TISSUE-CONDUCTED SPATIAL SOUND FIELDS

I McKenzie University of Derby, Markeaton Street, Derby, DE22 3AW, England
P Lennox University of Derby, Markeaton Street, Derby, DE22 3AW, England
B Wiggins University of Derby, Markeaton Street, Derby, DE22 3AW, England

ABSTRACT

We describe experiments using multiple cranial transducers to achieve auditory spatial perceptual impressions via bone (BC) and tissue conduction (TC), bypassing the peripheral hearing apparatus. This could be useful in cases of peripheral hearing damage or where ear-occlusion is undesirable. Previous work (e.g. Stanley and Walker 2006, MacDonald and Letowski 2006)[1,2] indicated robust lateralization is feasible via tissue conduction.

We have utilized discrete signals, stereo and first order ambisonics to investigate control of externalization, range, direction in azimuth and elevation, movement and spaciousness. Early results indicate robust and coherent effects. Current technological implementations are presented and potential development paths discussed.

1 INTRODUCTION

1.1 Early History

Mechanical transduction of sound used to produce auditory perception has been a known for many years. As far back as the 16th century Girolamo Capivaccio[3] employed this technique using an iron rod held against the teeth to assess ear pathology. The patient would grip one end of an iron rod with the front teeth; the other end of the rod would be placed against the strings of a zither. If the patient heard sound when the strings were plucked the hearing loss was attributed to a disease of the tympanic membrane; if no sound was heard then cochlear deafness was the prognosis.

Although little was known about how sound reached the ear via mechanical transduction the first bone conduction hearing apparatus, the Fonifero, was reportedly developed in 1876 by Giovanni Paledino and the Audiphone in 1879 by Richard Rhodes. Both devices used the teeth to aid hearing by converting speech into mechanical vibrations, the Fonifero could also be placed against the listener's forehead.[4]

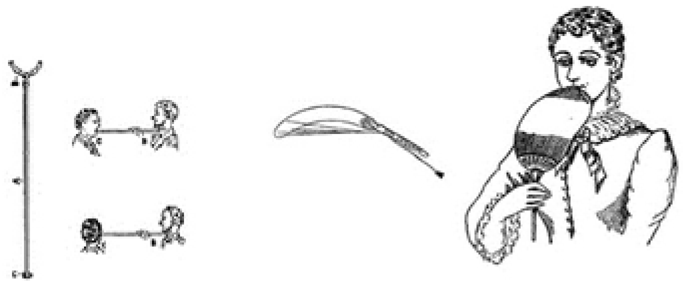


Figure 1.

Left – The Fonifero, shown held against the listener's teeth or forehead.

Right - The Audiphone shown held like a fan.

A more widely known example is that of Beethoven, who using a wooden rod, one end held between his teeth and the other resting on the piano was able to continue composing. Beethoven produced some of his finest work using this method, these famous pieces of music being composed after he had lost most if not all of his tympanic hearing.[4]

The three examples previously mentioned all employed the teeth as a means of receiving mechanical vibrations and passing them to the inner ear. Although little was known about bone conduction at the time, it is bone conduction that befitted the user of such devices by delivering and audible experience via alternative pathways thus improving their ability to hear; they would have been suffering a form of conductive hearing loss.

Despite early interest bone conduction, technology barely progressed past hearing aid devices and tuning forks used in clinical testing. In 1944 early opportunities for bone conduction communication devices were not taken and 50 years went by until the 1990's sparked new interest and growth in bone conduction technology. Emergency services, police forces and the military are now considering bone conduction communication as a viable option; it has the ability to provide communication while the ears remain uncovered allowing sounds in the environment to be heard.[2]

1.2 Current Thinking

The term bone conduction is still currently used today. However there are several transmission pathways that may be employed to deliver an audible experience, these pathways are often collectively referred to as bone conduction transmission pathways; soft tissues and cerebrospinal fluid feature significantly in these. This study has adopted the term 'Tissue Conduction' as preferred, encompassing the idea of these additional pathways.

Four pathways have been identified in numerous research studies as primary bone 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."[5]

Hearing via air conduction (AC) has been the subject of a considerable amount of research of a long period of time; many investigations and experiments have given a refined understanding of how the hearing system functions. Questions not only of how we hear sound but of how we perceive and localize sound sources have been asked and answered. Psychoacoustics has provided information about the brain/ear relationship utilizing subtle differences between the two ears; intensity, temporal differences, spectral attributes and phase relationships all act as cues allowing us to localize sound sources.

Although interest and research into tissue conduction has seen a healthy increase over the last three decades, scepticism prevailed until early 2000 about its ability to employ the same localization cues as air conduction. Stanley and Walker[1] in their opening statement briefly discuss scepticism on the topic; however they go on to discuss experiments that indicate that, using inter-signal variations at two tactile transducers in contact with the head, lateralization performance equivalent to that in binaural lateralization experiments is feasible. Similarly, MacDonald et al.[2] using similar apparatus but alternative locations showed lateralization performance that was almost identical to those utilizing stereo headphones.

There are several binaural tissue conduction devices are available today; the Aftershokz Sportz 2 BC Headphones[6] are marketed for cyclists and the iCharge 4GB Swim[7] Bone Headphones for swimmers. Both allow the user to listen to personal audio in stereo format, while leaving the ears open to the environment; in the case of the cyclist there are obvious safety benefits with this approach.

Figure 2. Aftershokz Sportz 2 BC Headphones

Figure 3. iCharge 4GB Swim Bone conduction headphones

Recent testing of similar device showed a low percentage of mechanical transduction actually taking place, far more airborne sound than expected was produced possibly making such devices more of a hybrid listening device rather than that of being bone conduction devices. Putting aside their performance it is encouraging to see emerging technology revisiting an old technique.

2 3D SOUND VIA TISSUE CONDUCTION

Having established that coherent control of lateralization in auditory perception is feasible via tissue conduction and new devices are exploiting this capability[8,9], is a more complete range of auditory spatial experience possible utilizing these pathways? If so it would include the localization of sources and features within a sphere surrounding the perceiver, front/back discrimination, externalization, featuring elevation, range perception and movement perception including auditory looming. It might also include ‘background’ attributes such as shape, spaciousness, enclosedness, of room, surface textures, and ‘clutter’.

However some signal qualities may be insufficiently robust to survive transmission via the multiple paths outlined above; consequently, it is not clear what useful spatial information can be presented in this way. The question that interests us, then, is whether and to what extent these other spatial attributes may be preserved and coherently controlled

In 1932 von Bekesy showed that the perception of hearing was the same whether the sound transmission was via air or bone conduction. He used a pure tone perceived by bone conduction and caused cancellation by means of air conduction thus arguing that the final process in hearing is the same.[10]

Stenfelt 2011 agrees with this and states:[11]

“Even if the BC sound transmission involve several pathways including sound pressure induced in the ear-canal, inertial forces acting on the middle-ear ossicles and cochlear fluids, alteration of the cochlear space, and pressure transmission through the 3rd window of the cochlea, the BC sound ultimately produces a wave motion on the basilar membrane similar to that of air conducted sound.”

Whilst coherent differences in time and amplitude of the signals arriving via tissue conduction at the basilar membrane can govern perceived source lateralisation sufficient for “stereo” presentation, the result is still “in the head”, lacking a sense of externalisation of sources or soundstage. As Hartmann and Wittenberg (1966) note, “sound externalisation is a delicate and complicated percept. Laboratory controls needed to study it can disturb it”[12]

By extension, perceived “range” (source-perceiver separation), a fundamental ingredient of spatial hearing, has not hitherto been within the purview of tissue conduction experiments. Similarly, the problems of front-back reversals (even if some degree of externalisation is achieved) especially where the head-target stimulus relationship is fixed, require something beyond the lateralisation paradigm.

Further, in the issue of source elevation, we know that monaural spectral (pinna) cues are of primary importance in normal air-borne spatial hearing. Normally, these would be utilised in conjunction with head-movements to achieve robust spatial judgements of target sources’ locations. There are other percepts that feature in spatial hearing that need to be taken into account; image size or “apparent source width”[13], image focus[14], sense of *spaciousness* in terms of image properties and environment properties[15], relative range of multiple sources and the perception of sources moving through the environment.[16]

Since the signal properties associated with some of the above percepts are exceedingly fine and, indeed, “delicate” as Hartmann and Wittenberg note above, it should be noted that most previous research in the area of tissue conduction has employed either monaural presentation via tissue conduction, visiting numerous locations on the skull or binaural presentation at the Condyle or Mastoid[17,18]. Plausible 3-dimensionality may be realised via air conducted binaural presentation whilst relying on coherent control of Head Related Transfer Functions (HRTF’s). Improvements in binaural performance via tissue conduction have been reported by using a generalized Bone Adjustment Function (BAF) [19], however, similar to AC and due to the individuality causing variability in the BAF’s it was suggested BAF’s may have to be measured for each person; individualised coherent control of HRTF’s may be achieved by one to one mapping of transducer to ear, especially in respect of pinna encoding.

An alternative approach might be to obviate the need for individualised BAFs, using multiple transducers to deliver a spatial sound signal set to the cranial tissues. Such a signal set need not be acoustically identical to the normal air conducted binaurally-received set. Rather, in the principle of *sensory substitution* [20, 21], it is necessary to maintain coherence between a signal set and that which it represents. In such a case, a significant learning period may be entailed and the degree to which the substitute set may be readily comprehended may very between individuals across time; finding the ‘best fit’ set for the majority of users would be a development goal.

3 QUALITATIVE STUDY

3.1 Style of Audio presentation and Apparatus

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 controlling azimuth and elevation localization. Five fairly equidistant transducers were used in the array; the placement of these may afford a degree of control of left/right, front/back and height localization.

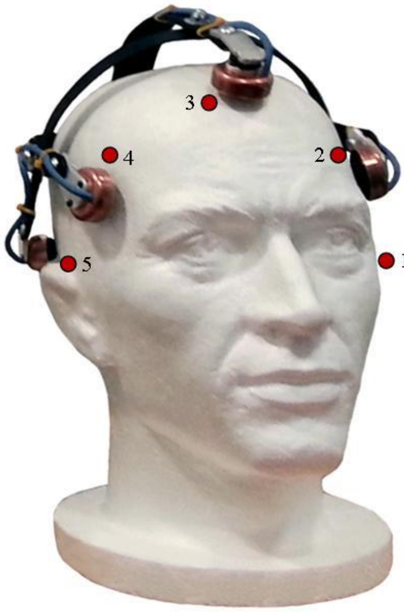


Figure 4. Headset Array Transducer locations

1 – Left Mastoid

2 – 1” above Left Temple

3 – Between Forehead and Vertex

4 – 1” above Right Temple

5 – Right Mastoid

The five tissue conduction transducers held in place by a flexible plastic framework were able to rotate in an arc created by the mounting bracket; this afforded a small amount of local adjustment for head size and shape. Contact with the head in the desired locations was made via a semi-circular hard plastic medium and each transducer had its own discrete signal feed. Dayton Audio BCT-1 tactile transducers were used to provide the mechanical transduction, each weighing 9 grams, having 8 Ohms impedance, an RMS power handling of 1 Watt and a reported frequency response of 300 – 19 kHz.

A certain level of force applied to the transducer is required to overcome the impedance of the skin, allowing for differences between individuals ANSI standards recommend a force between 4.9N and 5.9N to be used with tissue conduction transducers during clinical testing; exceeding 5.9N may cause physical discomfort [2]. The flexible framework of the array provided sufficient force for task, taking diameters, 18cm for Male and 17cm for female [22], the framework would exert between 2.49N and 3.4N. Effectiveness of the transducers to couple with the skin is also dependant on the surface area of the contact medium.

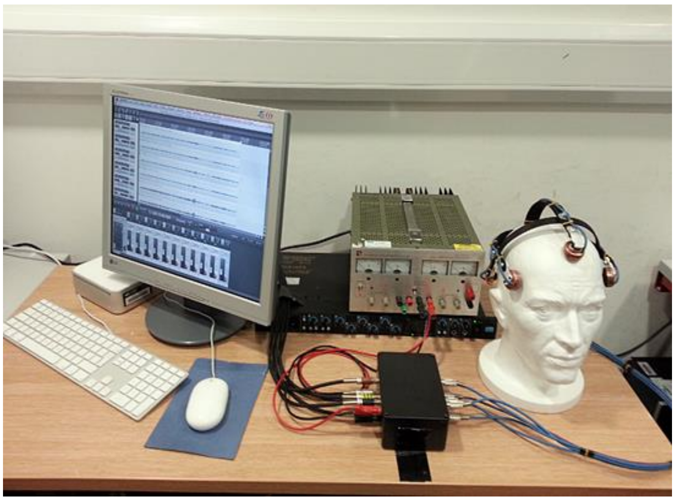
Von Bekesy in his 1932 experiments found 2.45N of force sufficient to transmit his test signals via a 5mm^2 contact area; however, a contact area of this size would cause discomfort after fairly short period and therefore unsuitable for the array. Improvements in signal transmission of up to 30dB have been reported when comparing contact areas between 16mm^2 to 53mm^2. In contrast, more reliable threshold data was observed with a contact area of 10mm^2 rather than one of 32mm^2.[23,24]

Head shape and airborne noise supported the final size and shape used as a contact medium. A slightly curved contact area of 25mm^2 was initially tried, whilst this provided comfort it produced significant sound. The type of framework mounting in conjunction with a contact area of this size and shape resulted in poor surface contact across some of the transducers; the range of head size and shape of the listeners caused a poor fit. Several materials differing in size and shape were tried; eventually a 16mm diameter, hard plastic semi-circular bead was selected as a contact medium. Facilitating a more uniform contact across varying head dimensions, the semi-circular shape gave an acceptable level of comfort and sufficient signal transmission; the airborne noise levels produced by the plastic bead were acceptable.

The decision to use only five locations was partly driven by data and the rest by budget and time constraints. Data was obtained from a study conducted by McBride et al. [18] comparing the sensitivity of the skull with regards to the detectability of signals delivered as a vibrational stimulus via tissue conduction; the transducers were placed at eleven different locations in turn. According to the data examined the condyle gave the best performance outperforming the other locations considerably; based on the Condyles dominant performance the decision not to use it as a suitable location was taken. The five locations chosen had performed reasonably well across the board producing far similar data providing the belief they would complement each other.

Figure 5. Equipment used for setup

- Mac mini3,1 running Mac OS X version 10.6.8, Firewire 800
- Reaper v4.32 DAW
- Focusrite Saffire Pro 40 multi-channel audio interface
- 5 x 1W LM386N-3 based amplifiers, set Gain of 50 with input attenuation
- Topward DC supply TPS-4000
- TDS3014B Digital Oscilloscope
- Piezo contact microphone
- Digital scales
- Clamp



3.2 Calibration

With each transducer mounted in its housing and 300g (2.49N) of force applied, the output intensity was measured; the same intensity white noise signal was presented to each transducer in turn and the signal recorded the oscilloscope. The output intensity of the transducer-amplifier combinations was found to vary slightly requiring calibration with respect to each other.

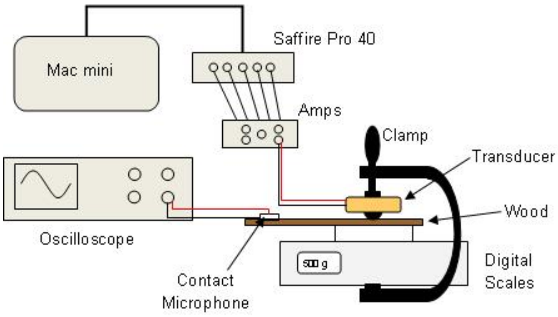


Figure 6. Calibration of individual transducers

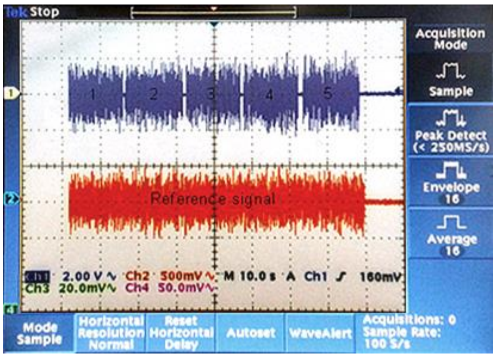


Figure 7. Recorded outputs of calibrated transducers with respect to each other

3.3 Subjective testing

Pilot testing was carried out prior to the subjective testing to establish a short series of tests that were of interest to the project. Lateralization performance having previously been established via tissue conduction pathways[1, 2], we were looking at the attributes of any combination of signals providing any degree of externalization, elevation or phantom image control. Subjective tests were carried out with the aim of finding where in relation to the head individuals perceived the test sound to be when stimulated at different locations, singularly or combined. Five subjects, male and female, having no known hearing deficits with ages ranging from 18 to 56 were used during the initial testing. After calibration the equipment was set up in the same way for each test. Following a brief explanation of the test procedure the participants were seated, the headset put in place and adjusted for location and comfort. A test signal, delivered to all transducers equally, was gradually increased to a comfortable level; the tests were carried out with low ambient noise, the ears were not occluded.

3.4 Test one

Pink noise was used as the test signal and presented individually at each transducer in a random order. Participants were asked to identify the area of the head where the sound was perceived to be. The aim of the test was to establish left/right separation and determine perceived any front/back or height differences between the signals when presented at different locations. All participants were able to discriminate left and right presentation, however no front to back was observed between the Temple and the Mastoid on the same side, the sound being perceived in or around the ear inside the head.

During the second part of test one the test signal was additionally presented at location three while presenting at the other locations and the perceived effects observed. With this combinational presentation all participants experienced a degree of height, some front/back along with left/right discrimination.

3.5 Test two

With a degree of externalization having been experienced during pilot testing, the aim of the second test was to evaluate the location combinations producing any perceived externalization in the participants.

A pink noise signal presented to each participant at the Mastoid was gradually increased in amplitude until the signal was just audible; maintaining the same level the signal was then swapped to the same side temple location. The test signal was then presented at both locations simultaneously and repeated for both left and right sides; comments were invited.

The lower level of signal presented enabled all participants to distinguish a difference in characteristics of the signal when presented at the same side Mastoid or Temple but the sound still remained in or around the ear inside the head. When the signal was presented at the Mastoid and Temple locations simultaneously all participants experienced some degree of externalization with the sound moving outside the ear.

3.6 Test three

The aim of the test was to observe the effect of signal delay on perception when sound was presented via tissue conduction at multiple locations. A delayed signal was presented at one Mastoid and an unmodified signal to the other; a solo singing voice was used as the test signal.

The test signal was presented at both Mastoids at an audible level and delayed by 0.65ms at each location, after a short period one of the delays was removed and the effects this had on the perceived sound observed via comments. The sound was initially heard in the centre of the head by all participants; when the delay was removed from one Mastoid it was noted the sound was perceived to move towards that side. The test was repeated in random order several times and the results were the same each time.

Repeating the test with the addition of location three was then tried, the same test signal was presented at all three locations with a 0.65ms second delay applied to each. After a short period the delay was removed from one of the locations and comments invited. All participants experienced signal movement and some phantom imagery; when delay was removed at location three increased height perception was experienced. Interestingly when the delay was removed from either Mastoid individually the test signal was perceived as externalised to some degree and presenting somewhere between the Mastoid with delay removed and location three.

3.7 Informal testing

Pilot testing had provided direction in the areas of interest and a small amount of subjective testing had shown that with very little signal manipulation a degree of height, externalisation and phantom imagery could be experienced. The aim of the informal testing was to evaluate how a further range of sounds may be presented and in what further ways could the signals be manipulated to give positive results; we were interested to know what effects this might reveal.

Test sounds were selected and using Reaper digital audio workstation software (http://reaper.fm) the signals were modified and manipulated with a range of plugins, the same unmodified recordings were also presented Ambisonically via the tissue conduction array; this is discussed in a later section.

Test signals:

- Various music pieces in modified stereo format
- Barbershop Quartet - individual modified stems; Bass, Baritone, Tenor and Lead
- 1st order Ambisonic recording of a Motorbike
- A mono recording of a Chainsaw in a forest.

Signal Manipulation:

- Amplitude
- Delay
- Filtering – Highpass, Lowpass, Bandpass
- Phase reversal
- Modified 1st Order Ambisonic decoding using WigWare VST Plugins
- Reverb – FX Plugins and constructed first and late reflections

As anticipated, there was an adaptation period for the participants; when presented with music through the array it took a little while for their hearing to adjust to the sound presented via tissue conduction. Many of the participants had not experienced audio presented via tissue conduction before and clearly seemed a little confused by the alternative pathways in use. After a short adjustment period they were able to make sense of spatial separation and appreciate a degree of externalization.

The period of time taken to 'settle in' varied between participants, this may lend insight into additional perceptual systems being stimulated. The somatosensory system processes information from several modalities of somatic sensation[25], these in turn may be divided into sub-modalities each of which can be divided into sub-sub-divisions. If we consider Touch, this divides into itch/tickle/crude touch and discriminative touch; the latter being of particular interest by dividing into touch, pressure, flutter and vibration. Compensatory plasticity and sensory substitution[21] are areas of further interest and to be included in later studies; for now an audio signal of the same level and attributes was presented to each listener and sufficient time allowed for each to appreciate left/right separation.

The music signals were then manipulated by adjusting the pre-set delay times, amplitude and filter bands; as changes were made comments were invited and the process continued until the best perceived sound for the participant had been achieved. The levels of any altered values were noted and these values were used to make adjustments to the Barbershop Quartet constructed in Reaper. An unmodified version of the Quartet was presented followed by the personalised version and comments were invited about the perceived changes; although the changes made were tailored to individual preferences, ultimately, similar settings were obtained across the group.

The unmodified Quartet stems were then presented via first order ambisonic decoding and comments invited, ambisonics is discussed further in the following section.

4 AMBISONICS

The range of signal manipulations were chosen as tissue conduction is different from headphone listening as there is not a 1-1 mapping of transducer to ear. In many ways, this makes tissue conduction listening and particularly transducers equidistant from the ears, more akin to loudspeaker listening with respect to phantom image construction and spatial rendition. Ambisonics is included as a convenient method to manipulate the presented audio as it possesses many useful attributes. As a speaker agnostic with-height system, ambisonically panned audio can be presented over a multiplicity of transducer arrangements through the use of custom decoders at any azimuth or elevation angle using freely available software tools such as WigWare [26, 27]. All reproduced directions are treated equally, in that preference in the performance of the system isn't given to transducer locations. Ambisonics has also been shown to produce coherent binaural auditory cues for a centrally seated listener and compare favourably to simple pair-wise panning using loudspeaker reproduction[29]. Three-dimensional recordings are also available allowing for realistic sound fields to be presented over the transducer array[28]. For this test, a standard 3D cube decoder was used; the decoded loudspeaker signals were patched to combinations of transducers (figure 8) and processed to elicit a comparable directional response to the speaker positions expected by the decoder.

A 1st Order ambisonic recording of a motorbike riding on country lanes was processed in Reaper, decoded and displayed to the participants via tissue conduction several times, comments invited each time.

A mono recording of a chainsaw in a forest was then used, as it presented a clear 'image' participants were able to move the image around their heads using Ambisonic panners; they were asked to evaluate the perceived location against the panner locations.

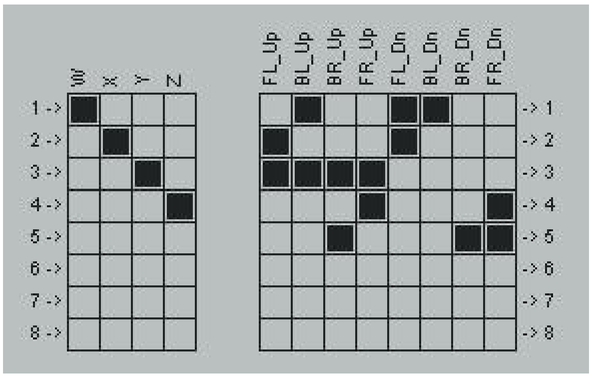


Figure 8. Reaper Transducer patch

5 DISCUSSION

Three areas of interest had been generated during pilot testing and then briefly explored providing sufficient feedback to warrant a further period of informal testing. Some degree of height, externalization and phantom image control were the areas we wanted to explore both the formal tests and the informal setting yielded positive feedback. Amplitude panning via tissue conduction is able to provide a similar lateralisation as to that experienced with headphones. When presented via multiple locations, amplitude by itself was able to produce limited image movement and a small degree of externalization. When amplitude and delay was used to modify signals presented via multiple locations a greater level of image control was realised.

Good separation with a widened image was achieved with the modified stereo presentation, some degree of externalization was experienced and in some cases height and range perception comments were made. The manipulation of the Quartet stems provided the participants with four spatially discernible voices and information about the type of space they may be performing in; the latter was achieved with reverb plugins and manufactured early and late reflections.

As previously mentioned, other perceptual systems being stimulated may be providing additional sensory information; front-back discrimination and elevation discrimination might well not be due to components of the signal set mimicking pinnae filtering, these might be achievable by vibro-tactile sensory substitution. This, of course, we have to undertake to investigate, also further focus on adaptive learning experiments may feature as an objective in their own right in later studies.[20,21]

Whilst trying to replicate acoustic head-shadow, the use of filtering was experimented with; normalising for power loss and adjusting delay times yielded inconclusive results at this time; further investigation regarding their use and some creatively designed formal testing may provide us with useful data. The application of low-pass and high-pass filters was used with the modified Quartet feeds to help with image control and externalization gaining positive results.

Surprisingly the ambisonic set-up often provided the most positive feedback; the main reason this was unexpected was that the cubic decoder was not designed for use with the array. The alterations made to the decoder were empirically derived yielding positive results. Acceptable image control was experienced in the main although frontal presentation of externalised sound was poor. Elevation panning was possible with fairly smooth control and reasonable height achieved. The recording of the motorbike elicited good range and externalization; many of the participants had previously listened to this recording presented via a 24 channel speaker rig and were surprised with the performance of the headset array.

The on-going project so far has revealed some interesting possibilities; the ability to evince an enhanced spatial image seems plausible. Having considered the feasibility of azimuth and elevation localization, a degree of externalised phantom image manipulation seems possible, further work is required to evaluate and develop these.

6 FURTHER WORK

Formal testing conducted so far has been of a qualitative nature; perception of sound fields and related imagery presented via multiple tissue conduction transducers was unknown. The tests were of a more exploratory nature producing areas of further interest rather than quantifiable data. The authors are currently investigating test methodologies in order to elicit more robust results for quantitative analysis.

The use of Ambisonic presentation provided positive results considering the decoder used was not designed for the task. Developing the use of ambisonics via tissue conduction presentation will see the design of a purpose built decoder; improved and targeted test methodology may help us to understand if the need for individualised BAFs is mitigated and why.

Further quantitative investigation examining perceptual attributes that may be realisable via a multi-transducer tissue conduction array could include:

- Externalisation
- Elevation
- Image properties (apparent source width ASW)
- Range perception
- Spaciousness
- Movement
- Multiple sources (ref Cocktail party effect)
- Precedence Effects in azimuth and elevation

Testing methodology, signal manipulation and presentation will be considered. The following points may have some relevance.

- Investigate perceptual training periods
- Investigate how the sounds are captured for presentation against perception
- Investigate the use of Anechoic recordings for manipulation as test signals
- Investigate higher order ambisonic encode/decode
- Develop reverb for:
- Simplified room modelling (spaciousness)
- Simplified range manipulations

It is our aim to produce further devices; these may use different locations on the head/body, employ more transducers with varying levels of force applied over different surface areas. Future transducers may be frequency dependant much the same way as speaker drivers and cross-over systems are, this would allow a different level of control over the vibro-tactile stimulus; further papers will follow with data and analysis for consideration.

Finally, topics for future discussion include:

- Cognitive mapping within this spatial tissue conduction paradigm
- Possible ways to introduce head tracking
- Neural plasticity
- Vibro-Tactile stimulation using other parts of the body for input as sensory substitution

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