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Review

Sensory substitution as an artificially acquired synaesthesia

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ABSTRACT

In this review we explore the relationship between synaesthesia and sensory substitution and argue that sensory substitution does indeed show properties of synaesthesia. Both are associated with atypical perceptual experiences elicited by the processing of a qualitatively different stimulus to that which normally gives rise to that experience. In the most common forms of sensory substitution, perceptual processing of an auditory or tactile signal (which has been converted from a visual signal) is experienced as visual-like in addition to retaining auditory/tactile characteristics. We consider different lines of evidence that support, to varying degrees, the assumption that sensory substitution is associated with visual-like experiences. We then go on to analyse the key similarities and differences between sensory substitution and synaesthesia. Lastly, we propose two testable predictions: firstly that, in an expert user of a sensory substitution device, the substituting modality should not be lost. Secondly that stimulation within the substituting modality, but by means other than a sensory substitution device, should still produce sensation in the normally substituted modality.

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1. Introduction

In most examples of sensory substitution, visual information is presented to the auditory or tactile modality by systematically converting properties of vision (usually luminance, vertical and horizontal positions) into auditory properties (e.g. amplitude, frequency) or tactile properties (e.g. intensity) by means of a man-made device. It offers a way of restoring some loss of functioning to the blind and visually impaired. Strictly speaking, such devices are not multisensory because the sensory input conveyed to the user is unimodal hearing or unimodal touch. Nevertheless, there is convincing evidence that the use of these devices (at least in experts; typically users who have become proficient over tens of hours) does resemble vision in certain ways. In this review, we summarise and evaluate the various criteria that have been proposed to determine whether sensory substitution resembles the substituting modality (hearing or touch) or the substituted modality (vision). In particular, we consider the following five criteria:

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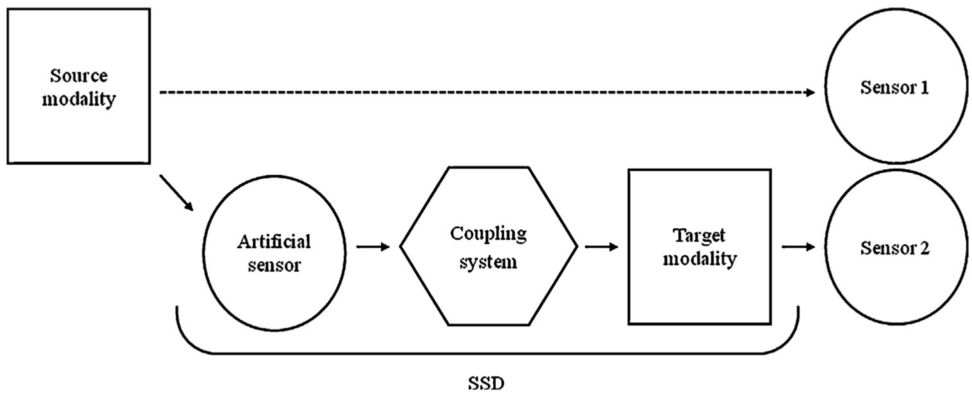

Fig. 1. The basic principles of sensory substitution. In a typical SSD the source modality would be visual information, Sensor 1 would be eyes, and sensor 2 would be the skin or ears. An 'artificial sensor' is typically a camera, the coupling system is the software and the target modality is the hardware relating to the substituting modality (e.g. headphones, vibro-tactile array).

- a behavioural criterion; i.e. the modality is determined by the actions facilitated by use of the device
- a sensory organ criterion; i.e. the modality is determined by the sensory organ that is stimulated and its connections to the brain
- a sensorimotor criterion; i.e. the modality is determined by the way that the sensory signal changes as a result of the users' interactions with the device
- a neurophysiological criterion; i.e. the modality is determined by activity in modality specific neural substrates
- a phenomenological criterion; i.e. the modality is determined by the content of the users' experiences

Whilst we concur with others that sensory substitution has visual-like properties (according to most of the criteria considered), we offer a novel formulation of this. In synaesthesia, a unimodal input (termed the inducer) elicits a percept-like experience (termed the concurrent) that is not normally evoked by that input (this can occur between features of the same sensory modality as well as between modalities). Thus, music may trigger vision (e.g. Goller et al., 2009), sounds may trigger touch (e.g. Beauchamp and Ro, 2008), and touch may trigger vision (Simner and Ludwig, 2012). Similarly, in sensory substitution we suggest that the substituting modality (hearing, touch) is akin to the inducer and the substituted modality (vision) is akin to the concurrent. Importantly though, in synaesthesia the concurrent does not *substitute* for the inducer; for example, music is heard as well as seen. We argue that the same applies to sensory substitution.

Our main position is that sensory substitution shares the characteristics of synaesthesia, but it needs not share the same causal pathways. Certainly the distal (or ultimate) causes of synaesthesia are very different in both cases – developmental synaesthesia is linked to early development and a genetic predisposition (Asher et al., 2009) whereas sensory substitution is linked to experience alone (expertise with the device). It is conceivable however, that they share some of the same proximal causes; for instance, in terms of functional and structural changes to the brain. Whilst others have previously noted a similarity between synaesthesia and sensory substitution (e.g. Cohen Kadosh and Walsh, 2006; Proulx and Stoerig, 2006), in this article we flesh out the similarities in more detail and in the context of the wider literature.

2. Basic principles of sensory substitution

Our working definition of sensory substitution is the artificial conveyance of rich, abstract sensory information of one sense via a different modality. The information is abstract in that it is non-symbolic – that is, the software does not seek to interpret the signal during substitution such as by using object recognition algorithms. The sensory signal is rich in that multiple dimensions within the substituting modality are used to carry visual information.

Sensory substitution is performed by "Sensory Substitution Devices" (SSDs), which are comprised of a sensor, a coupling system and a stimulator. In modern SSDs, the coupling system is typically realised in software. This is illustrated in Fig. 1.

Since the first SSD ("Tactile-Vision Sensory Substitution" or TVSS) was created in the late 1960s (Bach-y-Rita et al., 1969), visual impairment has been the central focus of sensory substitution research. In the original version the information was encoded by touch, but due to the technical difficulties associated with generating tactile stimuli the proliferation of SSDs for the visually impaired have largely targeted audition (Meijer, 1992; Arno et al., 1999; Hanneton et al., 2010). The exception to this trend is the Brainport/TDU (Tongue Display Unit). As a direct descendent of the TVSS, the TDU uses an array of electrodes to deliver electrical stimulation on the tongue (Bach-y-Rita et al., 1998).

All of the aforementioned systems take an image, convert it to greyscale and reduce the resolution. (A notable exception would be the "see ColOr" device, which encodes colour using sounds based on orchestral instruments; Bologna et al., 2009.) Tactile devices map the 2D array of pixels directly onto a 2D array of vibrating points, such that the brightness of each pixel controls the level of vibration (in TVSS) or electrical stimulation (in TDU). Of the auditory systems, it is "The Vibe" that most closely resembles its tactile cousins as it uses the localisation ability of the auditory system to encode the horizontal axis (Hanneton et al., 2010). Due to the relatively poor spatial resolving ability this provides, systems like "The vOICe" encode the horizontal axis in time, so that each image captured by the camera is scanned from left to right over the course of a one-second "soundscape" (Meijer, 1992). Both the vOICe and the Vibe encode the vertical axis using frequency (related to subjective pitch), and encode luminance as intensity (related to subjective loudness). The PSVA functions in a very similar manner to the vOICe, but emulates a human fovea by weighting the centre such that an area one-sixteenth of the total area is responsible for just over half the sounds produced (Arno et al., 1999).

There are certain devices that have a family resemblance to SSDs but would not meet our more restricted definition of sensory substitution. These include white canes and Braille. Both are intended to enable a degree of 'normal' functioning for the blind, and are considered by some as a form of SSD (Bach-y-Rita and Kercel, 2003). Braille systems and Optical Character Recognition (OCR) convert at the symbol-level (letters, words) rather than sensory level. (Embossed letters might be an example of a coupling system at the sensory level.) Language may be better