Learning to hear sounds through skin

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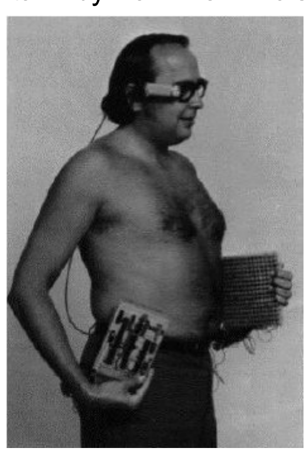
BACKGROUND

First sensory substitution system can be noted with the development of Braille with the intention to aid blind people acquiring visual information through touch. Kazimierz Noiszewski in 1897 invented the first technical sensory substitution device using light sensitive selenium cell called Elektroftalm transmitted visual information through vibrations stimulating the skin of the forehead. Sensory substitution was revolutionsed by Bach-y-Rita in 1960s where he developed Tactile Visual Sensory Substitution (TVSS). This device transmitted camera signals to vibro-tactile stimulators. The results showed that, visually impaired subjects identified lines and shapes. This study opened a large avenue in the area of sensory augmentation and largely, human brain plasticity.

Elektroftalm by Kazimierz Noiszewski

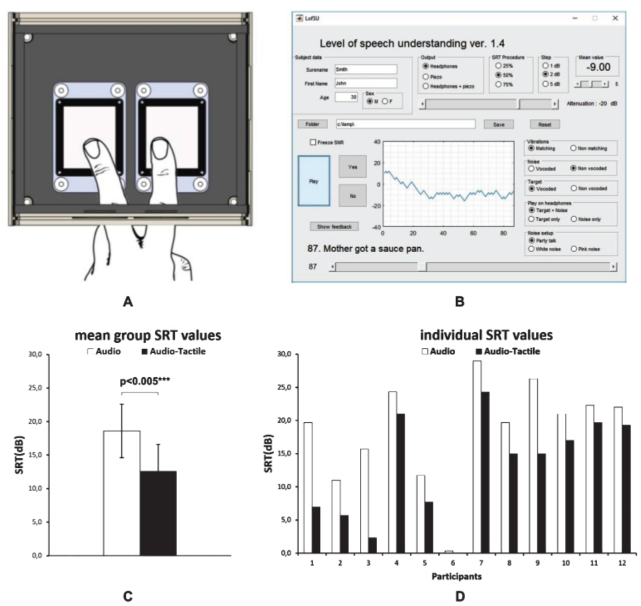


Early sensory substitution experiments by Paul Bach-y-Rita.

In the following years and decades, devices were not only developed for tactile vision but also for other kinds of substitution like ultrasonic vision (The Sonic Pathfinder, 1984 [16]), audible vision (The vOICe, 1992 [19]), tactile hearing (The Tactaid, 1995 [30]) or tactile balance (Vestibular aid TDU, 1998 [30]).

The vOICe equipment is demonstrated by one user.

In 2019 Cieśla et al. developed an auditory to tactile sensory substitution device which found immediate and robust improvement in speech recognition.



A) vibrating interface of the Vibrating Auditory Stimulator; B) Matlab GUI for stimuli presentation and control; C) Speech Reception Threshold values obtained for auditory and auditory-tactile speech in noise stimulation, at the group level and in individual subjects [subject 6 showed an improvement from 0.3 to –3.0 SRT(dB)].

In our lab we are developing a unique and affordable wearable device which will sense external sound signals and transform into haptic vibrations, altogether augmenting to the downstream cognitive circuitry via multisensory channels. We aim to use the principles of sensory augmentation and transformation, and facilitate learning, memory and cognitive development, by banking on the advantages of multisensory representation and its integration.

METHOD

Research has suggested that sound-to-tactile devices improve indexical properties of speech (Butts, 2015) and increase the efficiency of cochlear implants (Fletcher et. al., 2019). Studies have also shown an increase in speech to noise ratio (Ciesla et. al., 2021; Ciesla et. al., 2019) effect in cognition-that is, it has been shown that haptic stimulation improves sound detection, modulates perceived loudness, and influences syllable perception (Fletcher., 2021). Moreover, as a part of training, we will use reinforcement learning strategies to strengthen the association between the multisensory stimulus to desired action. The outcome measures include learning, memory and cognitive efficiency scores that are tracked through time.

Currently, two devices, that is Emoti-Chair which aims to use tactile stimulation for enhancing music experience and Aural Antennae system which provides the tactile perception of sound signals. In the case of Emoti-Chair, the user experiences sounds by sitting on a chair with an implemented Model Human Cochlea system. The Model Human Cochlea system uses several audio channels, each assigned to a specific frequency range. Vibrating devices, which in turn are assigned to these channels, are responsible for tactile stimulation.

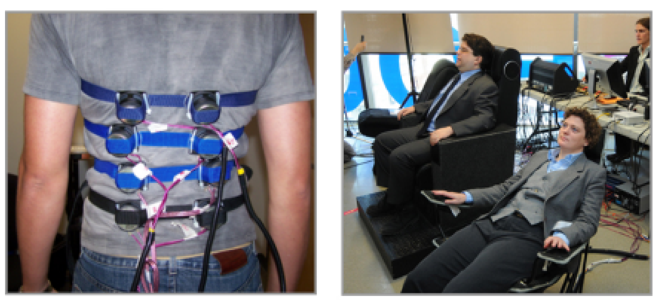


Fig. 8. *Left:* MHC prototype with four audio channels and eight speakers [14]. *Right:* Two prototypes of the Emoti-Chair, used to experience music (picture detail from [27]).

The Aural Antennae uses an electret microphone as sensory input modality. A vibrotactile display is used to transmit audio information to the user's skin. The application of Aural Antennae extends widely. The developers suggested the usage of the Aural Antennae system in road traffic: a driver who is not able to perceive an audible warning signal like honking (or a siren) because of hearing impairment or environmental noise, may be alerted by tactile stimulation on the part of the body which is nearest to the signal source.

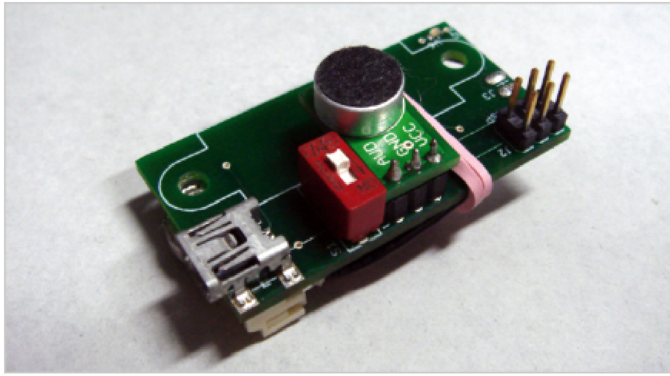
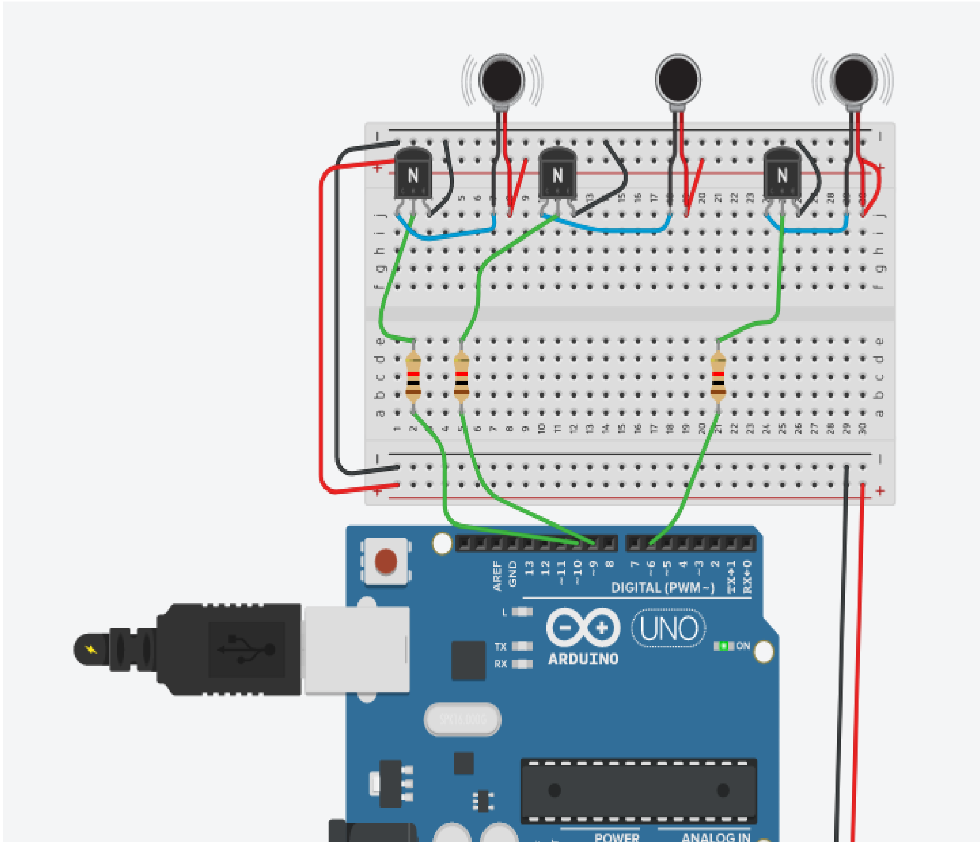


Fig. 12. Aural Antennae prototype [26].

In the Translational NeuroScience and Technology (TRANSIT) lab we introduce a fairly resourceful sensory substitution system that integrates three sensory modalities, sound, haptic, and vision to provide a more wholesome sensory experience of music to those who deficient of normal hearing of it. A haptic body device, attached to hands or arms or other parts of the body can provide vibrations specific to certain frequencies or amplitudes of the produced soundwave as captured and processed by a microphone or similar sound sensor. One can choose to use the hand gloves with several Linear Resonance Actuators fitted in various positions. These vibrators can be activated independently, concurrently, sequentially in various combinations to stand for specific patterns of amplitude and frequency variations of a typical soundwave. This will enable a direct one-to-one mapping of perception of an audio signal wave to haptic vibrations on the hand or any other part of the skin. This haptic feedback device can add in accentuating the sensations of pitch, rhythm by accurately transforming the properties of the sound signal to vibratory patterns transmitting tactile to the skin. Additionally, an audio device in the form of a speaker can transmit the audio sound of the song or music while in the process emitting the vibrations of the soundwaves that the subject can secondarily hear or “feel”. Thirdly, there can be a complementing visual modality as well, like a screen on which the lyrics of the music, and the associated rhythmic waveform, both changing with time, may be displayed for the subject to view the changes in the frequency, amplitude, rhythm, beats and thereon match the visual perception to tactile and sound sensations. The integration of the three sensory modalities can provide a more holistic sensory musical experience for those otherwise deprived of it. This sensory substitution intervention can potentially enable them to enjoy other experiential benefits from music, like of social bonding, anxiety relief, and therapy.



WORKING PRINCIPLE

The basic physiological principle which enables sensory substitution is the fact that the human brain keeps the ability to use a sense, although the related peripheral receptor might not perceive signals anymore. For example, in audition the sound reaches our ears just like it is for other sound, because it is propagated as a wave or vibration through the air (or another medium) to be sensed by our ears. Such waves are of a certain frequency (pitch), amplitude (loudness), duration (rhythm), spectrum (tonality) and the frequency of the wave determines if our ears are sensitive to the sound. The brain processes and interprets such an input stimulus through a harmony of differing areas of it, but mostly though the sensory cortex, the auditory cortex, the nucleus accumbens, the amygdala, the cerebellum among others. For people who are deaf or deficient of hearing, these parts adapt with brain plasticity to perceive the stimulus from other sensations like vibrations that the waves of the sound produce. This gives the opportunity for intervening with a sensory substitution medium that will be suitable even for those patients suffering sensory loss because of cortical damage. Since vision, audition, haptics all feed into the sensory processing part of the brain in an amodal representation of experience for further cognitive processing using a multisensory integration system, equivalent intermodal processing between audition and perception can foster somewhat isomorphic perceptual representations that would then facilitate an efficient multimodal sensory substitution. If that is done effectively, then the patients can not only be able to associate auditory sound inputs and its related pitches and rhythms to certain tactile haptic feedbacks corresponding to its frequencies and amplitude but also be able to generalise the association to perceive and enjoy newer music and rhythms as well.

Perception is sensory as well as motor dependent. This has been proven by earlier literature and in Bach-y-Rita's study (looming response), where TVSS only worked if the subjects were able to manipulate the camera themselves. Our brain runs on the principle of adaptive plasticity. This means that the brain can allocate a modality to a brain area which originally receives information from another one. In this way it is possible to receive sensual information using modalities that originally have not been used for that and thereby to compensate a sensory impairment. More so, due to this same principle the sensory display and the sensor may be relocated without appreciable consequences to the functionality of a sensory substitution device.

Externalization, also called distal attribution, is yet another principle used in sensory substitution devices. Distal attribution is the phenomenon of perceptual experience of objects in external space, without proximal stimulation on the receptor surface (Harman 1990). Initially the patients (auditorily deficient) will be able to learn the associations between the basic behaviour of the vibration patterns and visual stimulus as corresponding to specific sound impulses and what rhythms or pitches or amplitudes correspond to what frequencies. This would be implemented using a simple algorithm which would first use Fast Fourier Transform to decompose a sound wave from the sound sensor into dominant frequencies and corresponding amplitudes fpr every 16ms chunk of the audio signal. The hand-gloves of IIT Madras Touchlab and Merkel Haptic Technologies can be considered for inspiration medium. Then, every dominant frequency corresponds to particular pattern of activation of the Linear Resonance Actuators. For the visual medium, a simple screen with lyrics and waveform display of the song can be shown. However, if using VR, one can additionally even emulate a passing soundwave, with the background of the song-lyrics as well, and the subject can indicate any timestamp in the wave and be played back the exact rhythm in both the sound speakers as well as the vibrating gloves to provide a holistic learning and enjoyment experience. Following training with vibration applied to the observers' skin, the sensation changed from the vibration itself being the perceived stimulation site, to being felt as coming from the environment.

FUTURE DIRECTION

We believe that having a multisensory integrative system can be very helpful for a broad range of subjects, for instance, people suffering from auditory (Weisenberger et al., 1991 & Cieśla et al., 2019), speech development and learning issues (Baharanchi et al., 2017 & Rizza et al., 2018) attention deficits and hyperactivity symptoms (Smit et al., 2015). The future prospects also include its accessibility for various people coming from different lingual and socio-economic backgrounds.

The ultimate aim with sensory substitution systems is to allow the user to build an effective mental representation of the environment, and experience from tactile or auditory stimulation. With further research sensory substitution will not only be restricted to the clinical population but also the normal population. An example for a sensory augmentation system is the Tactile Situation Awareness System (McGrath, 2004) which has been developed to help pilots in spatial orientation by tactile feedback. A 2007 study developed a pneumatic haptic feedback actuator array that is suitable for mounting unto surgical robotic tools. This haptic feedback has surgical applications which increases the possibility of accurate diagnosing and ease in surgical procedures (C.-H. King et al., 2007).