MEASUREMENT OF THE HEAD-RELATED TRANSFER FUNCTION OF A BAT-HEAD CAST

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1 INTRODUCTION

To model echolocation in bats, it is useful to separate each stage of the process. The emission, echo-generation and reception are the basic components which comprise the model [1]. The output of the emission stage depends on several variable factors including the type of echolocation vocalisation, as well as its duration and directivity. The type of foliage where the sound is transmitted, the type of the target and its sound scattering pattern, the atmospheric attenuation and interference from other bats are considered to be factors affecting the modelling of the echo-generation stage. Binaural hearing, the shape and the species-specific features of the external ears as well as the movements of the pinna are considered to be factors in modelling the reception stage. In particular, it is necessary to model two receptors which represent the two ears in the bat in order to understand binaural processing, as sound localisation is mainly dominated by interaural (between the ears) differences. The concept of the head-related transfer function (HRTF) contains the time and frequency information of binaural hearing. It is conventionally obtained by the measurement of the responses from the head, external ear, and/or body at different azimuths and elevations at a specified distance. There have been a few studies to measure HRTFs in various species of bat [2][3][4][5][6]. These studies are mostly based on using a real deceased bat head following chemical treatment.

First, we extend these studies to include the bat-head cast. A so called dummy head is commonly used in human study and there has been a considerable amount of data collection, analysis and application using a specific type of human dummy head such as KEMAR by many researchers. In this study a latex cast model of a bat head was made of the surface on the real head of an Egyptian fruit bat and filled with modelling clay to maintain its shape. So far there have been few studies which have adopted the artificial head and investigated the role of the HRTF in the bat's sonar system. Holland and Waters [7] have demonstrated the effect of the pinnae moving forward and backward by measuring the HRTF of cast from the same species. However, little attention was given to the HRTF measurement of the cast at various azimuths. Therefore, this study aims to provide the binaural information and analysis of the measured data from the cast. Furthermore, our measurement procedure is compatible with the echolocation model [1] of and hence can be used as part of the binaural processing model of bat echolocation. The second aim of this study is to examine the usability and reliability of the extensive dataset collected in our measurements. Positioning errors in the insertion of the microphone in the bat-head or the positioning of the bat-head in the centre of the rig can have a significant effect on the repeatability of the measurement results. Due to the small size of the objects involved and the high frequency of the measurement (up to 100 kHz), positioning errors of a few millimetres can introduce significant systematic differences into the results. In order to estimate those differences we repeated the same experiment after we disassembled the microphone insertion from the bat-head cast and re-positioned the rig. The repeatability of the measured results was then compared between these two datasets.

In this paper, the characteristics of the measured HRTF in different azimuths will be described. Our objective is to extract the general features for the physical size of the head and the frequency range of the current system. The acoustics of the sound travelling around the artificial head and pinna are discussed. Then the repeatability characteristics of the experiment are discussed based on the data analysis of the measured HRTF.

2 METHODS

2.1 MATERIAL

A head-cast of an Egyptian fruit bat (*Rousettus aegyptiacus*) was used to measure the HRTF. The Egyptian fruit bat is a member of the genus Rousettus which is the only one to use echolocation among Megachiroptera (Megabat). It produces a broadband echolocation sound by suddenly releasing the tongue upward and away from the floor of the mouth. The head is approximately 3-4 cm in diameter. The bat-head cast consists of a 'skin' which was taken from the cast of a real bat head, and it has been provided by the Department of Biology in the University of Leeds (with acknowledgement to Dr Dean Waters) through the BIAS consortium. Modelling clay is used to fill head cavity of the cast to maintain the shape of the head. Lacquering has been applied inside and outside the cast several times to enhance the sound reflection and to keep the shape fixed.

2.2 MEASUREMENT SET-UP

All measurements were conducted in the small anechoic chamber in the Institute of Sound and Vibration Research (ISVR). The signal was generated from an ultrasonic loudspeaker (Ultra Sound Advice S56, 10 kHz-200 kHz) and amplified (S55A Amplifier, 18 kHz- 300 kHz, ±3 dB). In the measurement, a right-angled connector was coupled with the microphone (B&K Type 4939) as shown in Figure 2. The right-angled connector can be screwed and attached to the microphone so that it changes the angle by 90° but does not change the frequency response of the original microphone. It enables the microphone shaft to be held straight during the measurement so that it reduces the positioning errors. The signal received in the microphone was amplified (B&K Type 2670 preamplifier 4 Hz-100 kHz and B&K 2690 conditioning amplifier with 140 kHz upper limit) and transmitted to the A/D converting data acquisition card with a sampling rate of 500 kHz. Measurements were controlled by a computer located in a room adjacent to the chamber. The two rooms are connected by a box-shaped tunnel for the connection of the cables.

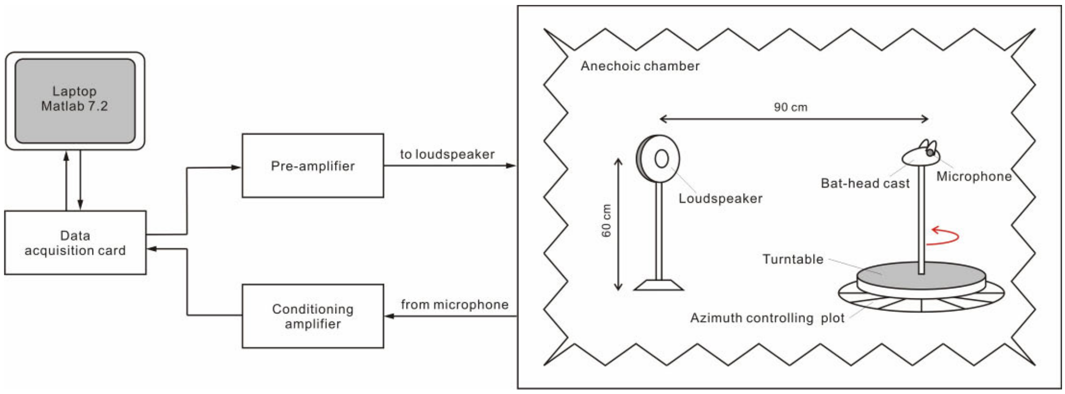


Figure 1: Measurement apparatus

The measurement apparatus is shown in Figure 1. The 10 cm microphone shaft was fixed into the bat-head cast and then mounted on a metal stand. The metal stand was in turn fixed on top of a turn table to record the microphone response at varying angles. The angle between the head and speaker could be set by rotating the turntable according to an azimuth controlling diagram fixed to the bottom of the turntable. The centre of the speaker was set at a distance of 90 cm away from the middle point between two ears of the bat-head cast. The height to the centre of the speaker was set to 60 cm above floor level, and the height to the microphone was also set to 60 cm above floor level to position the speaker and microphone in line. In order to position the centre of the bat-head cast and the centre of the speaker in line, a laser beam was projected from the top of the experimental rig and the positions were adjusted before each measurement. This central line adjustment was made when the bat-head cast was located at 0°, 90°, 180° azimuth and was repeated until the three positions were corrected.

The HRTF measurement was made separately for each ear. A complete set of azimuth measurements were made for the left ear and then for the right ear. After the left ear was measured for all azimuths, the microphone was completely disassembled from the bat-head cast. Then, the microphone was fixed at the position of the right ear and the measurement for all azimuths was taken. The process of disassembling the rig was intended to examine the repeatability of the measurements. All measurements were repeated twice. The measurement positions were made every 7.5° step in the azimuth, giving a total of 48 positions in the horizontal plane.

A pink noise signal with 256 thousand samples was generated and the received signal was deconvolved from the original signal to produce the impulse response. The gain in the signal generating program as well as the gain in the pre-amplifier of the speaker, were adjusted until the maximum SNR of the impulse response was achieved above 50 dB. Accordingly, the gain of the conditioning amplifier connected to the microphone for the signal reception was adjusted so as not to be overloaded.

2.3 CALIBRATION

The free-field measurement was made with the same microphone as used in the bat-head cast measurement but the response was recorded without the bat-head cast in place. The position of the microphone was re-adjusted using the laser beams to locate it in the same position as the middle of two ears of the bat-head cast. The measurement was made at a distance of 90 cm and height of 60 cm. As shown in the Figure 2, the frequency response is not flat but it can be easily removed from the measured transfer functions assuming its own shape is consistent during the measurement. The effective frequency range seems to be from 5 kHz to 100 kHz.

(a) (b)

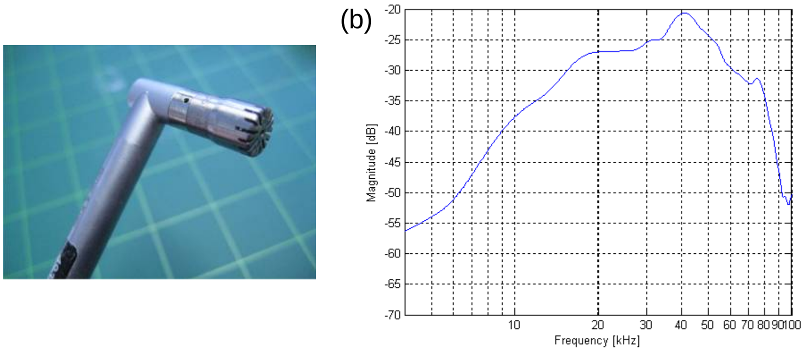


Figure 2: (a) Microphone coupled with right-angle connector (b) free-field response of the coupled microphone in frequency domain

2.4 DATA PROCESSING

To analyse the magnitude response or the interaural level differences (ILDs), all impulse responses were processed with a 250-point rectangular window around the maximum peak response and the windowed signal was zero-padded in the tail with 7942-samples to produce the post-processed 8192 samples. Then 8192-point FFT was applied which corresponds to an apparent frequency resolution of approximately 61 Hz in the analysis. The frequency analysis was limited to between 5 kHz and 100 kHz. The same processing was applied to the free-field response and the magnitude of the HRTF at each location was obtained by dividing the amplitude spectrum at that location by the free-field measurement response. On the other hand, the interaural time differences (ITDs) were calculated from the cross-correlation of the envelopes obtained from two ears measurements using the Hilbert transform in the time domain. The free-field equalisation was not applied in the processing of the ITDs to exclude the inevitable errors being induced by the centre positioning procedure as the sensitivity of the positioning error can be noticeable in the ITDs.

3 RESULTS

3.1 CONTOUR PLOTS

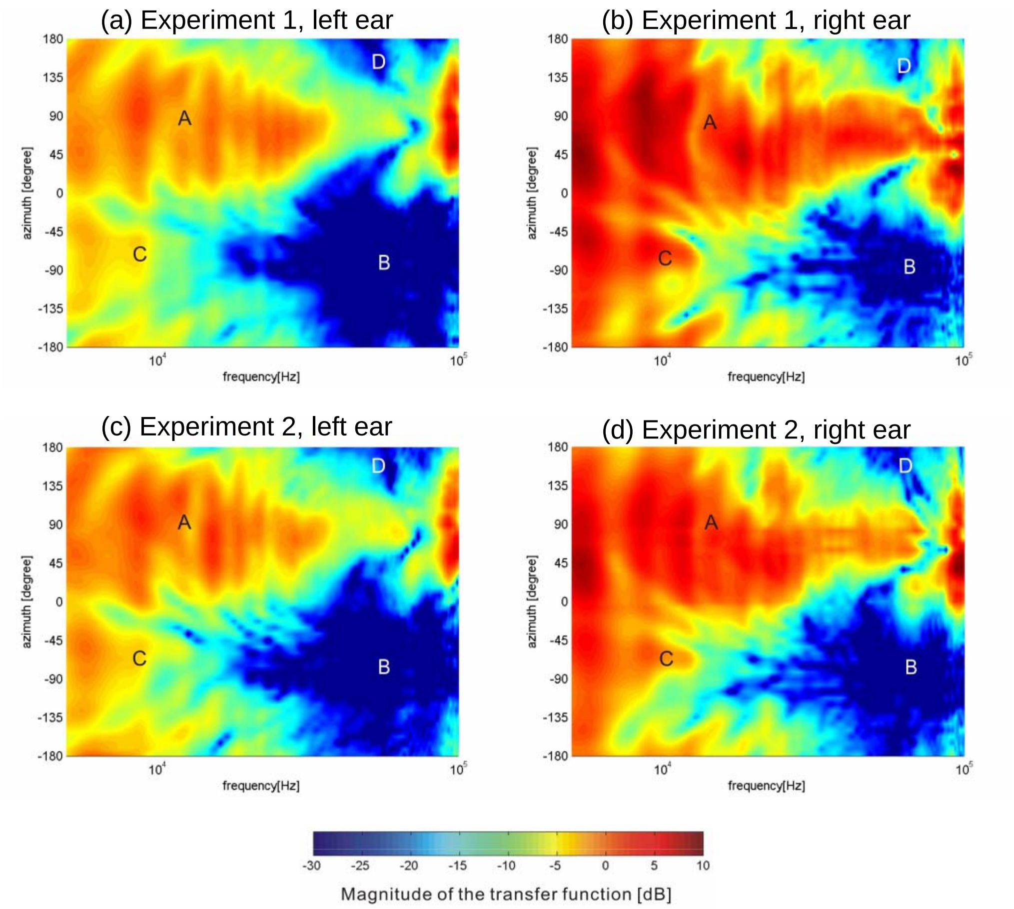


Figure 3: Contour plots of HRTFs in each ear obtained from two sets of measurements.

The contour plots of the HRTFs measured in all azimuths provide several characteristics which explain the acoustical phenomenon around the bat-head cast. Four contour plots from two measurements at each ear are shown in Figure 3. The 8192-point FFT was applied to the data and the results presented in dB at a frequency range from 5 kHz to 100 kHz. The obtained data from the 7.5° azimuth steps is interpolated to represent a smooth contour. Each contour appears to have a different range of maximum and minimum points, and there is asymmetry and differences in the two measurements. Therefore, all contours are plotted over the range of 40 dB with different maximum and minimum absolute values to aid the understanding of the characteristics in the same range of colours. Thus, the colour bar shown in Figure 3. represents the relative levels.

The general characteristics of the measured HRTF in all azimuths are shown to be consistent between the two sets of the measurements. They are observed to have similar patterns describing the principles of acoustics around the head. There are four major features shown in the contour plots. These are referenced as A, B, C and D in each figure at the same locations. The magnitude of the HRTFs relatively increases at high frequencies as the angle of the source increases towards the location of 90° in the azimuth (A). It is obvious that more high frequency energy is received in this direction. This is due to the fact that the sound waves at high frequencies reflect back in direction of the sound source when the sound source is located directly in front of the receiver. In other words, the original sound waves and the reflected waves are combined in phase and they produce the high-frequency superposition.

A large area of spectral notches was found for the sources located on the back of the bat-head cast (B). There is very low energy at high frequencies in this region as the travelling sound waves of high frequencies is shadowed by the head. Furthermore, the notch is somewhat extended and makes interference with the frontal region at around 70 kHz - 80 kHz (D). On the other hand, relatively higher energy of the low frequency is contained in the source located in the back. This effect is most obvious when the ear is located directly opposite the source. Assuming the head is symmetrical, the theory shows that low frequency sound components travel around the head by the diffraction and then combine in phase to produce the acoustical bright spot (C). As the bat-head cast used is not perfectly symmetrical the bright spot appears at less than -90° and the peak locates at the frequency of 10 kHz.

3.2 INTERAURAL DIFFERENCES

3.2.1 Interaural level differences (ILDs)

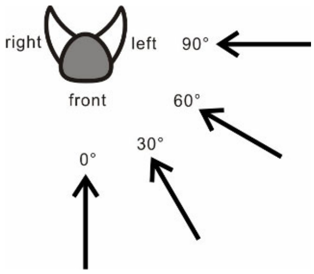
The ILDs are calculated for each measurement set. A few results from different azimuths are plotted in Figure 4. The ILDs are identified near 0 dB in the median plan and the ILDs of the low frequencies from 5 kHz to 10 kHz tends to stay near 0 dB or increase up to about 10 dB at maximum as the source moves towards the lateral positions. The ILDs in the high frequencies above 10 kHz vary dramatically compared to the low frequencies. Several peaks and notches appear as the source moves, and they are shown to be stronger at 60° and 90° where the direct paths of the sound travelling in the high frequencies are given from the source to the receiver. The maximum ILDs reach around 50 dB in the region of high frequency.

The differences between the two measurements in the ILDs analysis showed that the results are consistent at the low frequencies from 5 kHz to 10 kHz with the variation of less than 3 dB. However, the spectral peaks and notches above 20 kHz are irregular between the measurements, and the difference between the peaks in particular frequency is shown to be over 20 dB.

3.2.2 Interaural time differences (ITDs)

The ITDs are calculated for the two sets of measurements and plotted in Figure 5. The obtained ITDs were interpolated to represent the data in higher resolution in the azimuth between each step. The simulation of the ITDs (τ) based on the rigid sphere model was conducted for the head diameter (r) of 4 cm. The mathematical calculation for the simulation, which has been suggested by Middlebrooks [8], is described in Equation (1) (θ denotes the azimuth and c is speed of sound. c=344 m/s is applied). The range of the ITDs is shown to be from -150 μs to +150 μs for both simulated and measured data. The measured data seems to fit the sphere model in general. The ITDs increase as the source moves towards the lateral positions and decrease as the source moves towards the median plane. The negative values of the ITDs indicate that the right ear is closer to the source than the left ear. It is well known in the previous studies that the maximum ITD occurs at the position where the sound source is coming directly towards the ear (90° of azimuth). However, the maximum value of the ITD is not exactly shown in the source direction at 90° and it is shifted towards the smaller azimuth angle. The explanation is that the effect from the pinna is not included in the sphere model. Furthermore, the peak was shown to be less obvious for the second measurement and this seems to be due to the unstable repeatability at high frequencies.

In general, the results from the two measurements showed less variation for the sound sources from the front and they matched reasonably well to the prediction of the sphere model. However, it has shown the variation up to around 50 μs for the sound sources from the back. Thus, the measured data is shown to be less reliable when the direct path is shadowed for the receivers in both ears.



(a) Source positions

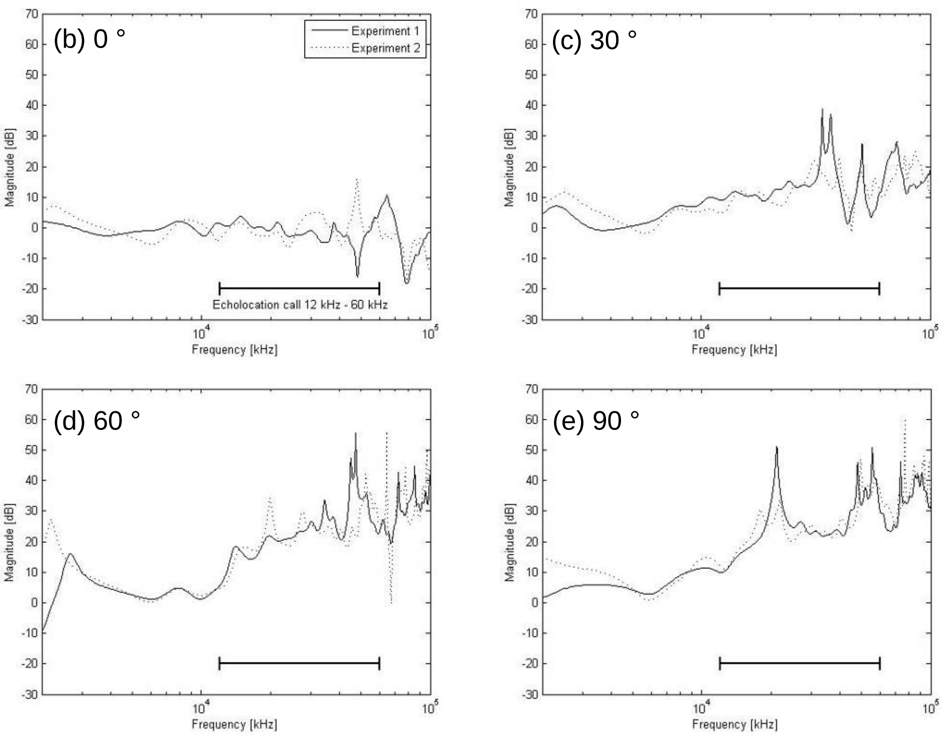


Figure 4: ILDs calculated from the two sets of measurements

$$\tau = \frac{r}{c}(\theta + \sin\theta) \quad (1)$$

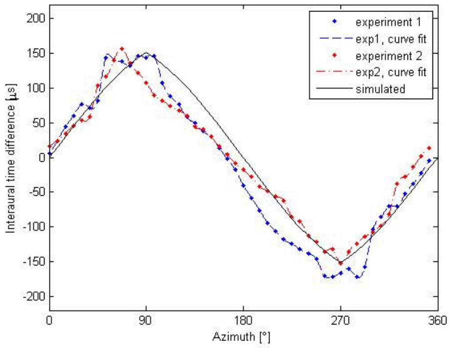


Figure 5: ITDs calculated from the rigid sphere model and the two sets of measurements

4 DISCUSSION

This study has successfully implemented right-angled microphone in the bat-head cast and the HRTF measurements have been made reliably in the frequency region from 5 kHz to 100 kHz. The measurements were made twice and separately at each ear. To investigate the repeatability, the microphone was completely disassembled from the bat-head cast and fixed again in each measurement. The centre position was adjusted again for each measurement.

The measured data was examined in the frequency domain and it showed that HRTF provided the change in the magnitude spectrum depending on the different azimuths measured. Also, the variation in frequencies above 10 kHz was larger than in frequencies below 10 kHz. It is interesting to note that common features have been found in the contour plots of measured HRTF and the human HRTF in the previous study [9]. The high-frequency superposition, head shadowing, acoustic bright spot and the interferences shown in the high frequency are shown in the results and they are regarded as the general characteristics of the measured HRTF. The same effect has been shown in the human HRTF and it seems likely that the scale has been shifted up to the frequency region of 10 kHz to 100 kHz in this study. On the other hand, even though the contour plots showed reasonably good repeatability in the measurements for the same ear, they also reveal a clear asymmetry of the head by comparing the results from the two ears.

The ILDs and ITDs were investigated in this paper. For the ILDs, the results from two sets of the same measurements have shown reasonably good agreement in the low frequency region but the variation appeared to be larger in the high frequency region. Some high frequency peaks appeared were not matched in frequency and magnitude across the repeated measurements The ITD results were in broad agreement with the results obtained by the simulated sphere model with better repeatability and agreement with the model demonstrated for angles of incidence in the front rather than in the back. In summary, it can be concluded that the ILDs and ITDs are more sensitive when the direct path between the sound source and receiver is head shadowed. It suggests that the measurement results may not be repetitive for high frequencies in the head-shadowed region although careful consideration of the microphone insertion and the positioning of the rig are taken.

It is known that Egyptian fruit bat uses an echolocation call ranging from 12 kHz to 60 kHz. Also its behavioural audiogram is known to show a hearing ability which ranges up to around 60 kHz [10]. It seems that the frequency range of Egyptian fruit bat's echolocating call almost corresponds to its hearing ability. The measured HRTF in the current study contributes to the acoustical characteristics of the sound reaching at both ears within this frequency range. Figure 4 shows the measured ILDs in four different azimuths including the frequency range of the Egyptian fruit bat's echolocating call.

5 CONCLUSIONS

In this study we presented results that contribute to the development of the experimental methods necessary for the investigation of binaural processing in bats. We did this by studying the characteristics of binaural receivers fixed on the artificial bat-head cast. It is obvious that the binaural receivers provide the localisation information for the different azimuths and it is similar to the results from the human studies and other HRTF measurement in bats. In fact, the binaural characteristics can be divided into two: the effect from head, and the effect from the pinna. Most studies of HRTF in bats have focused on the characteristics of the pinna and their contribution to the localisation using a specific type of echolocating signal. In contrast, the studies regarding the relationship between the presence of the head and its contribution to the *echolocation* task (not passive localisation) are relatively limited. Thus, the role of the head and the binaural receivers on the echolocation motivates further study for future work.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

1. T. Papadpoulos and R. Allen. Experimental method for the acoustical modeling of the echolocation process in bats. Proc. Inst. Acoust. 29(3), 2007

2. M. K. Obrist, M. B. Fenton, J. L. Eger, and P. A. Schlegel. What ears do for bats – a comparative-study of pinna sound pressure transformation in chiroptera. J. Exp. Biol. 180: pp. 119-152, 1993

3. Z. M. Fuzessery. Monaural and binaural spectral cues created by the external ears of the pallid bat. Hearing Research, 95(1-2): pp. 1-17, 1996

4. P. H. S. Jen and D. Chen. Directionality of sound pressure transformation at the pinna of echolocating bats. Hearing Research, 34(2): pp. 101-118, 1999

5. M. Aytekin, E. Grassi, M. Sahota, and C. F. Moss. The bat head-related transfer function reveals binaural cues for sound localization in azimuth and elevation. J. Acoust. Soc. Am. 116(6): pp. 3594-3605, 2004

6. U. Firzlaff and G. Schuller. Directionality of hearing in two cf/fm bats, pteronotus parnellii and rhinolophus rouxi. Hearing Research, 197(1-2): pp. 74-86, 2004

7. R. A. Holland and D. A. Waters. Echolocation signals and pinnae movement in the fruitbat Rousettus aegyptiacus. Acta Chriopterologica, 7(1): pp.83-90, 2005

8. J. C. Middlebrooks and D. M. Green. Directional dependence of interaural envelope delays. J. Acoust. Soc. Am. 87(5): pp. 2149-2162, 1990

9. D. S. Brungart and W. M. Rabinowitz. Auditory localization of nearby sources. Head related transfer functions. J. Acoust. Soc. Am. 106(3): pp. 1465-1479, 1999

10. G. Koay, R. S. Heffner and H. E. Heffner. Hearing in a Megachiropteran Fruit Bat (Rousettus aegyptiacus). J. Comp. Psychol. 112(4): pp. 371-382, 1998