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BINAURAL RECORDINGS AND THEIR APPLICATION IN THE SUBJECTIVE ASSESSMENT OF MUSIC ROOMS AND CONCERT HALLS

Riduan Osman

Department of Architectural and Design Science
University of Sydney, NSW 2006, Australia

ABSTRACT

The application of binaural recordings for the comparisons and assessments of the acoustic quality of music rooms and concert halls are discussed. Correctly made binaural recordings can provide easy and precise subjective comparisons and ranking of the acoustic quality of music rooms and concert halls without enduring the disadvantages of relying on the subjects' acoustic memory. A review of the types of dummy heads, microphone locations, the resulting binaural recordings that can achieved and equalisation required are carried out. The various methods of binaural recording reproduction, using headphones and loudspeakers, for presentation to the listening subjects are discussed and methods of subjective assessments of binaural recordings made in music rooms and concert hall are recommended.

INTRODUCTION

The use of binaural recordings with artificial (dummy) heads have become more common and acceptable as a result in improvements in microphone technology and portable digital audio tape recorders with 'compact-disc quality' performance. Binaural recordings have been successfully used for subjective comparisons of the acoustical quality of concert halls and music rooms [1] [2] [3], and is also a useful tool in the assessment of the acoustical quality of concert halls and music rooms prior to and after refurbishments. Most binaural recordings for research work are made using the commercially available dummy heads made by Bruel & Kjaer (Head and Torso Simulator - HATS), Knowles Electronics (KEMAR), Neumann (KU100) and Head Acoustics (Aachen Head). Binaural recordings can also be achieved using live human heads and probe microphones inserted into the ear canals although variables introduced from head movements, swallowing, breathing, hair styles, and variations in pinna shapes and sizes can result in difficulties in achieving quality playback and repeatable equalisation. Notwithstanding this, there may be situations where the combination of live human heads and miniature microphones located close to the ear canal entrance may be used to make 'verification binaural recordings' where the use of artificial dummy heads are deemed to be intrusive or disruptive such as during full-house concert performances.

The primary advantage of binaural technique is that binaural reproductions allow rapid subjective comparisons to be made, especially when the recording is presented to the listener from a hard disc of a P.C., with the listener being in full control of the rapid selection and replay of the recorded material. This overcomes the problem of the listener's limited acoustic memory resulting in a more accurate subjective assessment when comparing the acoustic quality of different music rooms or various seating positions in a concert hall. Binaural recordings also present us with the opportunity of performing double blind tests on concert halls and music rooms where the appearance and reputation of the concert halls and music rooms cannot influence their selection and ranking. The reliability and repeatability of data and recordings obtained using dummy heads as compared to real human heads has been demonstrated by numerous research studies [4] [5].

THE BINAURAL TECHNIQUE AND THE DUMMY HEAD

The pinna, along with the ear canal, forms a system of acoustical resonators. The degree to which individual resonances of this system are excited depends on the direction and distance of the sound source [6]. To capture the correct three dimensional sound image, it is important to maintain the elements of the pinna and ear canal that preserve the correct acoustic image at the eardrum. Binaural recordings have been successfully produced by using probe microphones inserted in the ear canal but for the reasons described below, the dummy head has been the preferred option for making binaural recordings for comparisons and studies of music room and concert hall acoustics.

Some of the advantages of using the dummy head are as follows:
a. the dummy head can be standardised. Results of different laboratories should have maximum conformity.
b. The dummy head can be calibrated once so that a reference measurement in the reference sound field is not necessary.
c. The dummy head does not cause measurement errors that occur as a result of swallowing, sneezing, coughing, head movement or heavy breathing.
d. The dummy head does not require insertion of a probe microphone, there are no problems with the danger of hurting the eardrum and with hygiene.
e. Dummy head measurements can be carried out more quickly. [7]

There are three recommended recording points (microphone locations) for binaural recordings using dummy heads. They are:
a. At the eardrum
b. At the entrance to the ear canal
c. At the entrance to the ear canal, but with the ear canal physically blocked.

For each of these points, correct reproduction can be obtained by the introduction of an electrical equalising circuit. These recommended positions also apply to real human heads. In case 'c' where the ear canal is physically blocked, an 'open' type headphone is recommended so that electronic compensation will not be required to compensate for the transmission difference caused by different acoustic source impedances in the recording and listening situations [8]. True binaural recordings may not be achievable when the microphone is located outside of the above locations.

The Neumann, Head Acoustics and Bruel & Kjaer (Type 4100) dummy heads have their microphones located at the entrance of the ear canal. Although in the Head Acoustics dummy head, the pinna used does not exactly resemble a real human pinna, the structures used capture averaged features of different human pinnae. The Neumann head is not equipped with a torso while the Head Acoustics includes shoulders. The B&K and KEMAR heads are normally used with torsos. The artificial pinna used in dummy heads is usually manufactured of a soft pliable material (e.g. silicon rubber) similar in elasticity and shape to a real pinna.

In developing a test and evaluation tool for predicting hearing-aid performance, Burkhard and Sachs [11] incorporated the eardrum simulator portion of the Zwislocki coupler into the KEMAR, and substituted flexible pinnae and metal ear canals for the corresponding upper portions of the Zwislocki coupler. Acoustic measurements on the KEMAR manikin show close agreement with similar measurements on human subjects [9] [10].

The presence of a clothed torso causes a 3 dB lower sound pressure level at 1200 Hz and a 3 dB higher level at 600 Hz when compared to a head without torso in free field with the sound source originating from the front. With the sound source coming from 90° (the side), the level at 1500 Hz with the torso is 3 dB lower than without the torso [11]. Hence the inclusion of the torso during binaural recording is highly recommended. An added advantage of the torso is the easier support and positioning of the dummy head relative to a concert hall seat.

PLAYBACK EQUALISATION OF THE BINAURAL RECORDINGS

From the entrance of the ear canal, the propagation of sound in the ear canal to the ear drum is essentially one-dimensional and thus independent of direction and distance to the sound source. Outside and beyond the ear canal, the direction of sound incidence has a bearing on the magnitude of the sound pressure measured. The magnitude of the transfer function from different points relative to the ear canal and eardrum is shown in Fig.1 [8]. Fig.1 shows that it is possible to achieve approximately one-dimensional transmission at a location of 6mm outside the ear canal provided that the pressure probe (or microphone) is along the central axis of the ear canal.

For recordings made with microphones in positions a, b, c and d described in Fig.1, a one-third octave equaliser set at the inverse of the corresponding transfer function can achieve correct equalisation for headphone playback. For recordings made with the KEMAR head with the eardrum simulator, equalisation can be similarly achieved by inversing the transfer function graph on a one-third octave equaliser or by inserting a simple bridged-T equalisation filter designed by Killion [12] in place of the one-third octave equaliser. The other dummy heads are equipped with their built-in or specially produced equalisers.

Where separate equalisation is required (such as the KEMAR head), it is generally recommended that the equalisation be performed in the recording phase, with the equaliser being located between the microphone and the recorder input. Pre-equalising the microphone signal will preserve the recording headroom (approx.15 dB.) that would have otherwise been lost in the 2kHz and 10kHz range as a result of the pinna resonances. Post equalisation, i.e. equalisation during playback, is only recommended when recording equipment with better than 85 dB dynamic range (such as digital audio tape recorder) and low noise microphones are used. The advantage of post equalisation is that the recording is always that of the sound picked up at the microphone.

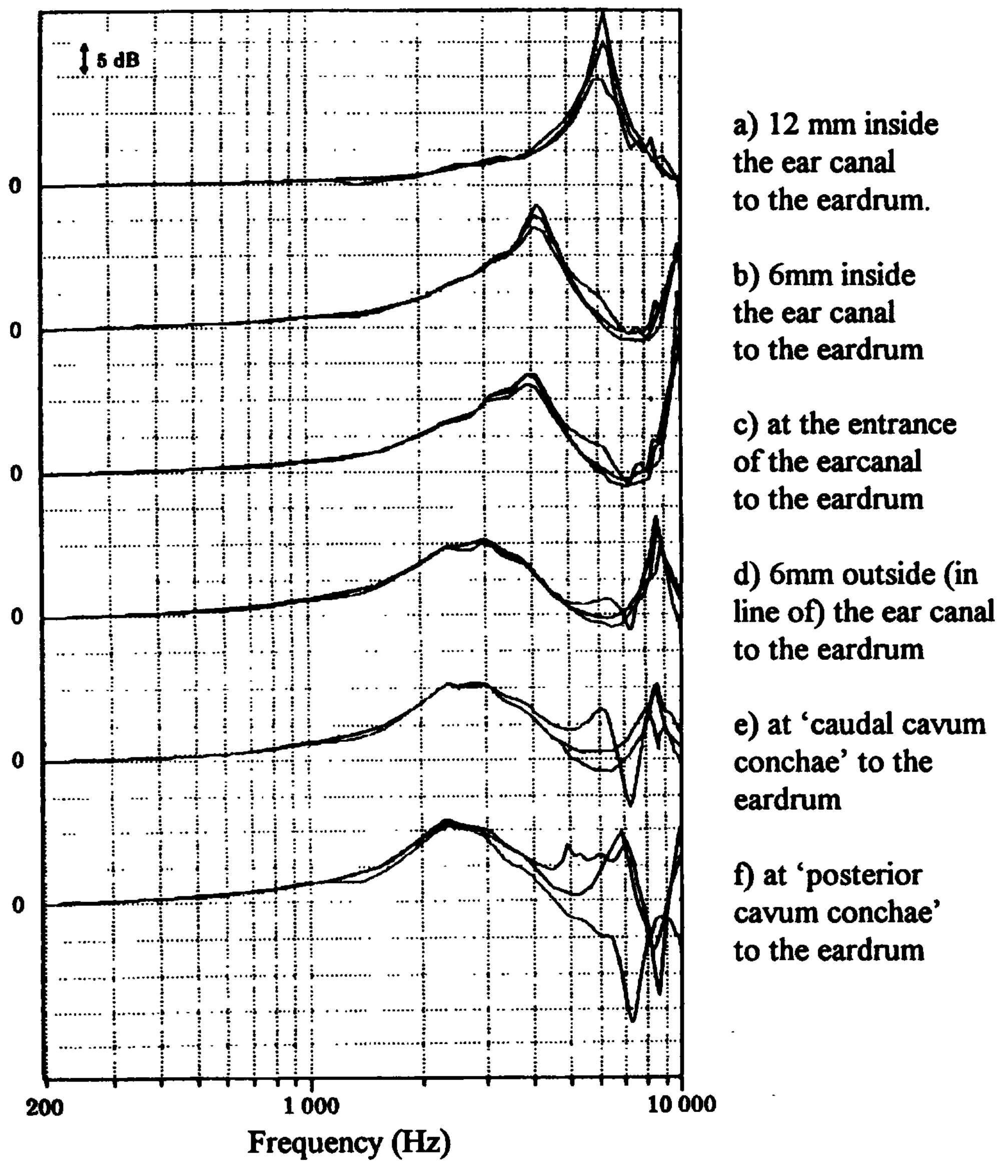

Fig.1. Magnitude of transfer function from different points in the ear canal to the eardrum on a typical subject. Each measurement position shows the results of sounds from three directions (left ear, $\phi = 0^\circ$, 90° and 180°, $\theta = 0^\circ$). [8]

REPRODUCTION OF BINAURAL RECORDINGS WITH HEADPHONES

The listening experience in a music room or a concert hall consists of air conducted sound to the eardrum, bone conduction resulting from absorption through the skull and sound received by tactile receptors (such as the hair at the nape of the neck) [6]. In conventional binaural listening situation, only hearing by air conducted sound to the eardrum is recreated by playing a binaural recording via headphones. As a consequence, the full listening experience is not recreated.

It has also been shown that differences are found in the sound pressure levels measured in the auditory canal in the range of 7.5-14 dB between loudspeaker and headphone reproduction, while the test subject considers both to have equal loudness. Headphone reproduction requires more sound level in the auditory canal than equal loudspeaker reproduction [7]. This discrepancy, which is much above the well-known 'apparently missing 6 dB' [13] that commences at about 300Hz and increases as the frequency drops, is probably due to the reduced level of bone conduction and the lack of body absorption elements during headphone reproduction listening, although this has yet to be conclusively proven. For most binaural recording subjective comparisons, where high levels of bass sounds is not a factor, this anomaly is not expected to cause any influence in the results.

The various types of headphones or earphones currently commercially available are as follows:

a) the insert-type earphones (similar in design to the hearing aid earpiece, such as the Etymotic ER4S)
b) the in-ear type (normally used with 'Walkman' type cassette or compact discs)
c) the supra-aural type (where the headphone flat pad presses on the pinna)
d) the circumaural type (where the pinna is fully enclosed by the headphone).

The circumaural type is preferred for reproduction of binaural recordings as the listening subject uses his/her own pinna for the binaural reproduction. The additional advantage of the circumaural type headphone is also that it generally provide better comfort than the other types in addition to its good isolation of external noise. Almost all circumaural headphone commercially available are diffuse field equalised. Circumaural headphones can either be of the 'closed' or 'open' type, where an 'open' type can be used for all dummy head recordings while the 'closed' type should only be used for dummy head recordings made at the eardrums or made at the ear canal entrance where the ear canal is not blocked [8].

The advantage of the insert-type earphones is their excellent 25 dB isolation of external noise but the total lack of bone conduction provide a different low frequency reproduction experience, although full frequency range is reproduced at the eardrum via air conduction. Its main disadvantage is that it does not utilise the subjective listener's pinna during the binaural reproduction. The supra-aural headphones are not recommended as they deform the pinna and ear canal, their precise position relative to the pinna and ear canal are generally difficult to repeat, and they provide poor sealing with the head/pinna. The in-ear type earphones are not recommended due to their relatively poor frequency response and poor sealing inside the pinna.

ALTERNATIVE METHODS FOR REPRODUCTION OF BINAURAL RECORDINGS

Various attempts have been made to reproduce binaural recordings using conventional loudspeakers in anechoic or near anechoic rooms. One method that has been successfully developed for the reproduction of binaural recordings through traditional stereo loudspeakers set-up in an anechoic room is by cancelling the crosstalk using specially developed digital filters in each channel. In this arrangement, it was also found that the system is relatively independent of head position as long as the distances from the loudspeakers are equal. To use the system in a non-anechoic room, more computer processing will be required for the digital filters to correct for the room reflections [14].

Binaural recordings can also be satisfactorily reproduced in a relatively dead room (reverberation time < 0.4 secs.) with four loudspeakers placed at a distance of 2 metres from the listener and the loudspeakers connected in a manner as shown in Fig.2 [15]. Although the resulting localisation may not correspond exactly to the original recorded event, some of the problems relating to the lack of bone conduction and other physical sensations encountered with the use of headphones can be overcome. This may also offset some of the 'missing 7.5 to 14 dB' described by Thiele [7] above.

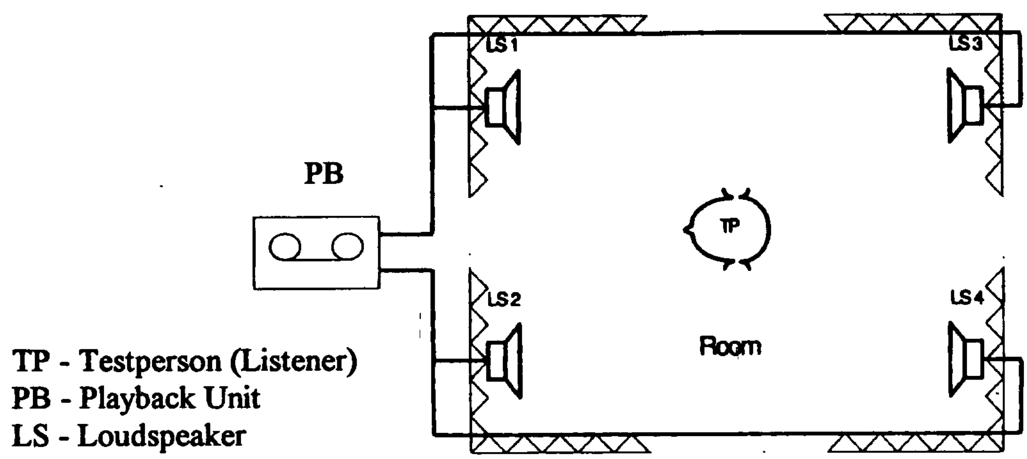

Fig.2. Arrangement for listening to binaural recording using four loudspeakers [15].

Another alternative method for binaural reproduction is the Near-field Binaural Reproduction System (NBR-System) as proposed by Miura [16]. In the NBR-System, small loudspeakers are set close 'ahead and in front' of the pinna (Fig.3). As a result of the closeness of the loudspeakers to the pinna, the measured crosstalk transfer functions are insignificant and hence the playback of the binaural recordings do not require crosstalk cancelling filters. When carried out in a relatively 'dead' room, the room reflections has no effect on the listening test. Fig.3 shows the arrangement of the NBR-System loudspeakers relative to the listener's head. The potential advantage of the NBR-System is the recreation of an acoustic environment around the listener's head which can generate bone conduction and skin absorption in an attempt to recreate as much of the aspects of 'the complete listening experience'. The amount and relative proportions of bone conduction and skin absorption relative to eardrum stimulation using the NBR-System is at present not quantified.

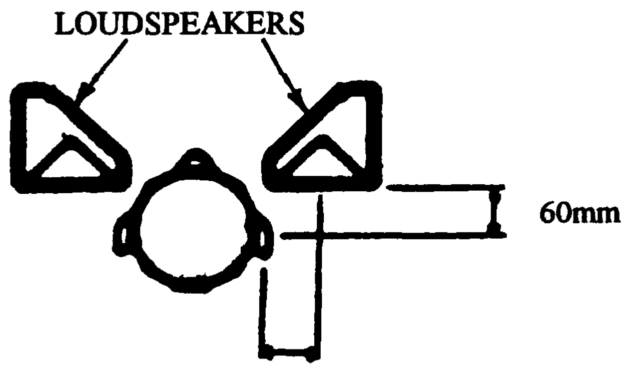

FIG. 3. Arrangement of the NBR-System loudspeakers for binaural Listening. [16]

SUBJECTIVE RATINGS OF BINAURAL RECORDINGS

The subjective ratings of concert halls have always been biased towards the large number of semantic differential scales. It is recommended that for binaural recordings this be reduced to five orthogonal dimensions of 'Reverberance, Balance and Blend, Intimacy, Definition, and Brilliance' [1] [17]. This will assist in simplifying and expediting the subjective listening test, and where a significant number of halls are being subjectively compared, will help in reducing listener fatigue and unreliable results.

For the subjective ratings of small music rooms where some of the orthogonal dimensions above may be difficult to define and assess, the two-alternative-forced-choice as proposed by Hansen & Munch [18] developed for loudspeaker and listening room assessment is recommended. This method overcomes the confusion with interpretation with the semantic differential scales and allows non-musically trained listeners to participate as listening subjects.

With the availability of better object-linked software, faster P.C. processing power and larger hard drive capacities, all the selection, randomisation, rating and ranking of the subjective listening tests can be simply and quickly carried out in full double-blind mode with full 16-bit linear (CD quality) audio. Using this process, the listening subject will be in full control of the listening test and, coupled with the double-blind technique, it should provide us with a very effective tool for the assessment and comparisons of music rooms and concert halls.

CONCLUSIONS

The availability of improved quality microphones, dummy heads and recording equipment has allowed us to make better quality and repeatable binaural recordings. It is preferable that dummy head recordings be made with clothed shoulders and torso. Where shoulders and torsos are not available, approximated corrections can be made with equalisation. It is recommended that open-type circumaural headphones be used for reproduction when assessing binaural recordings of small music rooms and of concert halls where the bass frequencies are not the main subject of the assessment. Where bass sounds are being examined, reproduction using loudspeakers, as described above, in anechoic rooms should be the preferred method. It is prudent to have the listening subject or subjects assess the same musical excerpts in a selected sample of the concert halls or music rooms being investigated to ensure that satisfactory correlation with the binaural reproduction is achieved. Binaural recording is also an effective tool in archiving music rooms and concert halls acoustical information that would otherwise be lost after refurbishment or demolition.

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