Increasing Obstacle Detection for Travellers with Visual Impairment: The AUDEO device

Alan Deacon[1], T. Claire Davies[1] and Shane Pinder[2]

(1) Department of Mechanical Engineering, The University of Auckland, Auckland

(2) Manukau Engineering, Manukau Institute of Technology, Auckland

An original refereed contribution to New Zealand Acoustics

Abstract

There are approximately 285 million visually impaired and blind persons worldwide who require some form of assistance during travel. Primary mobility devices including white canes and guide dogs can be used for mobility and detection of obstacles that are below waist height, but do not provide feedback for obstacles that are above the waist. Studies have shown that over 50% of individuals with visual impairment have head collisions on an annual basis. The Audification of Ultrasound for the Detection of Environmental Obstacles (AUDEO) device is a secondary mobility device developed to enable individuals with visual impairment to detect obstacles that are above waist height. This paper provides an introduction to the AUDEO device and the concepts of sound localisation and echolocation. It discusses two iterations of the device in an attempt to increase usability and provides some feedback from a blind user.

INTRODUCTION

Mobility is a part of everyday life but for those with visual impairments this task becomes far more difficult. For the visually impaired there are two predominant mobility aids available to them; either a guide dog or a white cane. These mobility aids take the place of the standard visual information by giving haptic feedback to the user.

Mobility devices, such as the cane or guide dog, have aided the visually impaired successfully for many years. The blind have navigated with the assistance of sticks and canes for centuries [1] [Note: the symbolic white cane was introduced in the 1920's [2]]. The environmental information given by these aids is fairly limited. Canes only provide information from a small arc in front the user at ground level. There are other significant risks to the visually impaired from objects such as wall mounted shelves that cannot be detected from ground level and from quiet running moving objects such as bicycles [3].

In New Zealand 8% of the adult population have sensory disabilities, in the form of sight or hearing impairments [4]. The World Health Organisation estimate that there are 285 million people who are blind or partially sighted [5]. There is a requirement for a secondary mobility device for those with visual impairment to further enhance their environmental understanding.

Several secondary mobility devices have been developed to enable perception of the environment above waist height. For the most part, auditory "pictures" are presented to the determined, diligent user who has forty or fifty hours to dedicate to training. Mapping of distance or pixel height to pitch and location to sound intensity seemed logical to the sighted inventor [6-8]. A study of individuals with functional blindness trained in the use of secondary mobility devices [9] found that although 86% reported having a device in their home, only 46% had used it in the 30 days prior to the interview. Although no dominant reason for lack of use was given, 21% suggested that design modifications would improve their usefulness. These devices have often been designed to provide as much information as possible, but require considerable concentration rather than allowing response to stimuli. Providing information that allows the individual to perceive their environments naturally may increase the usefulness of such devices.

From a New Zealand perspective, the Trisensor, later termed the Sonic Guide and more recently the KASPA, was developed by Kay in 1962 as a "wide-angle binaural" ultrasonic aid [6]. Information from the backscatter of ultrasonic reflections is transmitted to the ears binaurally using sonification. Sonification is a method of displaying information to a user by mapping a signal to a specific frequency or pitch. Cognitively, sonifications are abstract and analytical and require significant training [10]. In the case of the Trisensor, interaural intensity differences represent direction and pitch indicates the distance to an obstacle.

This TriSensor is a continuous scanning device that means the user is always provided with signals regardless of look direction. The signal masks most other sounds. An individual using this device cannot readily communicate with those around, limiting the device solely to independent travel situations.

The AUDEO (Audification of Ultrasound for the Detection of Environmental Obstacles) project aims to increase independence of persons with visual impairment by providing them with audible information to allow them to respond instinctively to head high obstacles with no prior training. A device that transmits and receives ultrasound is used to detect reflections off environmental obstacles and those signals are provided to the user in the audible range. Rather than mapping the signal, audification allows for skill based response (with little cognitive effort). Audification represents direct translation of physical energy into audible sound. For example, seismic data

have been presented very effectively using audification as the frequency of ground vibrations can be increased to be within the auditory range [11].

In the case of the AUDEO, the audible feedback relies on Doppler. Since Doppler is more pronounced at ultrasound, the audible difference resulting from movement is displayed to the user. The device can then be used to broaden the detection and understanding of obstacles within a user's environment. This paper provides an introduction to the sound localisation and echolocation before discussing the theory behind the AUDEO device.

SOUND LOCALISATION

Sound localisation is an observer's ability to localise the origin of a sound stimulus. In natural environments, it is valuable as a survival aid to indicate the approach of a predator or conversely for enabling detection of the location of prey. Localisation is also important for audible navigation as it allows the observer to interpret the position of obstacles within their environment.

Sound Localisation can be broken down into three operations; localisation in the horizontal plane, the vertical plane, and the plane that defines forward and backward relative to the position of the ears.

Horizontal Localisation

Horizontal localisation is defined as an observer's ability to detect whether a sound source is located to the left or right of the head. This is accomplished by processing the interaural time and intensity differences [12]. For example when there is a sound source to the left of an observer, the left ear detects the sound, while at the right, the signals from the source will arrive later and will be softer. As the sound arrives at the left ear earlier than the right, an interaural time difference is realised. Additionally, the sound at the right ear is subjected to an acoustical shadow as the head obstructs the path of the sound. This causes the sound to arrive at a softer level as compared to the left ear, causing an interaural intensity difference. This is called the head shadowing effect. The head shadow effect occurs for frequencies that can be obstructed by the head, e.g. sounds with a short wavelength relative to the head size. The short wavelength, high frequency sounds are blocked by the head while larger wave low frequencies are able to bend around the head due to diffraction. The combination of interaural time and intensity differences form the basis for directional hearing in the horizontal plane [13]

Vertical Localisation

Vertical localisation is the ability to distinguish sound sources from above or below the observer's ears. Unlike horizontal localisation the sound signal is not obstructed by the head and will arrive at each ear at the same time and with the same amplitude. This means that the interaural time and intensity differences cannot be used to distinguish the direction of the source. Instead the ability to localise sound in this plane results from the shape of the outer ear (pinna) [14].

The pinna is the visible, outer portion of the ear that is common among mammals [15]. The pinna plays a key role in vertical sound localisation. When sound reaches the pinna it is reflected in such a way to alter the high frequency spectrum which is channelled into the ear canal, and therefore what signal reaches the eardrum. The range of the spectrum typically affected is above 4,000Hz. The reflections, and therefore spectral cues, are dependent on where the sound strikes the pinna; hence the spectrum relates to the elevation of the sound source [16]. Simply, the elevation from which sound originates will relate to the sound spectrum at the ear drum [17].

Front-back Localisation

Localisation in the forward-backwards direction is the ability to distinguish if a sound has originated from in front or behind the listener. Again the auditory system relies on spectral filtering from the head, torso, and especially the pinna to resolve front-back confusions [18].

To summarise, binaural hearing (the use of two ears) enables localisation through two key components; detection of the interaural time and intensity differences to allow for horizontal localisation, and pinna reflections that engage natural filtering and alteration to the high frequency spectrum to enable vertical and also front back localisation. These concepts were further demonstrated by Moss & Chui in 2006, when they investigated the effect of manipulating the outer ear (tragus) of the Eptesicus fuscus bat on its ability to localise its prey. As with humans, the outer ear and its shape plays an important role in localisation. With the tragus deflected there was significantly more localisation error than under normal conditions. The majority of the localisation error occurred in the vertical plane [19].

It was also observed that with the tragus deflected, the bat's flight adapted during the attack phase on the prey as a result of the change in hearing ability. The bats approached the prey by dropping more directly down than usual. This would suggest that the bat would travel in the vertical plane until the target was reached, then align itself horizontally with its prey to eliminate the need for vertical localisation.

Localisation of objects in the surroundings can be achieved by understanding environmental echoes.

ECHOLOCATION

Passive echolocation capitalises on the localisation principles when interpreting sounds from environmental sound sources. However, as not all obstacles produce sounds themselves, active echolocation relies on the sounds being produced by the observer. These occur in the form of a tongue click, a clap or even a cane tap. Reflections of these sounds are used to detect the presence and location of any objects within the environment. The sound waves propagate until they come into contact with a solid object and bounce back in the form of echoes. The difference in time between the creation of the sound and the echo being received indicates the distance between the transmitter and object. This is because sound travels at a constant speed though a medium, e.g. air or water.

The time (t) for a sound to be reflected back to an observer is equal to the speed of sound in air (c = 340.29ms^{-1} @ sea level) divided by two times the distance between the source and the target (d). The multiplier of "two" represents the round trip that the sound must travel between the source and the object. Based on this formula, the distance from the object can be defined as:

$$d = c * t/2$$


Sylomer®
made in Germany
sold by Pyrotek noise control
renown globally
Getzner's Sylomer® and Sylodyn® are the leading materials on the international market for vibration technology.
They are elastic polyurethane materials (PUR elastomers), which deform when subjected to tension or compression loads, but always return to their original shape. In doing so, this materials isolate and reduce vibrations which can have negative effects on humans, the environment and materials.
Sylomer® and Sylodyn® have a wide stiffness range, allowing them to be used in a large range of applications in civil engineering and machinery. In most of them, they are used as elastic inter layers like a spring. The characteristics of this spring can be adapted to the need of application.
Pyrotek's sales engineers can support you with technical and design advice.
www.pyroteknc.com
exclusive agents
0800 226 878 427
(0800 ACOUSTICS)

Cadna A®

DataKustik

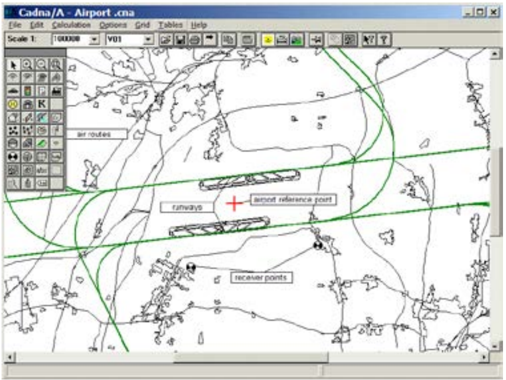
Option FLG -Aircraft Noise

New INM 7.0 Method Implemented!

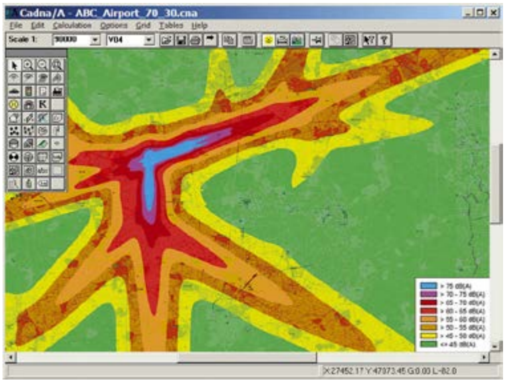
The YouTube introduction video shows some of the capabilities of CadnaA regarding handling and calculation of Aircraft Noise by using the INM Method.

http://www.youtube.com/watch?feature=player_embedded&v=s3gmH33eXHE

With Option FLG noise emitted from civil and military airports is calculated based on the calculation methods INM 7.0 (Integrated Noise Model), ICAN (AzB 2008), AzB (old), ECAC Doc. 29 (2nd / 3rd Edition) or DIN 45684-1. With these calculation methods Option FLG covers all procedures for aircraft noise assessment relevant at European and international levels. Option FLG can be applied, without any restrictions, to calculate the noise protection areas around civil or military airports as legally required.



The geometric objects for description of an airport



Noise contours around a heavily used airport

The calculation of aircraft noise with Option FLG is equivalent to the calculation for other types of noise like industry, roads, and railways. This means that in examining the total noise e.g. for the calculation of noise maps the aircraft noise emissions can be seamlessly integrated in the overall assessment.

Features

- Calculation of aircraft noise at predefined receiver points and on a grid
- All relevant international methods implemented (INM 7.0, AzB 2008, ECAC Doc. 29 (2nd/3rd Edition), DIN 45684-1)
- Calculation of noise contours for the noise indicators L_{den} and L_{night}
- Library with predefined aircraft groups (aircraft and helicopters)
- Import of flight traffic data via ODBC-connection
- Completely implemented into the CadnaA user interface
- Can be combined with all other noise types (industry, road, railway)

Echolocation in Nature

Echolocation is a localisation and mobility technique that is common in nature. Animals such as bats, whales, dolphins and even some birds use echolocation as their primary means of navigation [20]. Echolocation is usually used in environments where light is limited e.g. underwater, or in caves. The visual information in these environments is unreliable and animals have adapted to use a more reliable means to understand their environments in the form of sound.

Human Echolocation

Echolocation is also used by a small number of people with visual impairment as their primary means of mobility. Two of the most widely known users of echolocation are Ben Underwood and Daniel Kish. Ben Underwood lost his vision to retinal cancer at the age of two, discovering echolocation at the age of five he was eventually capable of complex tasks such as rollerblading, playing basketball and running relying solely on echolocation [21].

Daniel Kish, who is himself blind, teaches others how to use echolocation [22]. Nicknamed ‘FlashSonar’, Kish uses tongue clicks and hand claps to get instances of his environment from the echoes (hence “flash”).

Each click gives an instance of the environment around the person, but as environments tend to change constantly, the clicks have to be produced at a rate that will keep the person informed. When sense and logic was applied to simple information gained by echolocation (e.g. distance, height, width and density), Kish found he could form a detailed understanding of his surroundings. He writes:

> *For example an object that is tall and narrow may be recognized quickly as a pole. An object that is tall and narrow near the bottom while broad near the top would be a tree. Something that is tall and very broad registers as a wall or building [23].*

As a child, his self-taught version of echolocation allowed him to roam independently without the need from a cane or guide dog as a primary aid.

CURRENTLY AVAILABLE SONAR DEVICES

Sonar systems for the visually impaired [6, 8], virtual environments [24] and robots [25] have largely been designed to simulate the echolocation responses of bats. Is this the most reasonable approach to take for designing sonar systems for humans? Bats have large pinnae or outer ears that they can move independently to determine direction [26]. They can send out clicks that are frequency dependent and orient their ears upon approach to most effectively gather the information from the signal.

Humans don’t have the ability to change the direction of their pinnae, nor is interpretation of frequency sweeps intuitive. Systems that attempt to simulate bat echolocation require methods to compensate for this lack of pinnae movement. Dolphins also perform echolocation but they do not have pinnae that change direction. Perhaps a more intuitive display is required, similar to that of the dolphins, rather than one that requires processing of the signal.

THE AUDEO DEVICE

The AUDEO device transmits an ultrasound signal and provides audible sounds to the user based on the size and distance of any obstacles. In this sense, it is similar to a dolphin that transmits and receives ultrasound signals. However, unlike the use of ultrasound in nature, the AUDEO transmits a continuous signal from a point source ultrasound transmitter, then receives signals from environmental reflectors.

Continuous Transmit Frequency Echolocation

The AUDEO is described as an echolocation device as it uses sound reflections for guidance and navigation. It differs from standard echolocation methods, like those exhibited by bats, dolphins or modern sonar systems, in that it employs a continuous rather than discrete method of sound transmission.

As mentioned earlier, the discrete echolocation technique works by transmitting a brief ‘chirp’ or ‘click’ of noise then pausing, while the sound wave propagates until it is reflected off an object and the echo returns to the source. The difference in time from the transmitted ‘chirp’ and the reflected echo determines the distance to an object.

The AUDEO, however, transmits a continuous 40 kHz ultrasound signal. After reflecting off environmental obstacles, two receivers collect the echoed sound. The amplitude (intensity) is a result of the sound absorbance index of the reflecting surface and the distance from it.

The Doppler shift caused by the relative movement of the sound source and reflecting surface produces a relative sound frequency change as described below that can be heard within the auditory range.

Doppler Effect

The Doppler Effect describes the relationship between the wavelength of a sound, and the relative motion of the observer and source [27]. When a sound source is moving towards an observer the sound wave is compressed in the direction of movement, while the wave expands in the reverse direction (Figure 1). Therefore the wavelength is altered. As the wavelength and sound frequency are inversely proportional it can be seen that:

$$f = ((c+v_o)/(c+v_s))\, f_o$$

This equation shows that the observed frequency (f) is proportional to the relative speed of the source (v_s) and observer (v_o), the speed of the sound though the medium (c) and the frequency at the source (f_o).

Doppler Shift

The AUDEO uses 40 kHz transmission signals that are intentionally beyond the natural human hearing range. This means that the device can be used discretely without drawing unwanted or unnecessary attention to the user. This frequency is also above the range that a guide dog can hear. It is coincidentally the case that when echolocating using noise in an audible range the Doppler Effect is less pronounced. As the Doppler formula shows

$$f_{delta} = f_o(1 - (c + v_o)/(c + v_s))$$

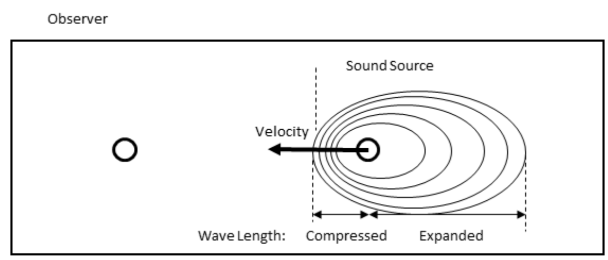


Figure 1 An observer perceives a shift in frequency as a result of movement toward a sound source.

The change in frequency (f_{delta}) is proportional to the transmitted frequency (f_o). Therefore a higher transmission frequency creates a larger, more detectable shift in pitch (frequency), given the same relative velocity between the observer and obstacle (v_o/v_s).

Down Sampling

The AUDEO device uses intentional aliasing to transform the received high frequency, Doppler shifted reflections to an audible range via the process of direct down-conversion or "down sampling" [28]. Using a 40 kHz sampling rate, equal to the transmitted signal, the sound is intentionally aliased.

The final output is the difference between the transmitted signal and the received signal which, at normal walking speeds, results in a signal within the audible range. If movement does not occur, no sound is received by the observer in the audible range, but when moving, the frequency of sound is based on the speed of movement toward or away from the obstacle. This signal is amplified and provided to the user via speakers.

Orientation of Receivers

Unlike typical sonar systems, the receivers on the AUDEO device are outward facing. Although this reduces the signal to noise ratio, it has been found that participants perform as accurately, if not more accurately with the outward orientation [29, 30].

AUDEO TESTING

When avoiding obstacles, the ability to localise the sound source is important as the direction of the hazard determines the reaction strategy. The AUDEO device's ability to localise an ultrasonic point source sound was compared to a person's natural ability to localise audible point source sounds [29]

The tests showed that the participants could detect the general direction of the sound source; however, the participants tended to underestimate the angle of direction the further the speaker was off-centre. Testing also attempted to gauge the participant's ability to localise sound in the vertical plane; however, no significant observations were discovered.

Another experiment was developed to compare an approximation of distance using echolocation via the AUDEO device as compared to audible echoes [31]. There was no discernible difference in the accuracy of approximation between the conditions at shorter distances (<2.5m). There was, however, a difference in accuracy at the further distances (>2.5). Under the auditory conditions, the perceived distance was much closer than the actual distance whereas the AUDEO device allowed a better distance estimate.

Recent Developments

Miniaturising the earpiece, from the large over ear earphones to smaller ear buds, allowed the receivers to be positioned much deeper inside the ear. With the new in the ear (ITE) buds, three additional human participant tests were performed to evaluate static and dynamic localisation [32].

As suggested earlier, horizontal localisation is largely dependent on interaural time, intensity and frequency differences. The horizontal sound source localisation task and the dynamic target localisation task, both of which are based on the participant's horizontal localisation ability, demonstrated that the ITE and OTE (outside the ear) receiver placement performances were equivalent. There was no evidence of diminished performance with the use of the ITE device.

As a result of the redesign, there was noticeable improvement in the vertical localisation ability of the participants using the ITE when compared to the results of the previous OTE style. The evidence suggests an improvement for the broad understanding of what is above or below them. There is also an apparent trend, from the limited test population, to suggest that the ITE design improves the finer details of sound source localisation.

The dynamic target localisation test demonstrated the AUDEO device's ability to differentiate among different materials. There was an observable difference in the participant's ability to locate the target relative to the material used, with more acoustically reflective materials easier to detect. As objects that are more acoustically reflective tend to be structurally more solid, it could be argued that they pose more of a threat to individuals with visual impairments and therefore the AUDEO device's ability to clearly identify them is an advantage. Overall, the change in the audible response provided by the device for different materials is important. This variation could be used by an experienced user to identify and distinguish different objects from one another, greatly improving the user's environmental understanding.

The most significant change to the testing procedure was to move the location of the experiment from an anechoic chamber into a standard room. The change from the anechoic chamber was expected to more truly represent the real-world conditions. The results in an echoic condition were consistent with results from earlier testing.

Testing with Visually Impaired Participants

While much of the device testing has been undertaken by blindfolded visually able participants, the AUDEO device has been evaluated briefly by two members of Royal New Zealand Foundation of the Blind (RNZFB) as well as an orientation and mobility instructor. The feedback has generally been fairly positive. Statements about the device include "A device like this enhances the potential of the blind traveller to be more independent and gives them more information to be able to make good decisions" [33] and "What the device was doing was giving me information through sound" "I could actually hear things around me I otherwise wouldn't have known were there."[34]

Positive responses from members of the Royal New Zealand Foundation of the Blind suggest that this device will be of benefit, but it is also important to remember that additional usability testing and iterative design must also be undertaken.

SUMMARY/CONCLUSION

The development and testing of the AUDEO device has been iterative and methodical, testing blindfolded users in an anechoic environment, moving to a more natural environment, and finally testing with blind users. The AUDEO has been shown to be effective as a "pick up and use" device with no training required by individuals with visual impairment. The next stage of this research is to perform focus groups and usability testing with blind users, with progressively smaller iterations of the device. For more information, and various videos of the testing, please see references [33, 34], and the website:
https://sites.google.com/site/tclairedavies/research-fun

Acknowledgements

We wish to acknowledge funding from AdviceFirst and AMP who are funding future stages of the project, as well as CIHR which funded Claire Davies for her doctoral research. We also wish to thank Catherine Burns and George Dodd for all their support throughout the development stages of this device. Finally, we'd like to thank the Royal New Zealand Foundation of the Blind and Chris Orr for testing the device and providing some feedback.

REFERENCES

1. Kelly, P. Historical Development of Orientation and Mobility as a Profession. 1999 [cited 2013 3 February]; Available from: http://www.orientationandmobility.org/.
2. Strong, P. The History of The White Cane. 2008 [cited 2012 11 May]; Available from: http://www.njcounciloftheblind.org/brochures/history_of_white_cane.htm.
3. Associated Press. Blind people say hyrbid cars pose saftey risk. 2007 10 May 2007 11 May 2012]; Available from: http://www.msnbc.msn.com/id/21112810/ns/business-autos/t/blind-people-say-hybrid-cars-pose-safety-risk/.
4. Statistics New Zealand, 2006 Disability Survey. 2006.
5. World Health Organisation, WHO Fact Sheet No. 282. 2012.
6. Kay, L., Auditory perception of objects by blind persons, using a bioacoustic high resolution air sonar. Journal of the Acoustical Society of America, 2000. 107(6): p. 3266-3275.
7. Meijer, P.B.L., An experimental system for auditory image representations. IEEE Transactions on Biomedical Engineering, 1992. 39(2): p. 112-121.
8. Kay, L., Bioacoustic spatial perception by humans: a controlled laboratory measurement of spatial resolution without distal cues. J Acoust Soc Am, 2001. 109(2): p. 803-8.
9. Blasch, B.B., R.G. Long, and N. Griffinshirley, Results of A National Survey of Electronic Travel Aid Use. Journal of Visual Impairment & Blindness, , 1989. 83: p. 449-453.
10. Sanderson, P. and M. Watson. From Information Content to Auditory Display with Ecological Interface Design: Prospects and Challenges. in Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting. 2005.
11. Dombois, F. Auditory Seismology, on free oscillations, focal mechanisms, explosions and synthetic seismograms. in Proceedings of the International Conference on Auditory Display. 2002. Kyoto, Japan.
12. WightMan, F.L. and D.J. Kistler, The dominant role of low-frequency interaural time differences in sound localization. Journal of the Acoustical Society of America, 1992. 91(3): p. 1648-1661.
13. Gelfand, S.A., Essentials of Audiology. Third ed. 2009, United States of America: Thieme Medical Publishers Inc.
14. Batteau, D.W., The role of the pinna in human localization. Proc R Soc Lond B Biol Sci, 1967. 168(11): p. 158-80.
15. Middlebrooks, J.C. and D.M. Green, Sound Localisation by Human Listeners. Annual Review of Psychology, 1991. 42: p. 135-159.
16. Hebrank, J. and D. Wright, Spectral cues used in the localization of sound sources on the median plane. Journal of the Acoustical Society of America, 1974. 56: p. 1829-1834.
17. Raykar, V.C., R. Duraiswami, and B. Yegnanarayana, Extracting the Pinna Spectral Notches in the HRTF. The J. Acoustical Society of America, 2005. 118(1): p. 364-374.
18. Langendijk, E.H.A. and A.W. Bronkhorst, Contribution of spectral cues to human sound localization. J. Acoustical Society of America, 2002. 112(4): p. 1583-1596.
19. Moss, C. and C. Chiu, The role of the external ear in vertical sound localization in the free flying bat, Eptescicus fuscus. Acoustical Society of America, 2006. 121(4): p. 2227-2235.
20. Thomas, J.A., C.F. Moss, and M. Vater, Echolocation in bats and dolphins, ed. C.U.o.C. Press. Vol. 2. 2004: Chicago: University of Chicago Press.
21. Moorhead, J., Seeing with Sound, in The Guardian. 2007.
22. Kish, D., Human echolocation: How to "see" like a bat. New Scientist, 2009. 202(2703).
23. Kish, D. and H. Bleier, Echolocation: What It Is, and How It Can Be Taught and Learned. 2000, World Access for the Blind. p. 1-22.
24. Waters, D.A. and H.H. Abulula, Using bat-modelled sonar as a navigational tool in virtual environments. Int. J. Hum.-Comput. Stud., 2007. 65(10): p. 873-886.
25. Kuc, R., Binaural sonar electronic travel aid provides vibrotactile cues for landmark, reflector motion and surface texture classification. IEEE Trans Biomed Eng, 2002. 49(10): p. 1173-80.
26. Walker, V.A., H. Peremans, and J.C. Hallam, One tone, two ears, three dimensions: a robotic investigation of pinnae movements used by rhinolophid and hipposiderid bats. J Acoust Soc Am, 1998. 104(1): p. 569-79.
27. Muldawer, L. and H.F. Meiners, New Acoustic Doppler-Shift Experiements. Am. J. Phys., 1967. 35(12): p. 1136.
28. Davies, T.C. and S. Pinder, Exploring Direct Downconversion of Ultrasound for Human Echolocation. 2007.
29. Davies, T.C., et al., Where did that sound come from? Comparing the ability to localise using audification and audition. Disabil Rehabil Assist Technol, 2012. 7(2): p. 130-8.
30. Davies, T.C., S.D. Pinder, and C.M. Burns, What's that sound? Distance determination and aperture passage from ultrasound echoes. Disabil Rehabil Assist Technol, 2011. 6(6): p. 500-10.
31. Davies, T.C., S. Pinder, and C.M. Burns, How far is that wall? Judging distance with audification. Proceedings of the Human Factors and Ergonomics Society 53rd Annual Meeting, 2009: p. 1091-1095.
32. Deacon, A., Perception of Spectral Cues for Audified Ultrasound, in Mechanical Engineering. 2013, University of Auckland: University of Auckland.
33. Abadia, K., Inventor's vision, in East and Bays Courier. 2013, Fairfax Media: Auckland.
34. Morton, J., Dolphin technique gives blind new view of world, in New Zealand Herald. 2013. ¶