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# Development of a head-movement-aware signal capture system for the prediction of acoustical spatial impression

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## ABSTRACT

This research introduces a novel technique for capturing binaural signals for objective evaluation of spatial impression; the technique allows for simulation of the head movement that is typical in a range of listening activities. A subjective listening test showed that the amount of head movement made was larger when listeners were rating perceived source width and envelopment than when rating source direction and timbre, and that the locus of ear positions corresponding to the pattern of head movement formed a bounded sloped path – higher towards the rear and lower towards the front. Based on these findings, a signal capture system was designed comprising a sphere with multiple microphones, mounted on a torso. Evaluation of its performance showed that a perceptual model incorporating this capture system is capable of perceptually accurate prediction of source direction based on interaural time and level differences (ITD and ILD), and of spatial impression based on interaural cross-correlation coefficient (IACC). Investigation into appropriate parameter derivation and interpolation techniques determined that 21 pairs of spaced microphones were sufficient to measure ITD, ILD and IACC across the sloped range of ear positions.

## INTRODUCTION

Acoustical evaluation of a listening environment or a sound reproduction system often involves listening tests, which require a number of subjects whose judgments need to be processed through statistical analyses in order to estimate the response of a wider population. The research reported in this paper is fundamentally motivated by the intention to simplify the procedure of the acoustical evaluation, by means of an objective listening model that can mimic and replace human listeners in subjective tests, or at least complement listening tests (e.g. by pre-screening potential algorithms, acoustic treatments or stimuli). In particular, this research focuses on the evaluation of spatial impression, one of the major attributes used to describe the acoustical quality of a listening space [1]. In addition, in order to represent human listeners as closely as possible, this research attempts to incorporate the nature of head movement in the development of the objective model.

Since Marshall [2] suggested spatial impression as an acoustical quality, many researchers have supported and further investigated its concept. Gradually it was generalised into two subcategories – source width and envelopment, which are now widely accepted as separate aspects of spatial impression [1, 3-5]. It has been revealed that interaural cross-correlation coefficient (IACC) is closely related to perceived source width and envelopment [11-15]. Interaural time and level differences (ITD and ILD), the two complementary binaural cues of azimuthal source localisation [16, 17], have also been found to affect the perception of spatial impression, particularly in the form of their temporal fluctuations [7, 18, 19]. These were later found to be less practical than IACC for indicating perceived spatial impression [20].

Head movement has been mainly known to help listeners localise sound sources by reducing the confusion caused by a given ITD and ILD cue corresponding to multiple potential source directions (often referred to as the cone or torus of confusion) [21, 22]. Movement of the head causes these cues to change in a manner that can indicate a unique direction, as long as the pattern of movement is known. Experiments aiming to find the patterns of head movements, especially rotation, generally tended to categorise them into three types: rotation in azimuth, elevation, and roll [23]. Amongst these, azimuthal rotation was found to be the most effective for localisation [24, 25]. However, little is known yet regarding the nature of head movement in other acoustical evaluation activities where source localisation is not of primary interest. Therefore, in order to successfully incorporate head movement into the objective evaluation of spatial impression, it is necessary to investigate the nature of head movment in listening activities to evaluate spatial impression.

In the following sections, the experiment investigating the nature of head movement in various subjective evaluation listening activities, including spatial impression judgment, is firstly introduced. Then methods of incorporating these movements into binaural signal capture techniques are introduced and evaluated. The accuracy of each of a number of approaches is evaluated, and techniques for optimising the results are tested. Finally, a practical measurement system is proposed as a valid head-movement-aware signal capture system.

## INVESTIGATION INTO HEAD MOVEMENT IN SUBJECTIVE LISTENING EVALUATIONS

This section introduces a set of experiments designed to investigate the nature of head movements made when listeners evaluate various subjective auditory attributes, particularly source width and envelopment as well as source location and timbre. The findings can lead to the design of a sound capture model optimised for spatial impression prediction.

### Experimental design and procedure

Subjective tests were designed where the listeners listened to various stimuli processed in different ways, and evaluated four attributes of sound – source location, width, envelopment and timbre, whilst their head movements were recorded. The listening tests were undertaken in a listening room of the Institute of Sound Recording (IoSR) that meets the ITU-R BS 1116 standard [26]. To create variations in the four attributes, eight Genelec 8020A loudspeakers were set up around the listening position, each 2m from the centre and spaced at 45° intervals in azimuth, hidden by acoustically transparent curtains. They were distributed over three different levels of height, so that the influence of source height, if any, could be examined as well. A Polhemus Patriot™ head tracking system, which uses an electromagnetic transmitter placed near a small electromagnetic signal receiver attached on the head for tracking, was used to track the head movements. Figure 1 shows the layout of the loudspeakers and the listening position. The difference in the sizes of the loudspeakers in the figure indicates different elevation.

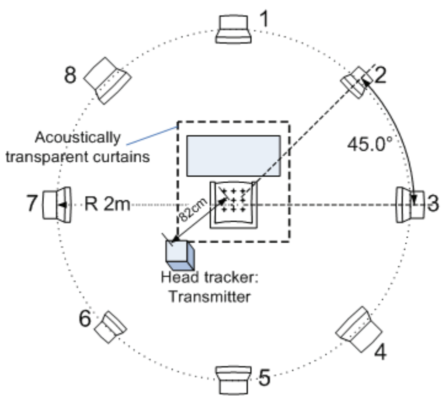



**Figure 1**. The layout of the loudspeakers and the listening position for the experiments. The difference in the sizes of the loudspeakers in the figure indicates different elevation, with small, medium and large icons indicating loudspeakers below, on and above the horizontal plane respectively.

The stimuli were created with the aim that they should be perceived to be different in terms of each of the judgement scales of source location, source width, envelopment and timbre. Four anechoic recordings were selected from the CD for the Archimedes project [27]. An acoustic guitar excerpt, a conga excerpt, one short beat of the conga recording, and an English male speech excerpt were used. The direct sound was positioned in one of four directions that varied in azimuth and elevation. Three levels of source width, and three levels of envelopment were simulated using one or more loudspeakers and by means of decorrelation and convolution with reverberation [28]. Three variations of timbre were also included: the original plus one low-pass and one high-pass filtered version. The filters used were $10^{th}$-order Butterworth, each with a cut-off frequency of 1kHz. Combinations of these processes were used to create the stimuli presented to the subjects.

Ten paid subjects, all of which were undergraduate Tonmeister students in the IoSR, undertook the experiment. They were instructed to evaluate each of the four attributes with the tracking device attached to the head by means of a headband. However, the actual purpose of the tests was hidden to attempt to limit any unnatural head movements that might have been caused if they had been told that the head tracking data would be more important than the answers in the experiment. Each stimulus was presented twice sequentially with a short delay in-between, mainly to test the repeatability of the results, and additionally to collect as large an amount of data as possible. The head tracker data were recorded at a frame-rate of 60Hz during each playback, with each frame consisting of the frame count and six numbers representing translational and rotational coordinates. After the two playbacks, the subject could then indicate his/her perception of the attributes with the user interface provided.

### Results and analyses: effects of evaluated attribute

From the captured head movement data, some head-movement parameters were calculated – such as the maximum range of movement, the mean position, and the maximum and mean speed of movement. These were calculated for each of the six degrees of freedom captured. Each calculated value was then considered with respect to the condition of each playback in terms of the subject number, evaluated attribute (type of the judgement task), source signal, run order (the first playback or the repetition), and processing (simulated source location, source width, envelopment, and timbre) using multivariate analysis of variance (MANOVA) tests.

A clear trend across all listeners was found in the dependency of the range of head movement on the type of judgement task. Figure 2 and Figure 3 show the trend in the forward-backward movement range and the azimuthal rotation range as examples. It can be observed that the subjects moved in wider ranges when they were asked to evaluate source width and envelopment, than when asked to evaluate source location and timbre. The results were similar along all the other axes of movement. The timbre judgement showed the smallest amount of movement along all axes.

### Results and analyses: locus of ear positions

From the rotational head movement data, the approximate positions of the ears were derived, assuming the head to be spherical with the ears halfway up the head and diametrically opposite each other. A three-dimensional modal analysis was conducted to determine the range and distribution of ear positions during the listening tests. Only the orientation data in azimuth and roll were used in the analysis, assuming that the head pivots directly around the ear axis. Spherical angular histograms were drawn as the results from all the collected data.

The histogram of the approximate right ear position is shown in Figure 4. The colour at a particular position indicates the sum of the number of frames during which the right ear was within the corresponding area, with a resolution of 5° in azimuth, and 2.5° in roll. The colour scale is logarithmic in order to view the areas with a relatively smaller number of occurrences more clearly. In addition, a threshold of 3% of the peak is applied to exclude the areas of the least occurrences. The nose is effectively half way up the right hand side in the plot.

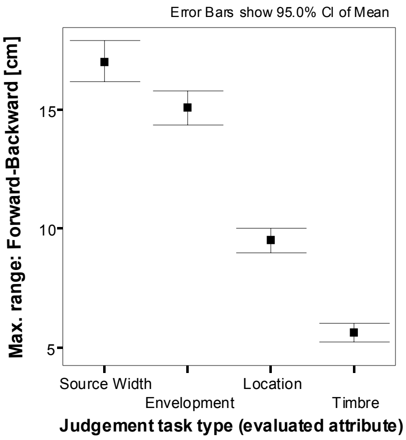



**Figure 2**. Means and associated 95% confidence intervals of the maximum forward-backward head movement range, drawn against the judgement task type. It is seen that the ranges of movement for the evaluation of source width and envelopment are significantly larger than those for localisation task and timbre judgement.

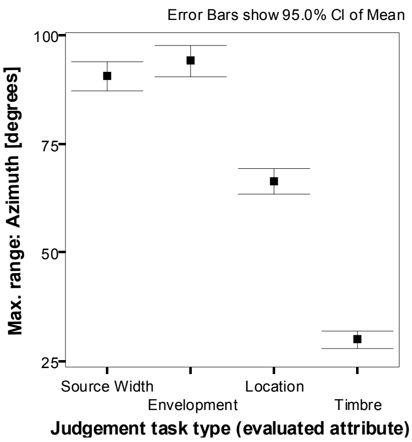



**Figure 3**. Means and associated 95% confidence intervals of the maximum azimuth head rotation range drawn against the judgement task type. It is seen that the difference in the task type resulted in significant difference of the movement range.

## Discussion

The purpose of the experiment introduced in this section was to examine the nature of head movements made when listeners evaluate acoustical attributes including not only source location but also source width, envelopment and timbre, as a preliminary stage of developing a head-movement-aware signal capture system as the first stage of a system to objectively evaluate spatial impression. Firstly, the results from the statistical analyses show that listeners make head movements when evaluating source width and envelopment as well as, and to larger extents than, judging source location. This implies that head movement should be taken into account when developing an objective listening model which mimics human listening behaviour. Secondly, the spherical histogram of Figure 4 shows that the pattern of ear positions does not follow the horizontal plane. Instead, it appears to follow a 'sloped' path which is higher towards the rear and lower towards the front. This is likely to be caused by the limited flexibility of the neck, and implies that rotation solely in azimuth may not be appropriate when designing a binaural capture device incorporating head movement.

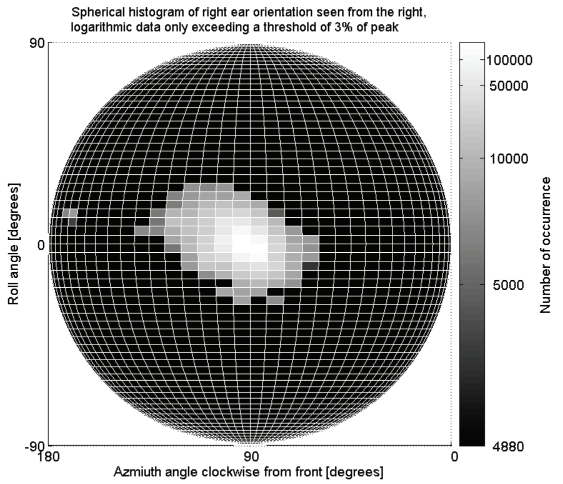



**Figure 4**. Spherical histogram of right ear position corresponding to the head rotation data collected from the experiments. Each grid corresponds to 5° angular distance horizontally, and 2.5° vertically. View from the right hand side of the head (the nose is effectively half way up the right hand side of the sphere). Logarithmic data were used. Only data above a threshold of 3% of the peak are displayed.

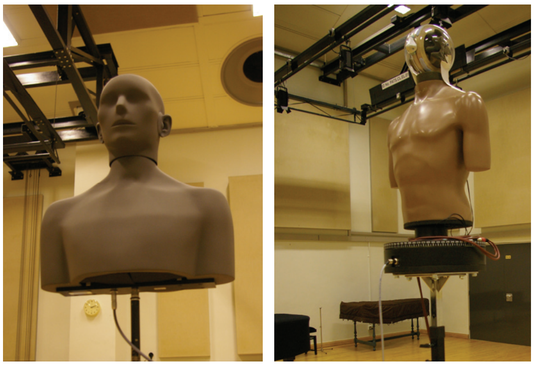
## INVESTIGATION INTO HEAD-MOVEMENT-AWARE SIGNAL CAPTURE TECHNIQUES

This section introduces and compares two signal capture techniques that could be used to take head movement into account when capturing binaural signals.

### Experimental design and procedure

Previous related studies on binaural signal capture techniques incorporating head movement have introduced two approaches in general: using a Head And Torso Simulator (HATS) that rotates, and using a sphere with multiple microphones. The latter has the benefits of shorter measurement time and the capability of time-varying system measurements, potentially at the cost of accuracy due to its simplification of the head shape. An experiment was designed to initially investigate the differences between these two signal capture techniques, particularly those caused by the simplification of the sphere, in the measurements of the spatial-impression-related binaural parameters introduced previously – ITD, ILD and IACC.

The HATS used for the experiment was a Cortex Manikin MK2, with a Microtech Gefell MK231 microphone at each ear, whose dimensions conform to IEC TR 60959 [29]. The sphere model was constructed as a plastic sphere of 17.2cm diameter, which was determined by averaging the sizes of the various head models in previous studies [30, 31]. Two omni-directional microphones (Countryman B3) were placed on the surface of the sphere through small holes, 180 degrees apart from each other. Binaural impulse responses were measured in a quasi-anechoic manner [32] using a loudspeaker and each of the two head models on a rotating table (Outline ET2-ST2). With the loudspeaker at the front facing the centre of the head models, the measurements were made with the head models facing from 0 to 360 degrees azimuth in 2.5-degree intervals. Some variations were made to the sphere model, such as adding a torso, pinnae (each from a KEMAR HATS [31], and/or a nose. This was to investigate the effects of these body parts on the differences of the measured parameters. Figure 5 shows the HATS and an example of the sphere model.



(a) (b)

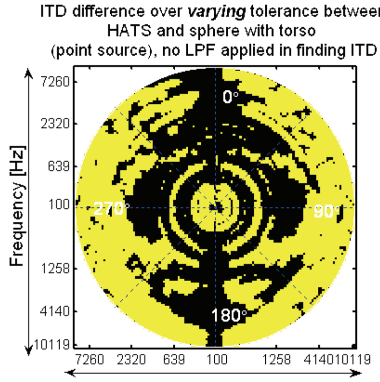
**Figure 5**. Binaural signal capture models used in the experiment. (a) HATS, (b) sphere on a KEMAR torso with a nose.

The binaural signals, from which the ITD, ILD and IACC were derived, were created by convolving one or more of the measured impulse responses with a mono white Gaussian noise signal. Two types of sound sources were simulated this way. Firstly, a point source with varying lateral angle (from 0° to 360° azimuth) with respect to head orientation was simulated for the comparison of ITD, ILD, and IACC. Secondly, a varying number of decorrelated noise sources spanned around the frontal direction (from a single one at 0° azimuth to 18 decorrelated ones spaced 20° apart covering the whole azimuth) was simulated for the comparison of IACC [33].

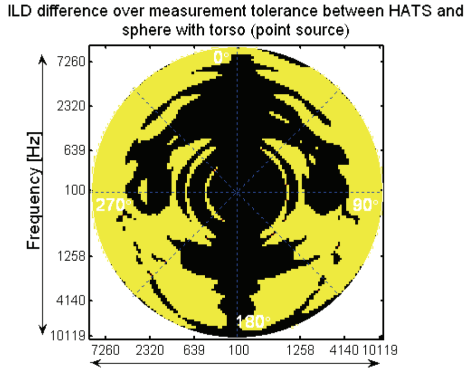
## Results and analyses: differences in measured binaural parameters

From the convolved binaural signals created as above, the ITD, ILD and IACC were calculated for each of the head models. The calculations were made in a number of different frequency bands, by firstly passing the binaural signals through a gammatone filterbank [34]. This was to take account of a previous finding of the dependency of the relationship between IACC and perceived width on frequency [35], and to allow for a more detailed observation of the results. The lower frequency limit was determined by the quasi-anechoic measurement method, and the upper frequency limit by the microphone response of the HATS. The ITD, ILD and IACC differences between the HATS and each configuration of the sphere were calculated in turn. These differences were compared to the corresponding perceptual just noticeable differences (JNDs) as measurement tolerances, so that it could be observed whether the differences would be perceptually noticeable or not. The JNDs to be used for the comparison were determined from a review of a number of previous related studies [36].

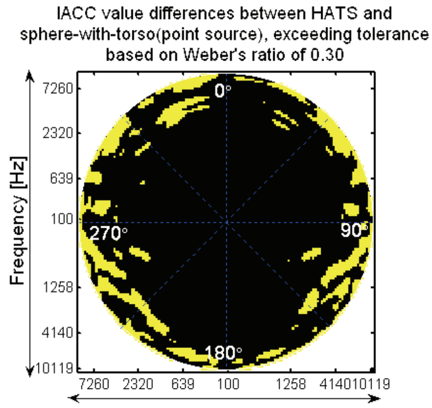
In the case of the point source, it was found that the ITD and ILD differences between the HATS and the sphere, regardless of the variation, were larger than the JNDs for the majority of frequency bands and source directions, except for source directions of around 0° and 180°. However, the IACC difference was found to be smaller than the JND in most cases except for those near the upper frequency limit. The plots of Figure 6 show the results of the configuration which resulted in the closest match to the HATS – when the sphere was mounted on the torso. The radius corresponds to a frequency band (the centre frequency of the gammatone filter) and the angle to the source angle. The bright area inside the disc indicates conditions where the difference exceeds the JND and would therefore be perceivable, and the dark area indicates conditions where the difference is within the JND and would be perceptually negligible.




(a)




(b)




(c)

**Figure 6**. Plots of ITD, ILD and IACC differences exceeding the tolerance determined from their JNDs. The bright area inside the disc indicates that the difference exceeds the measurement tolerance for the corresponding source direction and frequency band, and the dark area indicates that the difference is within the measurement tolerance.

In the case of the spanned decorrelated sources, the IACC difference was found to be mainly below the measurement tolerance, but above the tolerance at certain frequency bands and for certain angular widths of the spanned sources. The difference is perceptually negligible at lower frequencies, and is always negligible below approximately 800Hz, regardless of the variation of the sphere. Figure 7 shows the IACC results plotted against the frequency and the span angles of the farthest point sources. Since the number of decorrelated point sources increased from one by two symmetrically at each step, at 20° intervals, the span angle between the farthest sources increases by 40°. Thus the plot was drawn with the frequency on the horizontal axis and with these discrete span angles on the vertical axis.

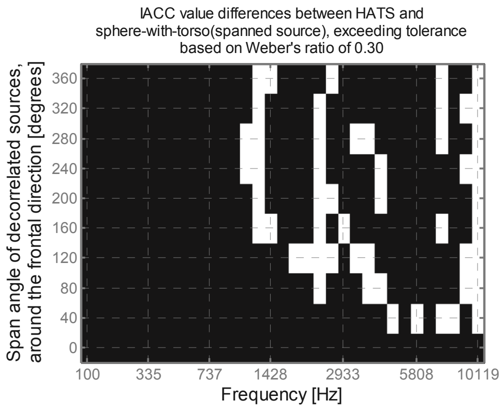



**Figure 7**. Plot of IACC difference for the spanned sources compared to the measurement tolerance determined from the JND. The bright area indicates that the difference exceeds the measurement tolerance, and the dark area indicates that the difference is within the tolerance.

### Results and analyses: look-up table approach to source localisation

From the measured ITD and ILD values for various source directions in azimuth, it is possible to create a database, with which one can find a source direction corresponding to a given ITD and ILD. This follows the look-up table approach used by Supper [37]. Firstly, from the measured ITD and ILD data using the sphere with torso, an ITD and ILD database was created in the form of a look-up table. Secondly, this database was tested using different sets of ITD and ILD values for some intended source directions. These test sets were generated by means of averaging two adjacent values for a single intended source direction. For example, the ITD values for the intended source direction of 2.5° azimuth (for all the introduced frequency bands from 100 to 10119Hz) were created by averaging those measured at 2.5° and at 5°. This way, a test set was created for the intended source directions of -177.5° to 172.5° in intervals of 12.5°, per each of the two parameters (ITD and ILD).

With the ITD and ILD test data for each of the intended source directions, the lookup table was used to predict the direction. Figure 8 shows the results of comparisons of the predicted source directions to the intended ones. It is seen that the prediction is almost always accurate, except for only one case of suspected front-back confusion.

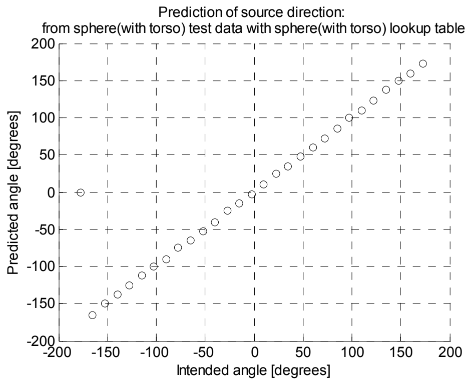



**Figure 8**. Result of horizontal source angle prediction from test ITD and ILD sets using a lookup table created with actual sphere-with-torso measurements.

### Discussion

The purpose of the experiment introduced in this section was to examine the difference between the HATS and the sphere as a potential head-monement-aware binaural signal capture system for the derivation of acoustical parameters related to perceived spatial impression. The results of the binaural parameter comparisons indicate that the sphere can potentially replace the HATS to measure the IACC, particularly at low frequencies. Previous studies on IACC have in fact revealed that IACC values calculated over low frequency ranges are closely related to the perceived source width or envelopment [11, 38, 39], which thus validates the use of the sphere for the prediction of source width or envelopment. The results of ITD and ILD comparisons showed that the differences between the sphere model and the HATS may be perceivable for a majority of the tested ranges of source direction and frequency. However, the accuracy of the source angle prediction using the lookup table indicates that although the sphere might not be able to completely replace the HATS in terms of ITD and ILD measurements, it can still be used, effectively on a torso, for the prediction of source direction. Consequently, the sphere appears to be valid as a binaural signal capture system for overall spatial impression prediction, including source direction.

## INVESTIGATION INTO PARAMETER DERIVATION TECHNIQUES FOR MULTIPLE-MICROPHONE SPHERICAL HEAD MODEL

This section introduces an experiment designed to investigate the detailed processes of deriving ITD, ILD and IACC from the binaural signals that will be captured with multiple microphones over the sphere introduced in the previous section. Specifically, this experiment aims to determine the arrangement of the microphones required for perceptually relevant derivation of the parameters, at any ear position over the locus found from the first experiment set, through direct calculation or interpolation.

### Experimental design and procedure

The experiment was designed such that a range of microphone spacing schemes and ITD, ILD and IACC derivation methods could be tested in terms of the perceptual accuracy of measurements. Comparisons were made between the parameters measured at a pair of microphones and those estimated from the measurements obtained at adjacent microphone pairs. The binaural signals for the measurements were simulated using the quasi-anechoic impulse responses obtained with the sphere in the second experiment. Three source types were simulated by convolving one or more of these binaural impulse responses with white Gaussian noise: single point source at 0° azimuth, two separate point sources positioned at +90° and -90°, and spanned multiple uncorrelated sources, from 0° to all around the head, distributed at 20° intervals on each side. For the first two source types, the measurements were taken for the azimuth head orientation angles from 0° to 357.5° at intervals of 2.5°. In the case of spanned multiple sources, the head was fixed facing 0° azimuth. Four different microphone spacings were introduced, from which the ITD, ILD, and IACC were calculated and interpolated to simulate a single target ear position: ±5°; +7.5° and -5°; ±7.5°; and +12.5° and -10° from the target position. These were chosen based on a review of previous studies related to the spatial sampling theorem and the angular differences of the source direction corresponding to the JNDs [36].

Three types of variations were also introduced and compared in the process of deriving the parameters for comparison. Firstly, two interpolation methods were used to approximate the parameter values or binaural signals at the target microphone positions from those acquired at the adjacent microphone pairs – linear interpolation which has been introduced in [30], and interpolation using the sinc function following the sampling theorem [40]. Secondly, the interpolation was applied at two different stages of the ITD, ILD and IACC derivation: that is, these parameters were calculated from the pairs of binaural signals at the approximating microphone spots separately and then interpolated afterwards to create single values at the target position; or the binaural signals were interpolated into single pair beforehand and then processed to derive ITD, ILD, and IACC. Thirdly, in the ITD calculation, half-wave rectification and low-pass filtering were employed to mimic the breakdown of phase locking in the human auditory system at high frequencies, which causes the loss of temporal details in the audio signals [35] and means that the ITD is determined by the amplitude envelope (rather than the fine detail) of the binaural sound. This processing was applied, and the results were compared to those without it.

The ITD, ILD and IACC values approximated with the microphone spacing schemes described above were compared to those obtained at the target ear positions. The differences between the measured and approximated parameters were calculated and in turn compared to the JNDs, as in the previous experiment. The comparisons were made for each of the variations in the derivation process.

### Results and analyses

Firstly, the clearest overall tendency noticeable in the results was that the larger the spacing between the microphone pair becomes, the worse the approximation becomes. More specifically, increasing the spacing decreased the frequency above which there are substantial errors. Therefore, a trade-off could be made between the frequency range of interest and the appropriate microphone spacing. Secondly, using the sinc function in the interpolation was not found to be beneficial over the linear interpolation, although the former is known to be more accurate in theory. This was due to the limitation of the interpolation to two input values or signals because of the need to minimise the number of microphones in the developed capture model. Thirdly, it was found in general that it was more accurate to interpolate the ITD, ILD and IACC after their calculation from the binaural signals. Although an exception was found for the case of an opposite uncorrelated pair of point sources, this signal type is less likely to result from natural sound fields and hence was considered to be less important to the development of a measurement technique. Lastly, the low-pass filtering of captured binaural signals in the derivation of ITD was found to slightly improve the approximation performance in the case of single point source, though no noticeable improvement was found in the other cases.

### Discussion

The aim of this experiment was to find a practical microphone spacing strategy for the spherical head model, through investigation into perceptually reliable binaural parameter derivation techniques. With the generally optimal measurement conditions applied – i.e., linear interpolation of the binaural parameters after the calculation from the binaural signals, and application of the low-pass filtering process for the ITD derivation – the trade-off between the microphone spacing and the frequency range of perceptually reliable approximation was such that 10° spacing of the microphones would enable perceptually accurate ITD, ILD and IACC measurements under most tested circumstances for frequencies up to about 2kHz. Figures 9 and 10 show some of the measurement results obtained under these circumstances, for varying head orientation in azimuth (indicated as angles clockwise on the plot), and for varying angular source span respectively.

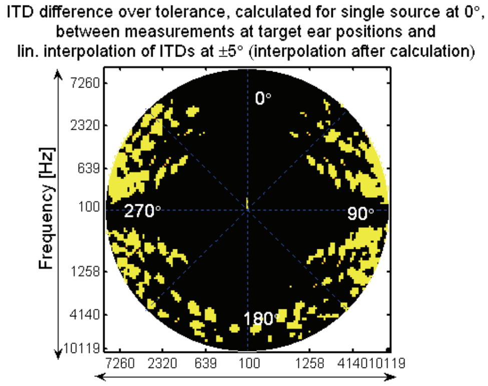



**Figure 9**. ITD difference for single point source, compared to the ITD measurement tolerance, between the measurement at the target ear position with varying head orientation and the one *linearly interpolated* from those calculated at the microphone pairs ±5° apart (*low-pass filtering applied* to binaural signals in finding ITD). The dark areas indicate that the differences are perceptually negligible, and the bright areas indicate that they are not.

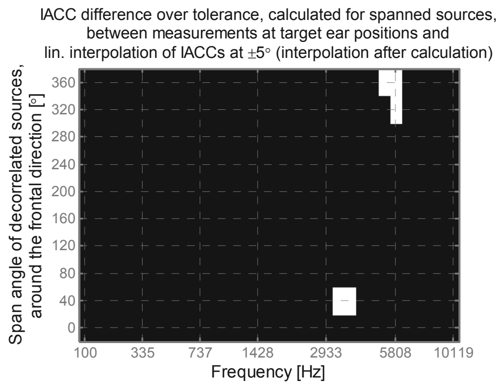



**Figure 10**. IACC difference for multiple uncorrelated sources spanned symmetrically around the listening position, compared to the varying measurement tolerance, between the measurement at the target ear position and the one *linearly interpolated* from those calculated at the adjacent microphone pairs ±5° apart. The dark areas indicate that the differences are perceptually negligible, and the bright areas indicate that they are not.

Following this microphone spacing scheme, the microphone positions were determined for the head-movement-aware signal capture system using the sphere, over the ear locus found in the first experiment set and displayed in Figure 4. Figure 11 shows the suggested layout of microphones, marked with white circles, over the spherical angular histogram showing the right ear traces. Note that the ear position for 0° head orientation is at 0° roll and ±90° azimuth on the sphere and that microphone spots need to have 1-dimensional symmetry about this point. This is because when a right ear spot is selected, the corresponding left ear spot also has to be selected symmetrically on the opposite side. The number of microphones required is 21 per side of head.

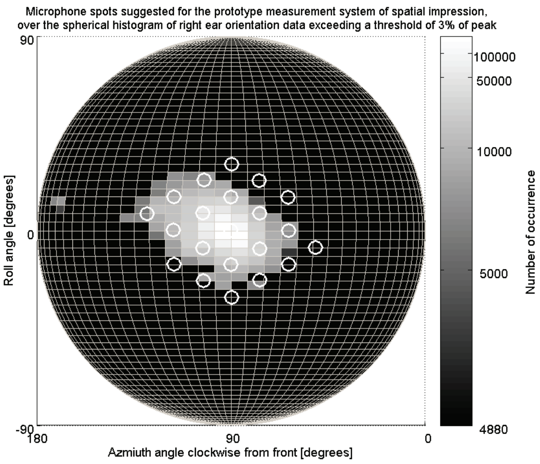



**Figure 11**. Suggested layout of microphones for the prototype measurement model of spatial impression incorporating head movements, drawn over the spherical histogram of right ear orientation exceeding 3% of peak seen from right. The white circular marks indicate the suggested microphone spots. The small outstanding spot to the rear was excluded due to practicality and the small number of occurrences.

## SUMMARY AND CONCLUSION

This research focused on investigating the nature of head movement in the perception of spatial impression and on incorporating this into a system for measuring, in a perceptually accurate and appropriate manner, the acoustic parameters which contribute to spatial impression – ITD, ILD and IACC

A subjective test was conducted where the listeners were asked to evaluate the source width and envelopment aspects of spatial impression, as well as the source direction and timbre, of a range of stimuli, with their head movements tracked and recorded. It was found that the amount of head movement was larger when evaluating source width and envelopment than when evaluating direction and timbre. In addition, the range of positions of each ear was found to form a bounded sloped area, higher to the rear and lower to the front.

These findings led to the evaluation of binaural signal capture and measurement techniques - using a sphere with multiple microphone pairs, and using a rotating HATS. Initial performance comparisons were made between the two, measuring the ITD, ILD and IACC of simulated sound sources varying in direction, width and envelopment. The results revealed that differences in ITD and ILD were not perceptually negligible, but that differences in IACC were. It was shown, however, that the sphere-and-torso measurements can be valid for the prediction of source direction through a look-up table approach, as well as for the prediction of source width or envelopment by means of IACC.

Further tests with the sphere-and-torso revealed that, through an appropriate interpolation and calculation technique, reliable derivation of ITD, ILD and IACC for any given head position was possible if the microphones were spaced at intervals of approximately 10 degrees. It was shown that a prototype signal capture system with 21 omnidirectional microphones on each side of the sphere, placed over the sloped ear coverage area, enabled perceptually accurate interpolated ITD, ILD and IACC measurements for frequencies up to approximately 2kHz.

## ACKNOWLEDGEMENT

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