that the two major technical challenges of these systems remain the limited resolution of “foveal” sensation and the lack of “peripheral” sensation. Unlike in vision, with currently available VTSenSub devices subjects not only receive impoverished “foveal” information, but are also in the dark in respect to the rest of the visual field. While foveal acuity can be facilitated in ASenSub devices, using appropriate motor-sensory strategies, peripheral sensation appears to require specific design of the actuators array and of its coupling with the sensor.

Additional challenges include financial and ergonomics considerations. The system should better be comfortable and easy to use, enabling free movement, as well as esthetical, while keeping the costs affordable to the end customer (Lenay et al. 2003).

**Research Interests**

The basic practical aim of SenSub is to provide a tool that can help the visually impaired in everyday tasks such as navigation, object localization and identification, and communication. In addition, SenSub serves as a research tool for neuroscientists addressing perceptual mechanisms, learning and plasticity (Bach-y-Rita 1995; Hanneton et al. 2010; Lenay et al. 2003; Sampaio et al. 2001; Visell 2009).
Importantly, SenSub gives a unique possibility to study the emergence of perception via a novel modality, addressing the development of specific perceptual aspects such as distal awareness (externalization), environmental structure and object familiarity (Loomis et al. 2012; Siegle and Warren 2010).

References


