Inside-outside: 3-D music through tissue conduction

by IAN MCKENZIE, PETER LENNOX, BRUCE WIGGINS

Citation


Abstract

Eliciting auditory perception by means of mechanical transduction bypassing the peripheral hearing apparatus has been recorded as early as the 16th century. Excluding its audiometric use to assess ear pathology, bone and soft tissue conduction has received very little interest until the last two decades. Previous work during this time (Stanley & Walker 2006, MacDonald & Letowski 2006) has indicated that robust lateralisation is feasible via mechanical transduction. This paper reports on an extension to this work, adding the front-back and up-down axes.
Inside-outside: 3-D music through tissue conduction

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Background

Eliciting auditory perception by means of mechanical transduction has been in use for hundreds of years. Several transmission pathways may be employed to deliver an audible experience; these pathways are often collectively referred to as bone conduction. As soft tissues and cerebrospinal fluid may feature significantly in these, however, we refer to them as tissue conduction (TC). Four pathways out of several have been identified in numerous studies as primary conduction pathways.

1) Inertial movement of the ossicular bones relative to the skull at low frequencies

2) Distortion of the temporal bone and cochlear shell at high frequencies

3) Osseo-tympanic transmission of sound radiated from the walls of an occluded ear canal

4) Sound conduction via fluid pathways connecting the cochlea to the brain cerebrospinal fluid

'The resultant sound level at the cochlea is a frequency-dependent vector sum of the contributions from each of these transmission mechanisms.' (Dietz, May, Knaus, & Greeley, 2005, p. 14-2).

Skepticism prevailed about the ability of tissue conduction to convey the same localisation cues as air conduction. Stanley and Walker (2006) discuss experiments which indicate that, using inter-signal variations at two tactile transducers in contact with the head, lateralisation performance equivalent to that in binaural lateralisation experiments is feasible. MacDonald, Henry and Letowski (2006), using similar apparatus but alternative locations, showed lateralisation performance that was almost identical to those utilising stereo headphones. Stenfelt & Zeitooni (2013) found a benefit in twenty normal hearing participants of bilaterally applied transducers,
indicating coherent use of binaural cues.

**Aims**

Having established the feasibility of coherent lateralisation control via tissue conduction, a greater range of auditory spatial experiences that might be available was explored. These could include: localisation of sources and features within a sphere surrounding the perceiver, front/back discrimination, externalisation, elevation, range perception and movement perception (including auditory looming, Seifritz et al., 2002). Other attributes might include environment shape, spaciousness, enclosed-ness, surface textures, and 'clutter'.

**Method**

A multiple transducer array was designed, constructed and used to present tissue-conducted audio signals via the head; initial experimentation would investigate the feasibility of using multiple transducers. Five approximately equidistant transducers were used in the array; the placement of these may afford a degree of control of left/right, front/back and height localisation.

Data from a study conducted by McBride, Letowski and Tran (2005), comparing the sensitivity of eleven locations on the skull, assisted in the choice of transducer placement. The five locations chosen here had been found to be reasonably equivalent in terms of attenuation for the frequencies in our investigation.
Dayton Audio BCT-1 tactile transducers were used (8 Ohms impedance, 1 Watt RMS and reported frequency response 300-19 kHz). Each transducer had its own discrete signal feed and contact with the head made through a 16mm hemi-spherical hard plastic medium.

**Subjective Testing**

Lateralisation performance having previously been established, a short series of tests were conducted to consider any degree of externalisation, elevation or phantom image control using a combination of signal attributes and transducer location. The tests were of a qualitative exploratory nature and are discussed in McKenzie, Lennox and Wiggins (2014).

**Informal Testing**

Informal testing into how musical stimuli and recordings of real environment sounds might be manipulated and presented yielded positive results. The signals were processed using Reaper digital audio workstation and a range
of plugins. The same signals were also presented Ambisonically using WigWare (Wiggins, 2014); additionally some 1st order B-format recordings were used. Ambisonics was included as a convenient method to manipulate the presented audio as it possesses many useful attributes. In 2014, the headset was on demonstration for three days at the National Exhibition Centre (NEC) during the Institute of Acoustics conference; thirty-five participants took place in the demo, providing feedback.

Results

Laterality was experienced when presented bilaterally and easily manipulated using amplitude panning, similar to that of headphones; the ears remain un-occluded providing 'openness' and a very different listening experience, often commented upon by test subjects.

When presented via multiple locations, amplitude manipulations alone produced limited image movement. Using amplitude and delay modifications, a greater level of image control, elevation and a degree of externalization was realised. Good separation with a widened image was achieved with modified stereo presentation, some degree of externalisation was experienced and, in some cases, height and range perception comments were made.

Ambisonic presentation, despite the transducer patch having been empirically derived, provided positive feedback. Acceptable image control was experienced in the main, although frontal presentation of externalized sound was poor. Elevation panning was possible with fairly smooth control and reasonable height achieved.

To most participants, sound presented via tissue conduction was a novel (and for some, initially confusing) experience. After a short adjustment period, most were able to make sense of spatial separation and appreciate a degree of phantom image control and externalization.

Conclusions

We note the anomaly that elevation, perceptible in normal hearing conditions due to pinnae filtering is achievable despite the absence of the outer ear contributions, possibly due to phase interference arising out of
multiple signal paths exhibiting fine timing differences. An intriguing possibility is that of multimodal cueing - conventional binaural auditory cues merging with additional information provided through the somatosensory system via haptic cues.

Somatic information can alter perceived auditory localisation - while investigating whether perceptual auditory localisation on the median plane could be altered by body vibration, Tajadura-Jiménez, Väljamäe, Kitagawa, and Ho (2007) suggested a multisensory integration of sensory information. Their findings indicate that vibro-tactile information concurrent with a sound source affects the perception of localisation on the median plane.

Meredith and Stein (1986) examined the convergence of inputs from different sensory modalities in the superior colliculus, concluding that multisensory integration may represent a basic mechanism by which the brain integrates complex environmental stimuli, profoundly influencing perception. 'The superior colliculus is a structure intimately involved in attending to, localizing, and orienting to sensory stimuli' (p. 641).

Several studies consider key elements of somatoperception - one such element is that of remapping information from the body surface into an egocentric reference frame (Longo, Azañón, & Haggard, 2010). With regard to body schema and spatial orientation, Lackner (1988) showed that, in a dark room, vibration of certain muscles can produce apparent displacement and motion. For example, if the subject were to hold the tip of their nose while a vibrational stimulus was applied to the biceps, they would perceive their nose to grow in length as the forearm extends away from the face. Although the lengthening of the nose is an illusion it shows that the anatomy and dimensions of the body are taken into account by the perceptual interpretation of the afferent signal.

It is known that sensory modalities interact, that they functionally reorganise, and that the characteristics of multimodal contributions may tend towards a perceptual viewpoint otherwise not achieved through a single modality. The 'settling in' period that was observed in participants when first wearing the headset may lend possible insight into the stimulation of alternative perceptual systems (Pantev, Wollbrink, Roberts, Engelien, & Lütkenhöner. 1999); compensatory plasticity and sensory supplementation are areas of further interest and to be included in later studies (Rauschecker, 1995; Good, Reed, & Russo, 2014; Bach-y-Rita & Kercel, 2003).
Although informal testing provided positive feedback, the presentation of music lacked low frequency content (< 150Hz). The novelty of avoiding the 'in head' experience when listening through earphones and perceptual differences gained via alternative information pathways may account for some initial interest. Improvement in transducer technology and dynamic range is required and will feature in further works; with regard to the low frequency content, alternative locations on the body may provide the answer based on the premise that good bass may be 'felt' in other regions such as the lower abdomen. Several participants at the NEC, however, were hearing-impaired and found the experience quite unique. One participant in particular, with unilateral conductive hearing loss, was able to appreciate stereo separation again, which was not possible using standard headphones.

In conclusion, multimodal presentation of music through tissue conduction seems feasible and may offer renewed enjoyment for those with hearing impairments. Improvements in transducer technology and low frequency consideration would enhance the quality. Alternative information pathways could lead to changes in music composition and reproduction, providing a different spatial perceptual experience.

Notes

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