Introduction

The Literature Review concluded by summarising the importance of inter-aural time differences (ITDs), inter-aural level differences (ILDs) and the head related transfer function (HRTF), all of which play an important part in auditory hearing. (Gasson, 2014). What makes binaural recording interesting and a possible contender for 3D sound, is that it encompasses and embeds these principles (ITDs, ILDs and HRTF) in its design. (Gasson, 2014). The Case Study therefore sets out to test and analyse the effectiveness of binaural recording with regards to 3D sound, against traditional stereo microphone technique. This will be achieved by conducting a sound localisation experiment, in which participants will be asked to localise a series of sounds recorded both in stereo and binaural. The most accurate localisation results will thus reflect the ability of the contested microphones to deliver.

Feeling engaged in the subject and a certain confidence in the ability of binaural recording to deliver, I have successfully sought sponsorship and 3Dio (2016) have donated a Free Space XLR Microphone (retailing at $799) for research purposes, in return for producing a video of the sound experiment for their website.

Figure 1. *Free Space XLR Microphone*. (3Dio, 2016).

In order for the methodology of the sound experiment to be valid, the Case Study will begin by looking at comparative studies, in which similar experiments will be analysed and studied for appropriate content. Following this, and with sufficient justification and supporting evidence, will be an outline of the proposed methodology of the sound experiment. The Case Study will conclude by a discussion of the results, as well as further areas of study a reader may find useful.

Case Study

Chapter 6 Comparative Studies

Batteau’s Experiment.

Chapter 7 Case Study Results

How do binaural and stereo compare in sound localisation ?

Chapter 8 Conclusion

What do the results mean ?

Further Reading

Useful Avenues to explore

Chapter 6 Comparative Studies

An investigation into comparative studies, revealed some underlining common threads, the most frequent being perhaps the use of white / pink / gaussian noise as a sound source in auditory experiments. The advantage of using noise, according to Mattes (2016, p10), appears to be its neutrality in the perceptual experience of the subject.

‘A familiar type of sound stimulus, such as the human voice, can result in an enhanced attentive perceptual experience compared to other types of sound stimuli, such as white noise which are very common in laboratory experiments. In that case it is apparent how knowledge can affect the perceptual experience of the subject and as a consequence the reaction to the stimulus.’ . Mattes (2016, p10)

Categories of Noise

Both pink and white noise contain frequencies spanning 20Hz to 20kHz, which correlates with the audible range of human hearing. (Castro, 2013). The difference between pink and white noise lays in the way energy is distributed. Whereas white noise has ‘*equal power per hertz throughout all frequencies*’, pink noise ‘*has equal power per octave*’. (Castro, 2013). Figure 2 demonstrates the effectiveness of pink noise in sound localisation, in which participants had to pinpoint which speakers were turned on in a room. The highest accuracy was achieved in cases whereby pink noise was utilised. (Pulkki, 2016, p37). Pink noise will be a feature of the case study’s experiment.

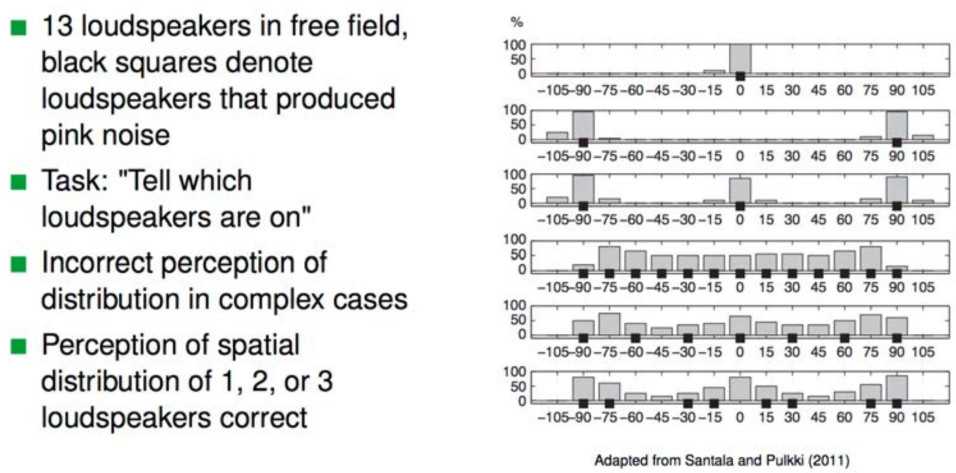

Figure 2. Accuracy of perception of spatial distribution of sources. (Pulkki, 2016, p37).

Duration of Noise

In general, research demonstrates that when noise is used as a sonic stimulus, its duration is usually shorter in comparison to the use of acoustic or real world sounds. Comparative studies reveal broadly speaking, that when the duration of a stimulus is reduced, more errors in accuracy become apparent. Specific case examples are discussed below.

Lower Bounds 3ms - 80ms

Comparative studies show that the duration of noise presented to a listener can be as low as 3ms-80ms. In using '*noise bursts*', Hofman and van Opstal concluded from their research that the '*human auditory system needs 80 ms of broadband noise to estimate the elevation of a sound source.*' (Paukner, Rothbucher and Diepold. 2014, p29). Elevation, as noted in the Literature Review, refers to the vertical plane of a listener. What is interesting about the findings of Hofman and van Opstal, is that although hearing a sound in the elevation plane requires a minimal stimulus of 80ms, hearing on the azimuth (horizontal) plane remained unchanged, regardless of the noise's duration presented.

Middle Bounds 100ms - 500ms

A great number of research experiments appear to use noise presented in the region of 100ms - 500ms. This is supported by the comparative studies made by Balan et al., (2014, p5), in which various auditory experiments are presented in table format. 500ms will be duration of pink noise used in the case study's experiment.

Upper Bounds 1000ms - 2000ms

Longer durations of noise appear to be justified when head tracking equipment is used by participants. (Paukner, Rothbucher and Diepold, 2014, p56). Head tracking in 3D sound experiments has a significant impact on front / back ambiguity with regards to increasing the accuracy of results. (Paukner, Rothbucher and Diepold, 2014, p29).

Noise Bandwidth

Carlile, (2016, p16) states that as the bandwidth of a sound source is restricted, an increase in the number of localisation errors becomes evident. Sound localisation experiments in which bandwidth is considered a critical variable, appear to use varying ranges with differing centre points, in which the octave is more often than not, a feature. For example Yosta and Zhong (2014), in investigating the influence of bandwidth, used a range of 1/20 to 2 octaves wide with a centre frequency of 250, 2000 and 4000Hz. Sound localisations experiments with a bandwidth greater than 2 octaves can be found in the comparative study made by Balan et al., (2014, p6), in which the original researchers, Susnik R., Sodnik J. and Tomazic S used white noise filtered at 350-2000Hz, 350-8000Hz and 2-8kKz.

The bandwidth of pink noise presented to subjects in the case study, will be organised as so to be an approximation of frequency bands which reflect those used by the auditory aids of ITDs / ILDs. This was achieved by referencing the guideline frequencies published by Oculus (2016), using a 2000 Hz high pass for the ILD, 800Hz to 1600Hz as the transitional zone between the two, 200 Hz low pass for the bass and full bandwidth pink noise to determine the hearing range.

Co-ordinates of Sound Source

Comparative studies reveal that in certain cases of sound localisation experiments, a number of speakers are used in free field across the perimeter of a room, with either a microphone or participant in the centre of the room. For example, in the case study of Batteau, which is referenced by Gerzon (1975, p3), 16 loudspeakers are set up in circular fashion around a pair of microphones approximately ear distance apart. Both microphones were omni, with one set having a replicated pinnae - so arguably very similar to binaural microphones. The output of the microphones were sent to a subject in a separate room via headphones, who was then asked where the sounds were originating from. (Gerzon, 1975, p3).

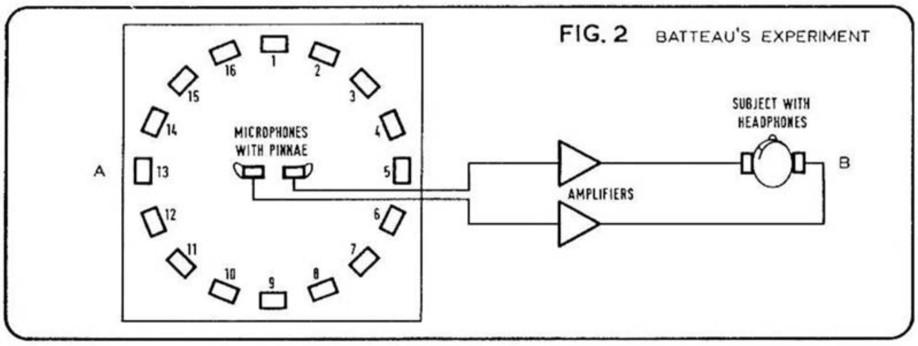

Figure 3. *Batteau's Experiment*. (Gerzon, 1975).

What is interesting about Batteau's experiment, is that the results show more accuracy when the pinnae fitted microphones were used, with no confusion between front or back localisation. (Gerzon, 1975, p3). However, results for the standard microphone, according to Gerzon (1975, p3) revealed - '*When no pinnae were used, the subjects found it difficult to localise the sounds, assigning them to more-or-less random positions*.'

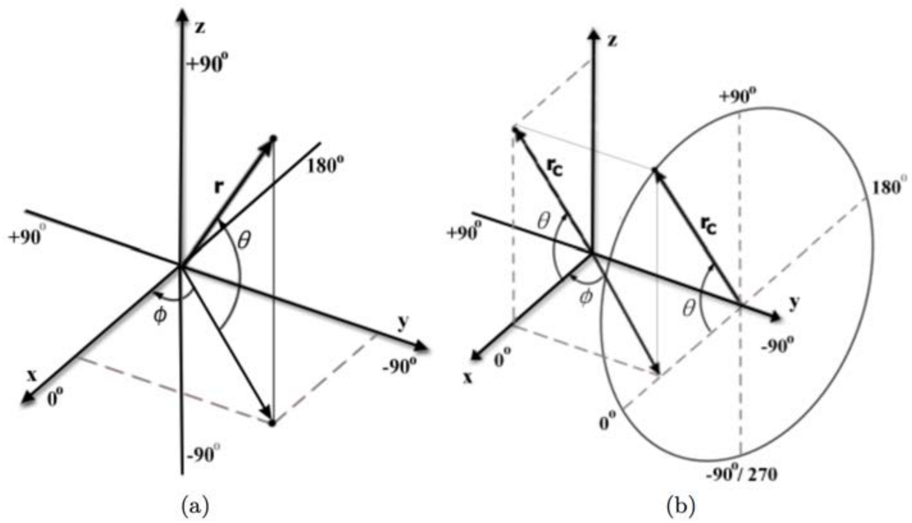

Figure 4. *Azimuth and elevation co-ordinates system*. (Mattes, 2016, p16).

Comparative studies show how a number of different azimuth and elevation combinations have been used in previous research. A common approach for azimuth, appears to be based on or derived from the speaker arrangement in Figure 3, in which speakers are arranged in a circular fashion around either a listener or microphone. This approach was also used by Jørgensen and Pedersen (n.d.), who used 16 speakers based on the co-ordinates -

- Azimuth: 0o, 24o, 72o, 120o, 168o, 216o, 264o, 312o
- Elevation: -90o, -66o, -44o, -22o, 0o, 22o, 44o, 66o, 90o

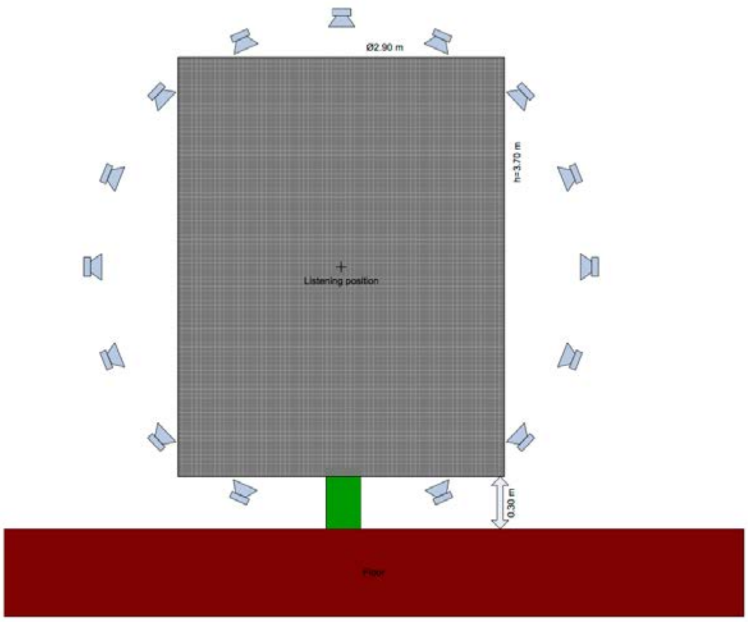

Figure 5. Speaker arrangement for the sound localisation experiment of Jørgensen and Pedersen (n.d.)

Musical Instruments in Sound Experiments

Whilst using noise appears to be arguably the norm in sound localisation experiments, little seems available regarding musical instruments. Incidentally, one of the few cases that has used musical instruments, which has also compared stereo and binaural, resulted in favour of stereo. (Hiipakka, Lorho and Marila, 2001).

The research, which included ‘*melody excerpts of two seconds’* (Hiipakka, Lorho and Marila, p3, 2001.) played by midi generated musical instruments, concludes by stating that, in being able to distinguish ‘*spatial discrimination*’ between 5 positions in reliable form, both stereo and HRTF prove effective. (Hiipakka, Lorho and Marila, p5, 2001.) However, stereo contained the ‘*surprising result*’ of being higher in ‘*performance and in preference*’. (Hiipakka, Lorho and Marila, p6, 2001.)

Evidently, this poses some threat, when considering and planning an experiment of similar variables - to what extent and justification can I expect my results to be different from Hiipakka, Lorho and Marila's ?. (2001).

Methodology Summary

As a first point of contrast to the research of Hiipakka, Lorho and Marila (2001), the way in which I use stereo will differ. Rather than using stereo samples which have been placed artificially by '*amplitude panning*' (Hiipakka, Lorho and Marila, p3, 2001.), the stereo samples used in the experiment will have their panning determined by a live recording played through a mono speaker.

Changes in phase, as a result of one sound arriving at the distant microphone mili seconds later than the first is, in effect, as the literature review demonstrated, an inter-aural time delay and one used by the human auditory system to hear low to approximately 1000Hz frequencies. As well as using phase to help give an indication or localisation of a sound, stereo recording can also be configured to demonstrate inter-aural level differences., responsible for the aural recognition of high frequencies.

Consider again the research of Gerzon, in which his work demonstrates stereo omni microphones measured to an approximate distance of a persons head. From the research of the literature review, it can be argued in figure 6, the sound coming from speaker 13, will arrive slightly quieter to the right ear due to the sounds being masked by the head.

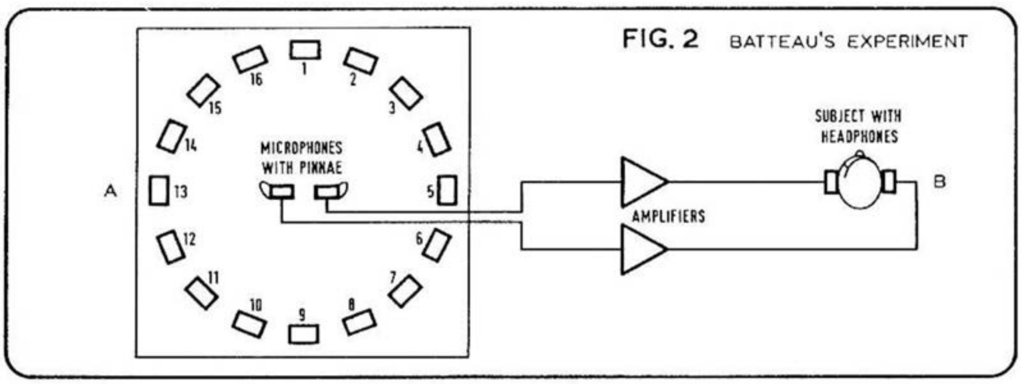

Figure 6. *Batteau's Experiment*. (Gerzon, 1975).

So if both ITDs and ILDs can be recorded in the manner that binaural seeks to emulate, this is surely a strong case for stereo ? In order to make the experiment fair, I will record using 2 stereo microphones, 7 inches apart, set in the same position as Batteau (Gerzon, 1975.) with the intention of comparing binaural and stereo, on what is arguably, their common grounds.

Not having the luxury of 16 speakers, but still strongly in favour and support of the technique used by Batteau, (Gerzon, 1975, p3), I decided to use a mono speaker, which was moved accordingly to specific co-ordinates in the room. Samples were then played through the speaker and captured by either the 414 (in figure of 8 mode) or the binaural microphone, which were both placed in the middle of the room, much in the same manner as '*Batteau's Experiment*' (Gerzon, 1975).

In addition to using musical samples and to make the experiment fair, I've decided to use pink noise in this experiment. Having grown familiar with the samples through much time and effort spent in recording and editing them, there does appear to be a bias towards binaural when noise is used. This does at least, cover some of the initial threat that Hiipakka, Lorho and Marila (2001) posed, when considering their rather negative results for binaural, when musical instruments were presented. I am satisfied that presenting both noise and musical samples ensures a balanced approach, with each demonstrating their own unique values strengths, and possible weaknesses.

Room Dimensions

Measuring the room, the approximate values were made -

Width = 21 ft
Length = 21 ft
Height = 7 ft

The centre, or midpoint of the room was calculated by masking the diagonals of the room with tape. Where the two lines intersected marked the centre and thus gave a starting point to work from. (Math Open Reference, 2011)

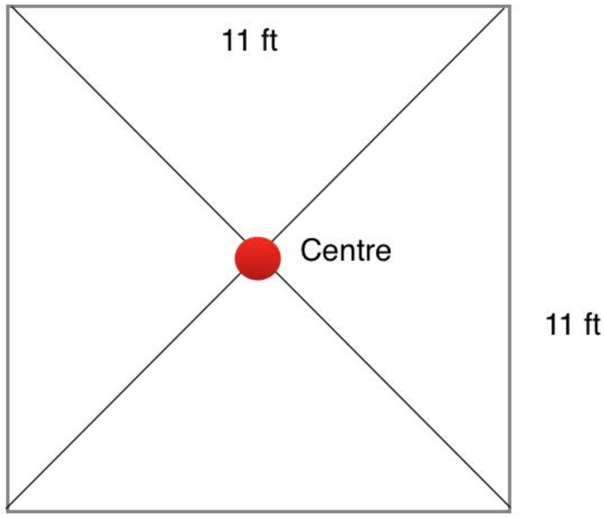

Figure 7. Finding the mid point of a room, by tracing the diagonals.

Figure 8. Preparation for the experiment.

In figure 8, the reader will note that the other lines added to the diagonals, form 0, 45, 90, 135, 180, 225, 270 and 315 degrees. Of particular interest, prompted by the comparative studies, are the angles such as 0 or 180 degrees in which confusion is common. (Oculus, 2016).

The height of the microphones was set at 4 ft high, which was a measurement derived from an approximate, average person's height in seating position. The decision not to use both microphones at the same time, even though that would have been much less time consuming in editing, was based on a commitment to keep the test fair and ultimately re-usable should another person want to evaluate the test for themselves at a later date.

The consequences of the second microphone being in the same physical space as its competitor, would have likely negatively affected the sound as some of its signal would have been masked. For example, if there were a pair of binaural and omni microphones positioned left and right respectively, as in figure 9, a sound coming from a 90 degree angle would arrive first at the right stereo pair microphone, then to its left, then arriving at the right of the binaural microphone, before finally reaching the left binaural microphone at a much lower amplitude. Such an obstruction was considered an unfair outcome, so both binaural and stereo were recorded separately.

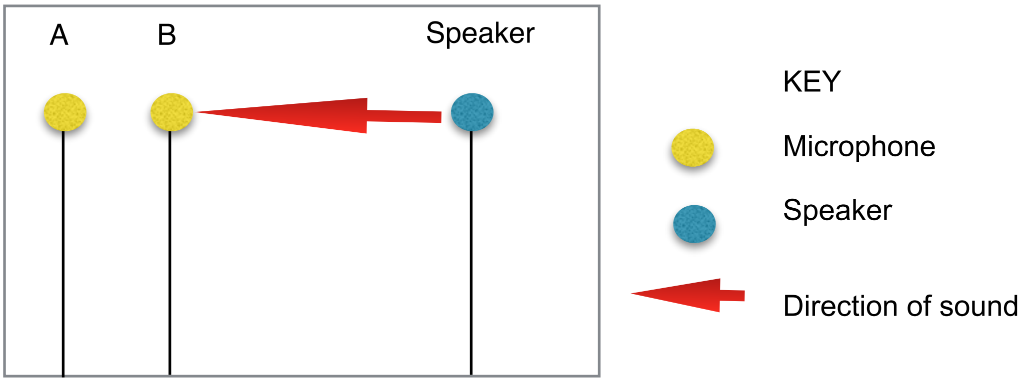

Figure 9. Microphone B would arguably mask a proportion of the sound arriving at A.

The speaker as well as being placed at 4ft in height, (0 degrees elevation or level to the microphone) and including 4.5ft and 9ft locations from the mid point of the room, was also recorded at floor level, again 4.5ft and 9ft from the centre. These measurements are illustrated in figures 10 - 13.

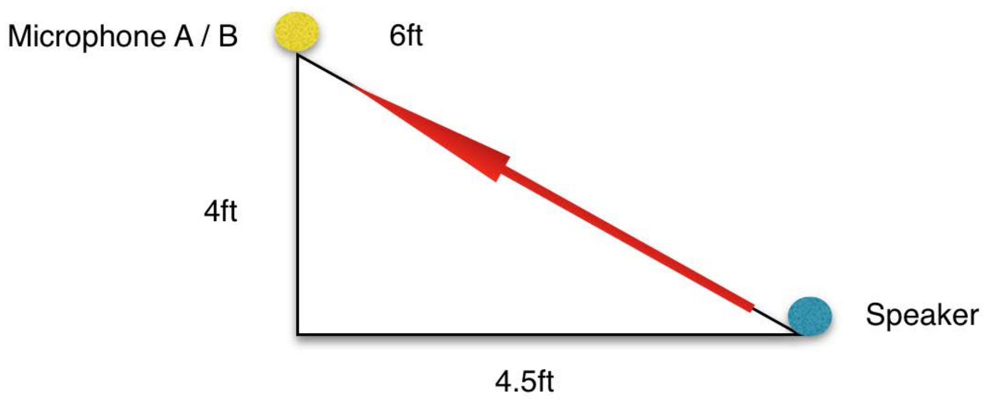

Figure 10. Microphone A / B, close position (4.5ft) with negative elevation (the angle formed from microphone towards speaker) of -48 degrees.

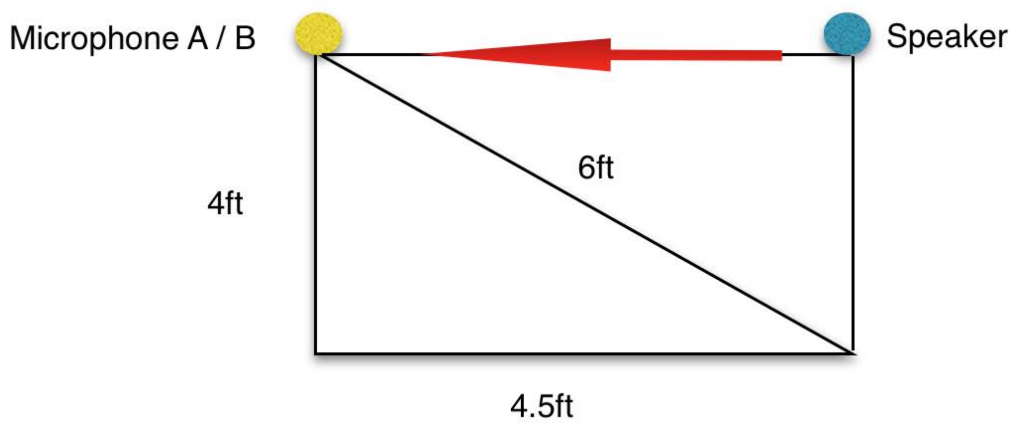

Figure 11. Microphone A / B, close position (4.5ft) with 0 degrees elevation

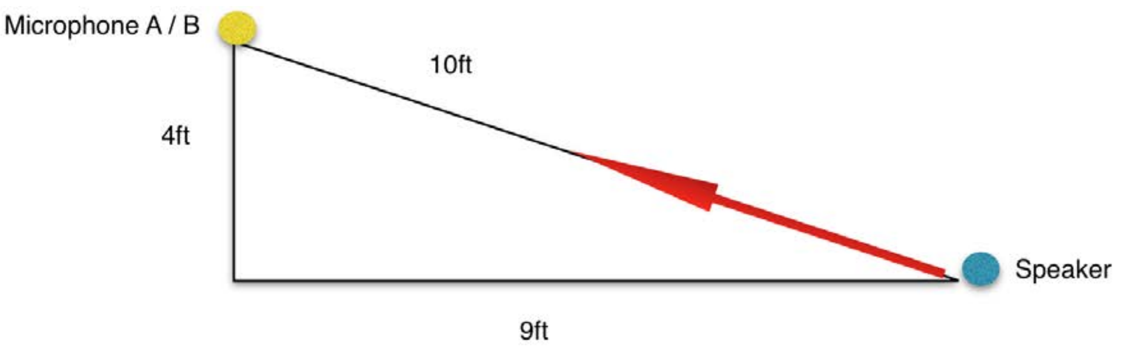

Figure 12. Microphone A / B, far position (9ft) with - 66 degrees elevation

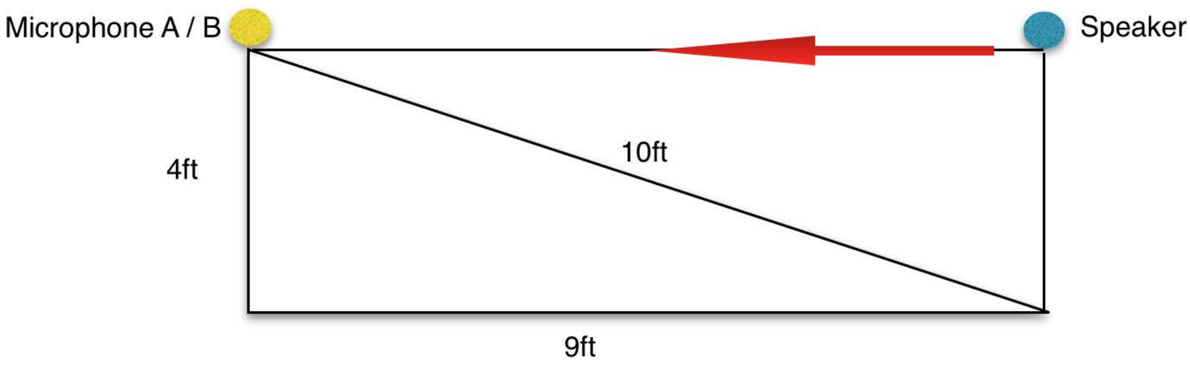

Figure 13. Microphone A / B, far position (9ft) with 0 degrees elevation

Elevation angles rounded to 2 significant figures, and the hypotenuse (the longer side of the triangle), were made using an online calculator, provided by the website, Math Portal, (n.d.).

Audio Samples

The musical samples were taken from a '*Freshtone*' audio sample CD (Sound on Sound, 2011) and consisted of 3 second and 7 second lengths in time. The samples were chosen because of the frequency space each instrument expressed, with the bass, guitar and organ all in different octaves and drums spanning the entire spectrum.

This approach was emulated in preparing the pink noise samples, which were 0.5 seconds in length. A low pass, mid pass and high pass filter were used to mirror the frequency bandwidth posed by the musical samples, as well as noise being unfiltered with no EQ, in order to hear its possible effects on sound localisation.

The experiment will be developed much in the way of Hiipakka, Lorho and Marila (2001), in the sense of a progressive difficulty in the tests questions.

As the test develops, participants will be expected to localise the sound with no prompts being made. The reason why no prompts or multiple choice questions exist for noise, as a category in this experiment, is its known favourable ability to be localised, which can be backed up by previous research of Pulkki (2016, p37).

Participants in the experiment will be given a visual chart (figure 14), which covers the 8 azimuth positions that the sounds will originate from. These co-ordinates are 0, 45, 90, 135, 180, 225, 270 and 315 degrees. For the sake of simplicity, questions regarding elevation will be presented to participants as option (1) - the sound coming from head level, or option (2) the sound is coming from the floor.

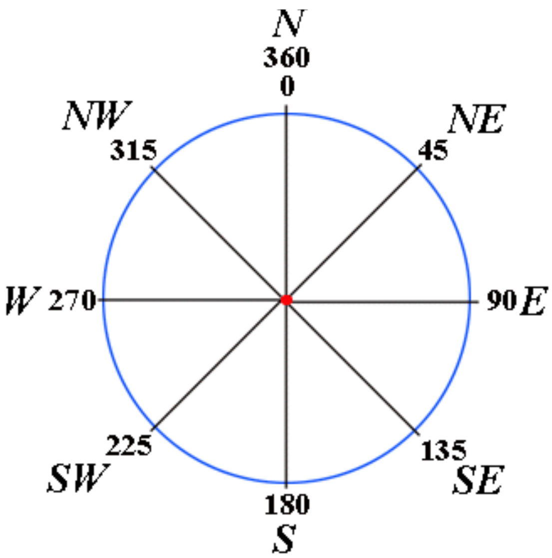

Figure 14. Visual aid given to participants in the experiment. Original image from Leveson, 2000.

Chapter 7 Case Study Results

Stereo vs Binaural Results - Overview

Overall, and as expected, participants who performed with the most accurate results, did so with the recordings made by the binaural microphone. However, despite being up to 30 % more accurate than stereo when music stimuli was used, (Figure16) and up to nearly 80% more accurate when noise stimuli was presented to subjects (Figure 17), binaural's overall performance in Stages 1 - 5 (music stimuli) at 36 % and 39 % in Stage 6 (pink noise stimuli) , reveal binaural has areas which need to be addressed and improved. (Figures 18 & 19). Whilst the arguably improved performance over stereo is important and was indeed the hypothesis of this paper, an analysis of the results broken down into various categories, may be useful in determining a more balanced view of the overall picture.

The test was conducted on 11 participants, categorised as A to K. Age ranged from 16 years (the youngest) to 55 being the eldest. (Figure 16). One participant (K) asked to remain anonymous with regards to age and name.

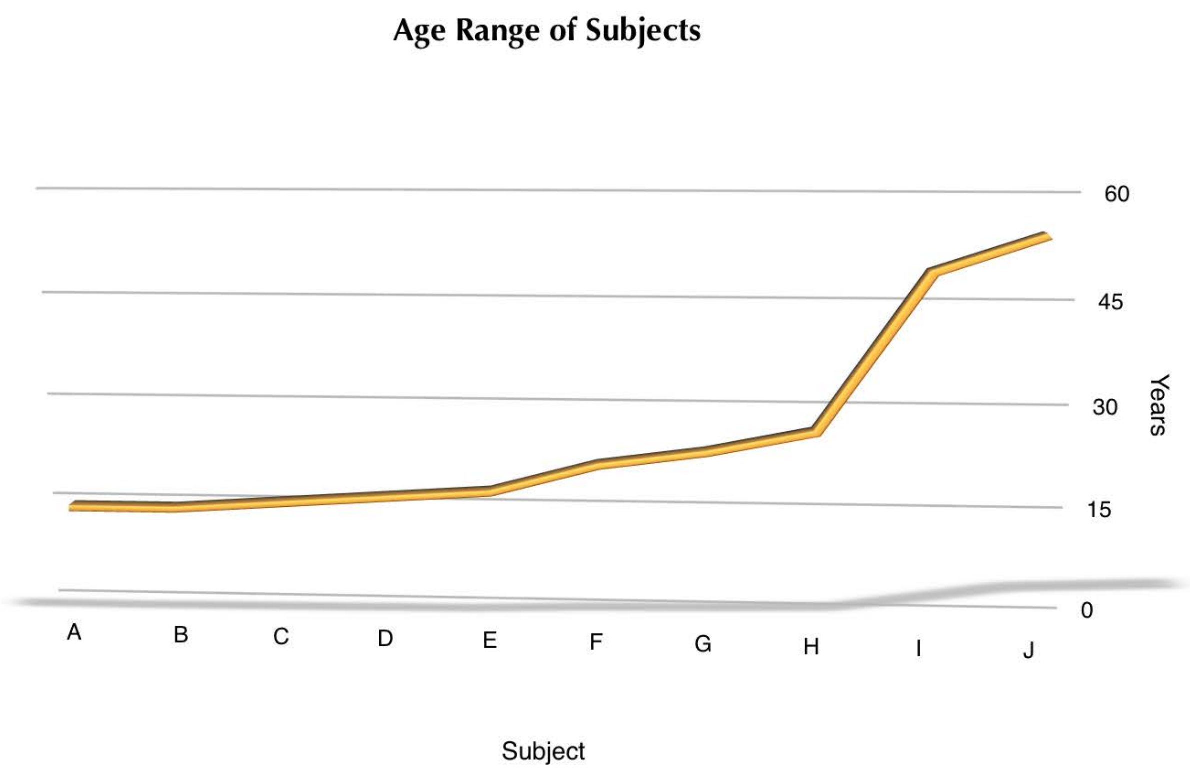

Figure 15. Age Range of Subjects in Sound Localisation Test. None disclosure for Subject K.

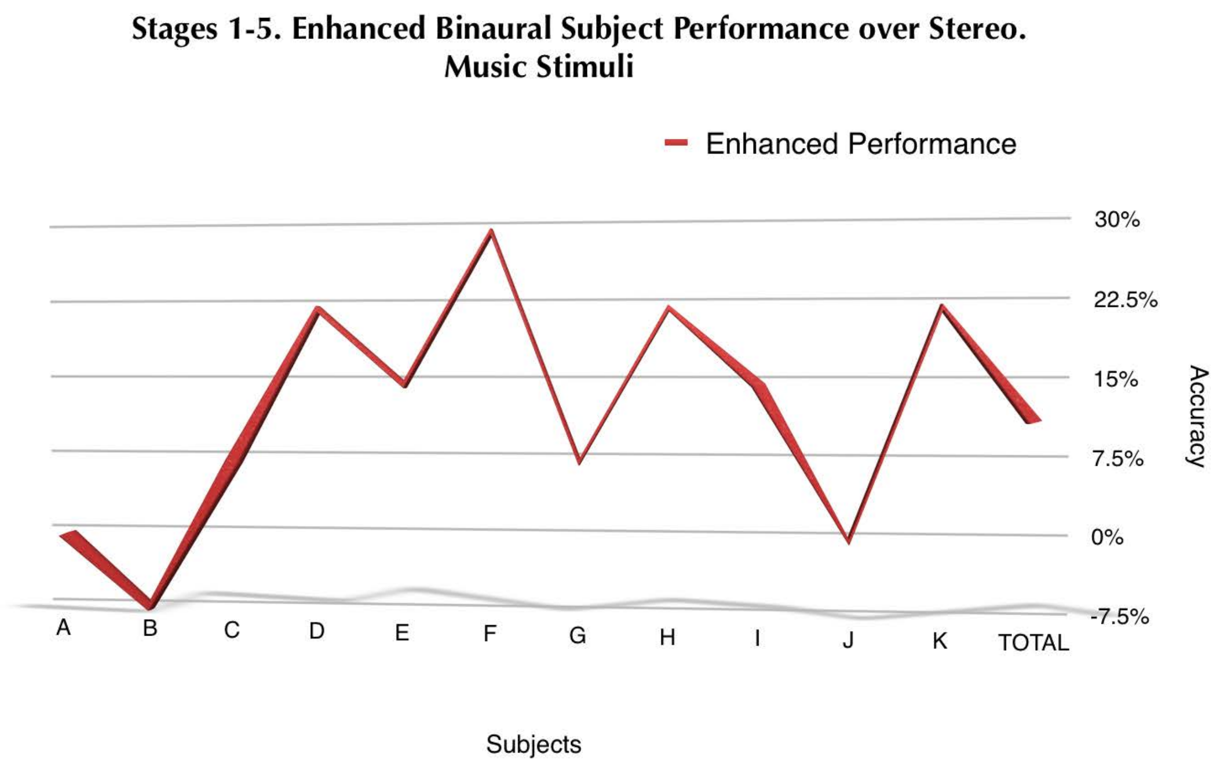

Figure 16. Performance Enhancement Chart for subjects accurately localising music samples.

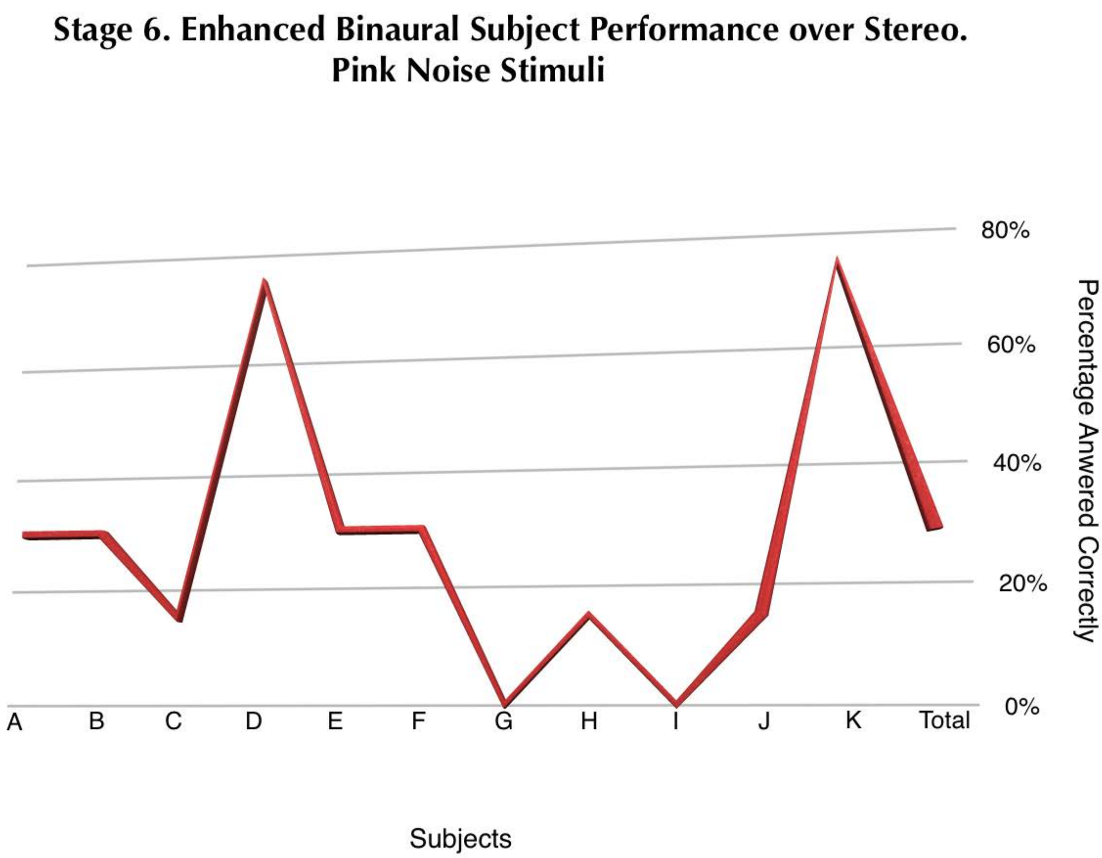

Figure 17. Performance Enhancement Chart for subjects accurately localising music samples.

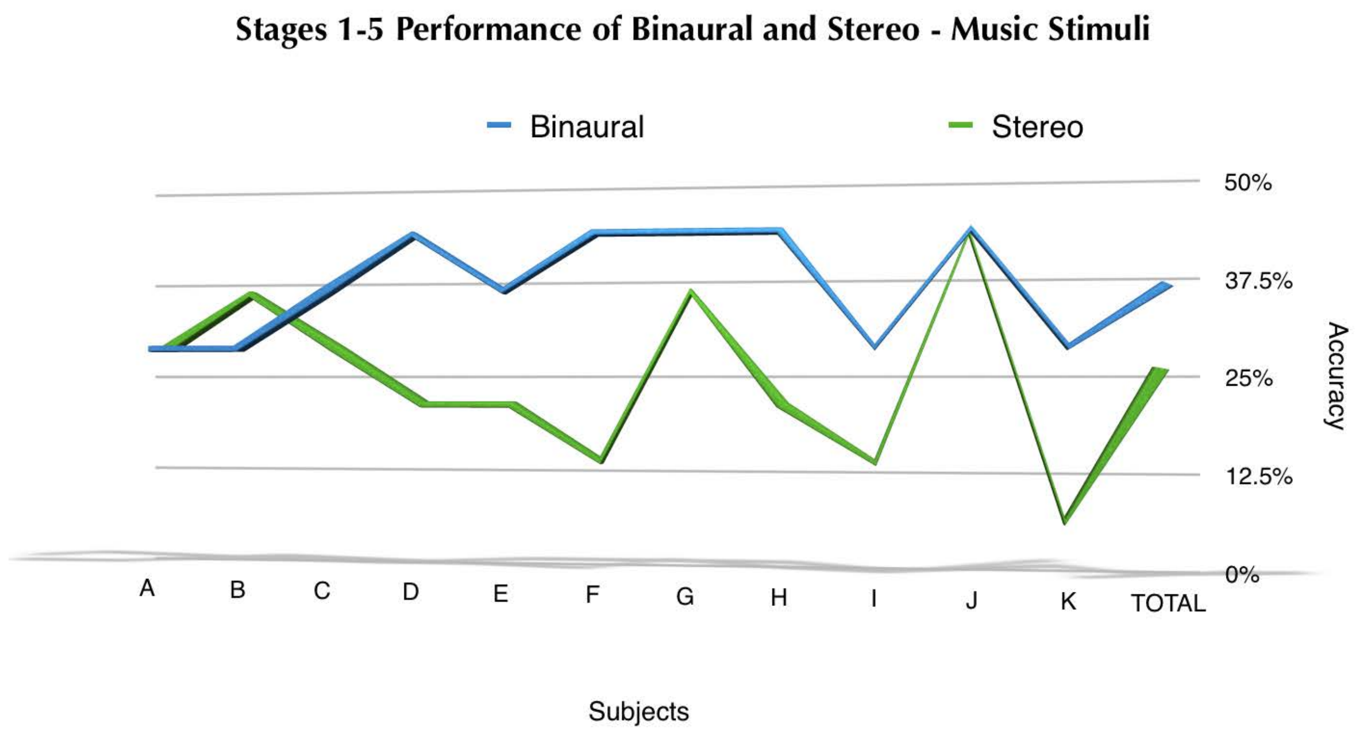

Figure 18. Performance comparison of Binaural and Stereo. Subjects presented with music stimuli.

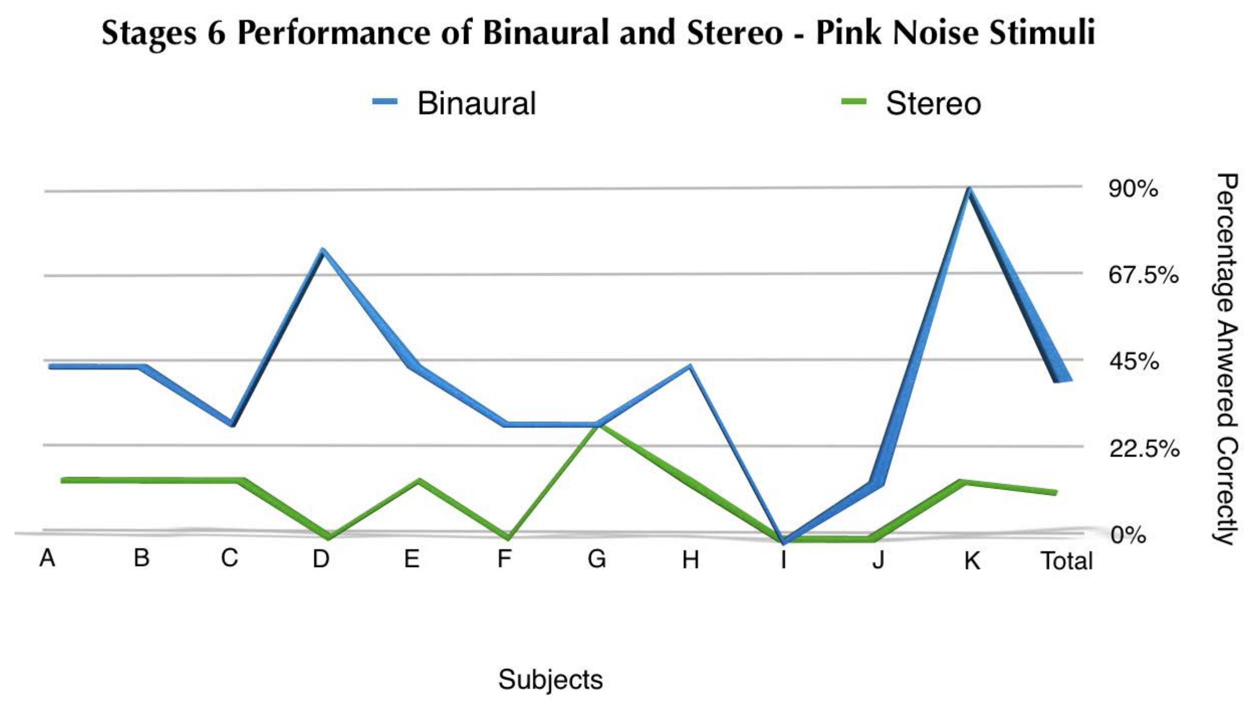

Figure 19. Performance comparison of Binaural and Stereo. Subjects presented with pink noise stimuli.

Stereo vs Binaural Results

Stage 1

In Stage 1 subjects were asked to state the correct elevation of the musical samples presented to them. The 2 questions were in multiple choice format, prompting the subjects to choose between ‘floor level’ or ‘ head height’ with regards to the apparent localisation of the sound in relation to themselves. Instruments presented to participants included guitar and drums, with both samples having the duration of 7 seconds. The results for Stage 1 reveal an equality of 41 % accuracy for both stereo and binaural. Subjects were more accurate in both binaural and stereo, when close microphones were used.

Binaural	**Elevation**	**Azimuth**	**Far / Close**	**Instrument**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	TOTAL MARKS	TOTAL PERCENT
STAGE 1																	
Practise Question																	
Question 1 Head height or floor ?	0 Degrees	45 Degrees	Far.	Guitar	0	0	1	0	1	0	1	1	0	0	0	4 Points	36%
Question 2 Head height or floor ?	0 Degrees	180 Degrees	Close.	Drums	0	0	1	1	1	1	0	0	0	1	0	5 Points	45%
Stage 1 Total					0	0	2	1	2	1	1	1	0	1	0	9 Points / 22 Points	41%

Figure 20. Stage 1 Results. Binaural.

Stereo	**Elevation**	**Azimuth**	**Far / Close**	**Instrument**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**Stereo**	
STAGE 1																TOTAL MARKS	TOTAL PERCENTAGE
Practise Question																	
Question 1 Head height or floor ?	- 66 Degrees	45 Degrees	Far.	Guitar	0	0	0	1	1	0	1	1	0	0	0	4 Points	36%
Question 2 Head height or floor ?	- 45 Degrees	180 Degrees	Close.	Drums	0	0	1	1	1	1	0	0	0	1	0	5 Points	45%
Stage 1 Total					0	0	1	2	2	1	1	1	0	1	0	9 Points out of 22	41%

Figure 21. Stage 1 Results.Stereo

Stereo vs Binaural Results

Stage 2

In Stage 2 subjects were asked to state the correct azimuth of the musical samples presented to them. The 4 questions were in multiple choice format, prompting the subjects to choose between a bass in either 0 - 180 degrees, a guitar in 45 - 90 degrees, drums in 135 - 315 degrees and a guitar in 225 - 270 degrees. All samples were 3 seconds long in duration, presented at 0 degrees elevation and were recorded in close microphone position. (4.5ft).

The results for Stage 2 reveal a bias towards binaural performance, with binaural leading with 50 % accuracy for the overall stage, compared to 39 % stereo.

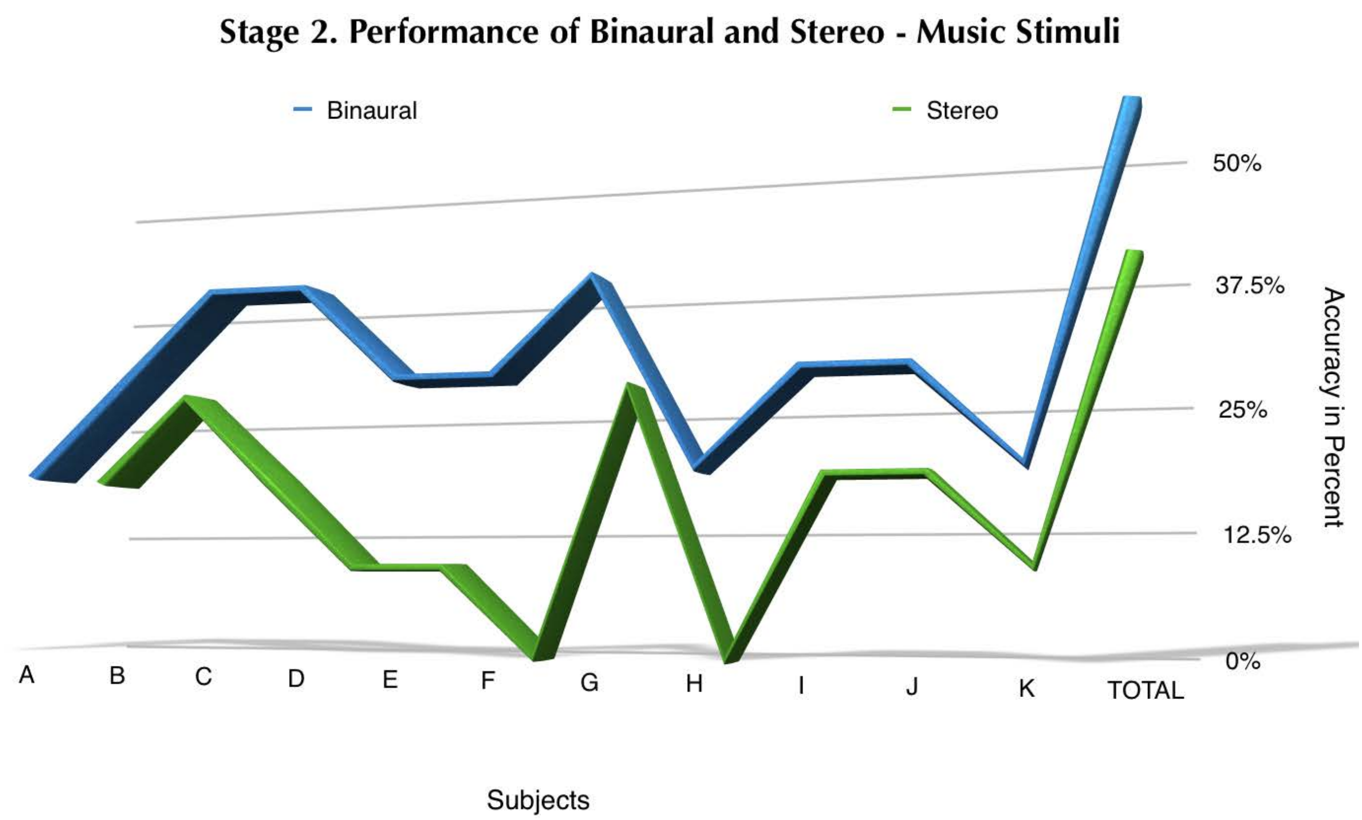

Figure 22. Results Stage 2. Stereo vs Binaural

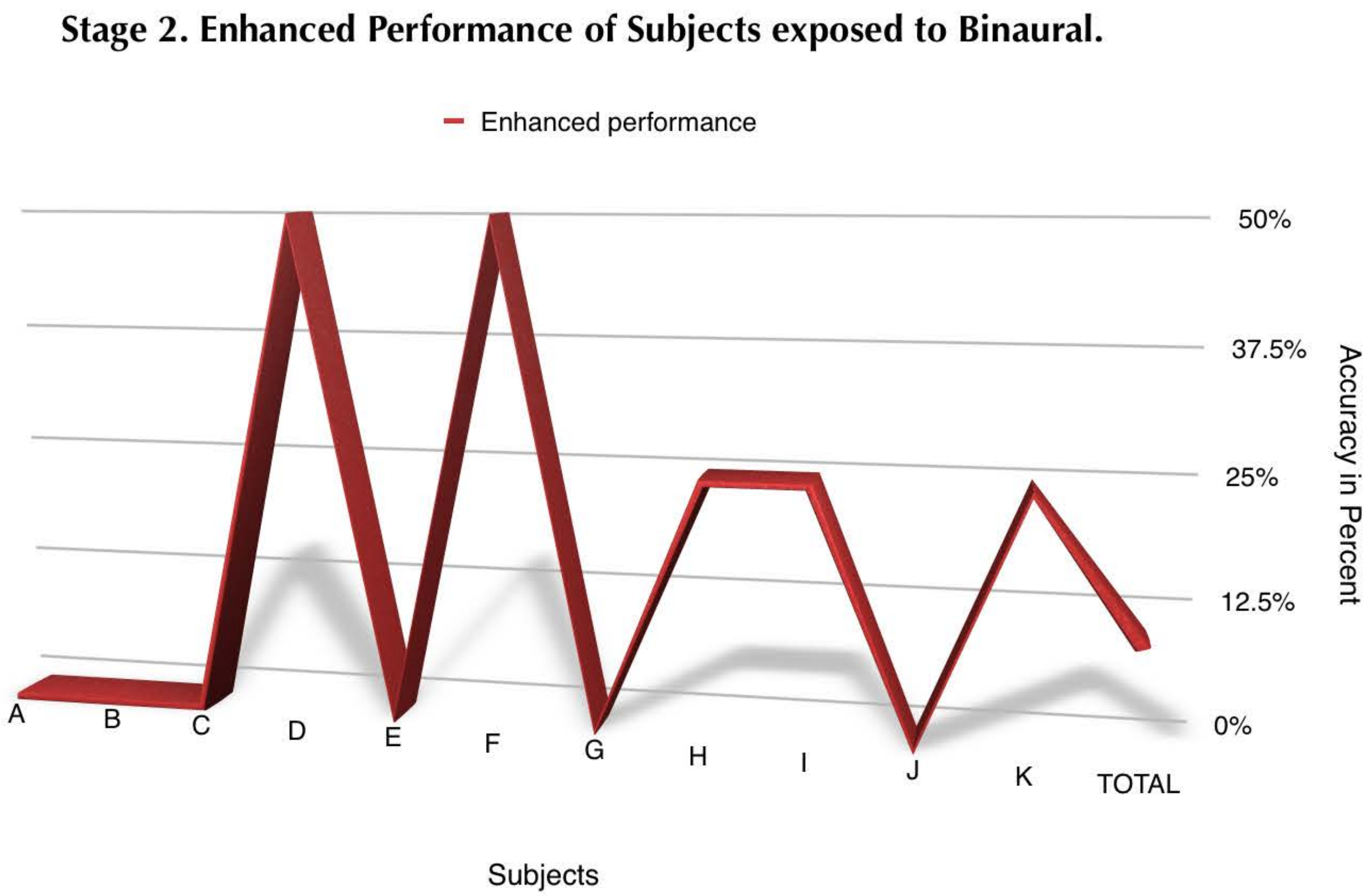

Figure 23. Performance Enhancement Chart for subjects accurately localising music samples.

Binaural	Elevation	Azimuth	Far / Close	Instrument	A	B	C	D	E	F	G	H	I	J	K	TOTAL MARKS	TOTAL PERCENT
STAGE 2																	
Question 1 0 or 180 Degrees ?	0 Degrees	180 Degrees	Close.	Bass	0	1	1	1	0	0	1	0	1	0	1	6 Points	55%
Question 2 45 or 90 Degrees ?	0 Degrees	90 Degrees	Close.	Organ	1	1	0	1	1	1	1	0	0	1	0	7 Points	64%
Question 3 135 or 315 Degrees ?	0 Degrees	135 Degrees	Close.	Drums	1	1	1	1	0	1	1	1	1	0	1	9 Points	82%
Question 4 225 or 270 Degrees ?	0 Degrees	225 Degrees	Close.	Guitar	0	0	0	0	0	0	0	0	1	1	0	2 Points	18%
Stage 2 Total					2	3	2	3	1	2	3	1	3	2	2	24 Points / 44 Points	50%

Figure 24. Table Results with Data Reference. Stage 2.

The highest scoring question in Stage 2, with regards to accuracy, was question 3, in which binaural scored 82 %. (Figure 24).

Stereo	Elevation	Azimuth	Far / Close	Instrument	A	B	C	D	E	F	G	H	I	J	K	TOTAL MARKS	TOTAL PERCENTAGE
STAGE 2																	
Question 1 0 or 180 Degrees ?	0 degrees	0 Degrees	Close.	Bass	0	1	1	1	0	0	1	0	1	0	1	6 Points	55%
Question 2 45 or 90 Degrees ?	0 degrees	45 Degrees	Close.	Guitar	1	1	1	0	0	0	1	0	0	1	0	5 Points	45%
Question 3 270 or 315 Degrees ?	0 degrees	315 Degrees	Close.	Drums	1	1	0	0	1	0	1	0	0	0	0	4 Points	36%
Question 4 225 or 270 Degrees ?	0 degrees	270 Degrees	Close.	Organ	0	0	0	0	0	0	0	0	1	1	0	2 Points	18%
Stage 2 Total					2	3	2	1	1	0	3	0	2	2	1	17 Points out of 44	39%

Figure 25. Table Results with Data Reference. Stage 2.

The highest scoring question in Stage 2, with regards to stereo, was question 1, in which subjects correctly answered 6 out of 11 possible marks.

Stereo vs Binaural Results

Stage 3

In Stage 3 subjects were asked to state the correct azimuth of the musical samples presented to them, without any multiple choice answer prompted. This may explain the poorer performance in both binaural (25%) and stereo (11%), however, binaural still maintains its bias in enhanced accuracy, with 6 / 11 subjects improving by 25 % when presented with binaural recordings. All samples were 3 seconds long in duration, presented at 0 degrees elevation and were recorded in far microphone position (9ft).

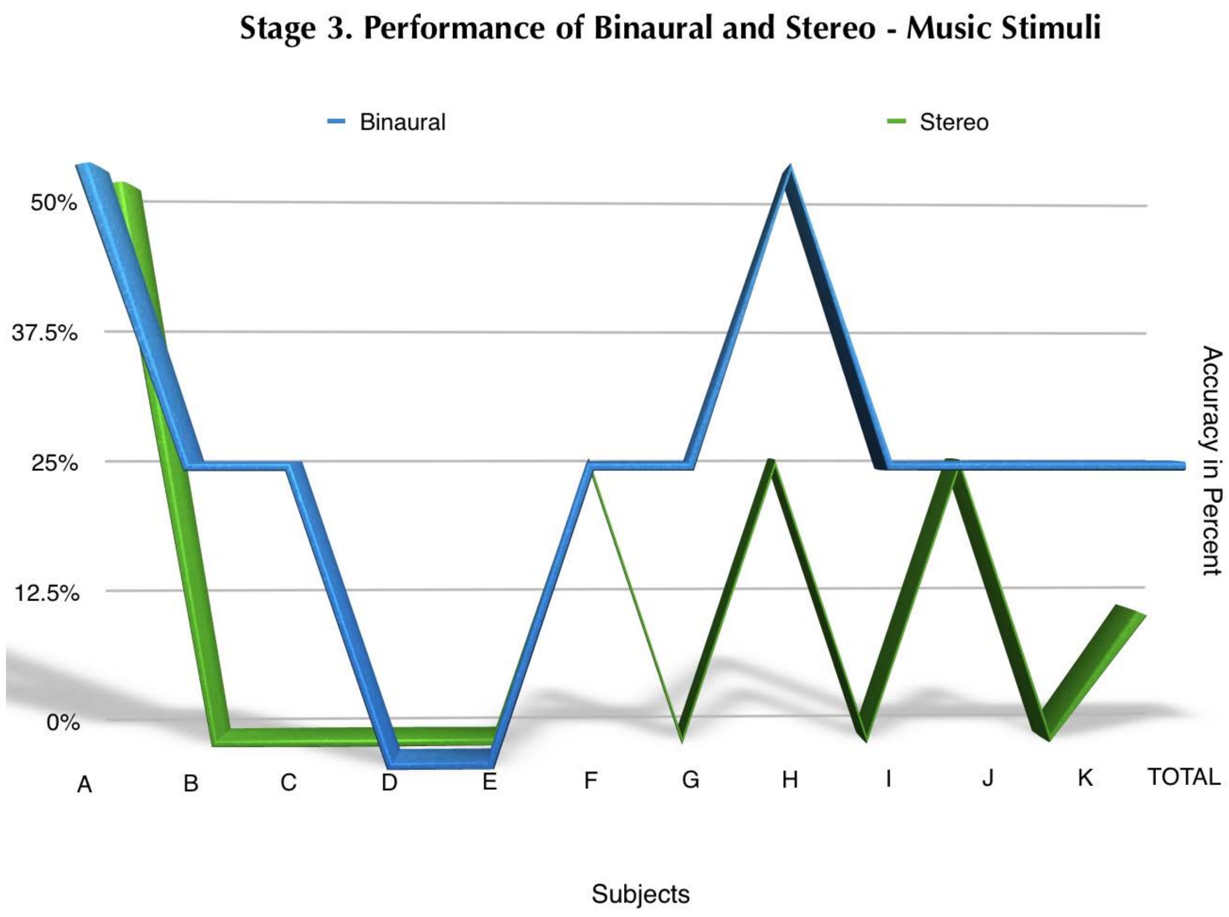

Figure 26. Results Stage 3. Stereo vs Binaural

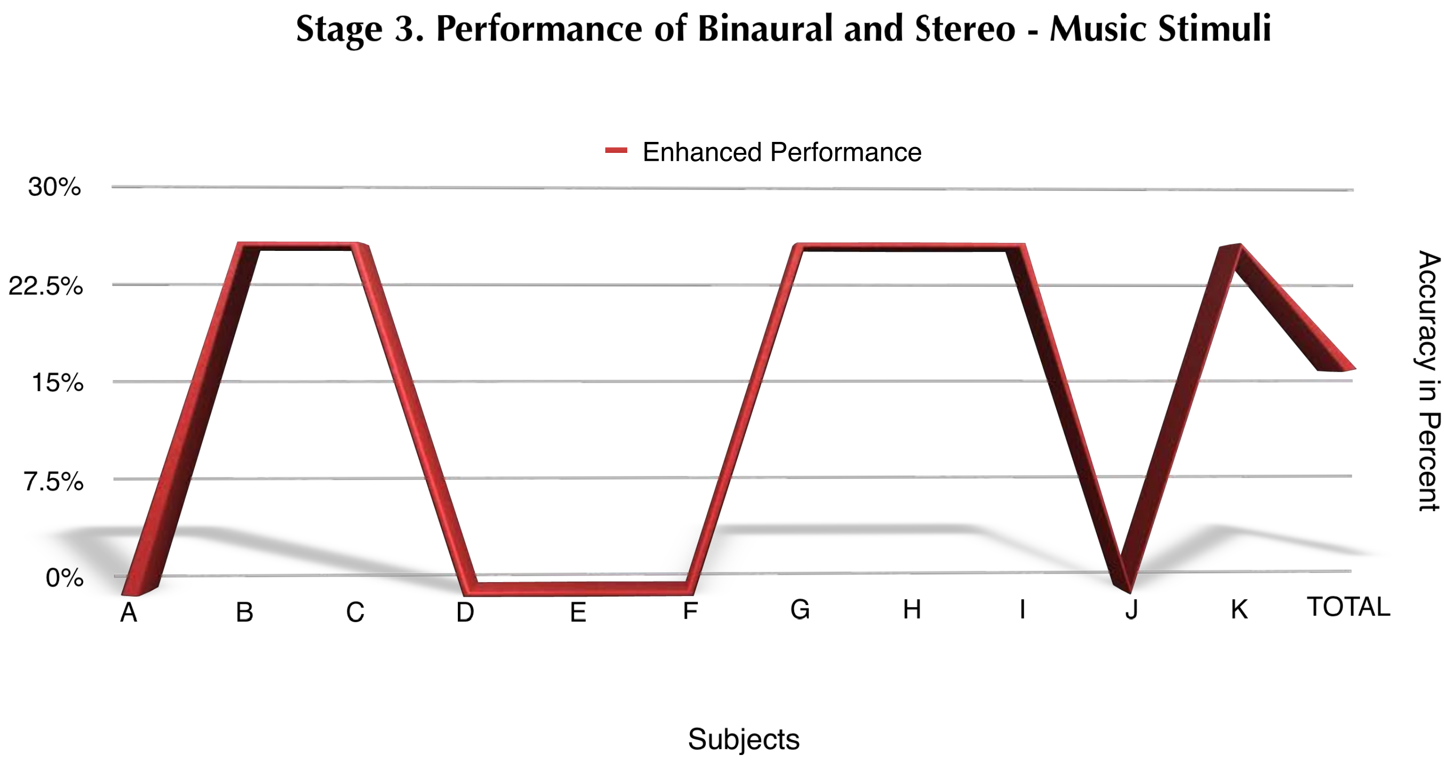

Figure 27. Performance Enhancement Chart for subjects accurately localising music samples.

In explaining the poorer results of Stage 3, one might look at Question 4 as a starting point. Figure 28 demonstrates that for Question 4, none of the 11 subjects answered correctly. This may be due to front and back ambiguity, as discussed in the Literature Review, since the samples played to the subjects are, respectively, 180 degrees and 0 degrees. In examining the data for Stage 3, 6 out of 11 errors (55%) that subjects made using stereo appear to be due to front back confusion This compares to 2 out of 7 (29%) for binaural.

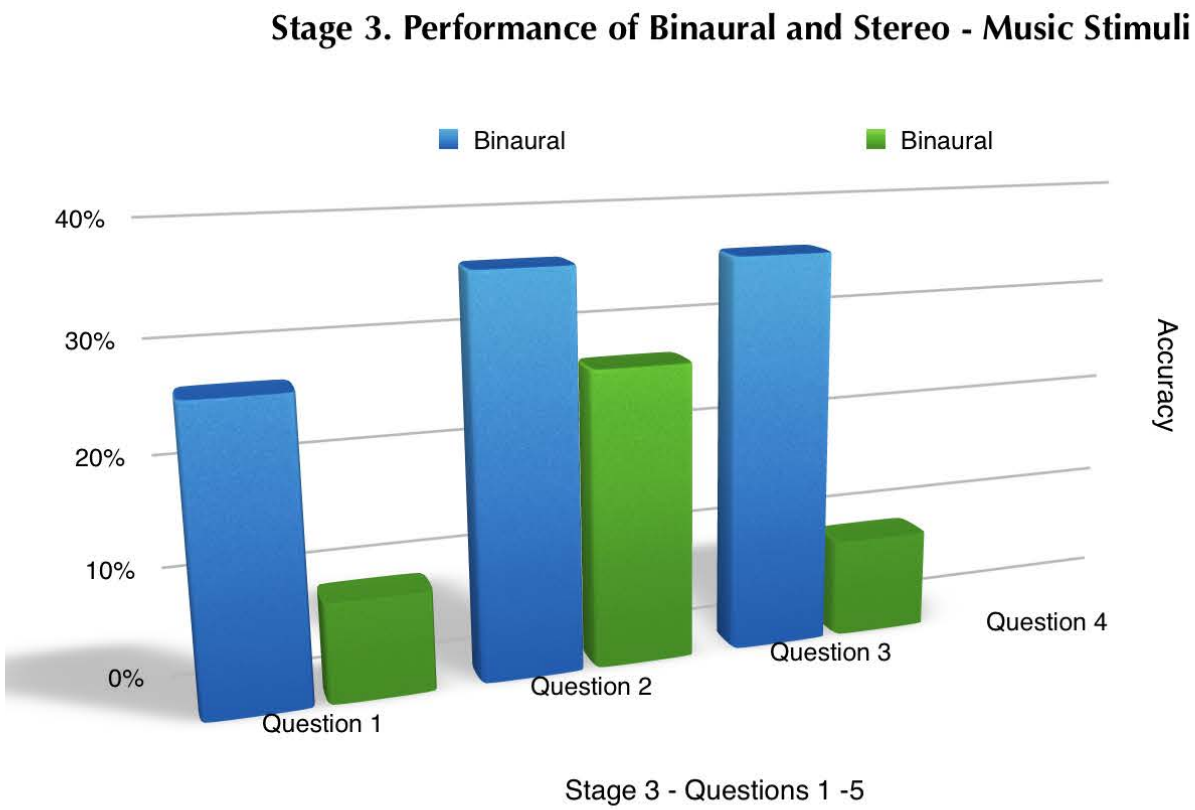

Figure 28. Stage 3. Results

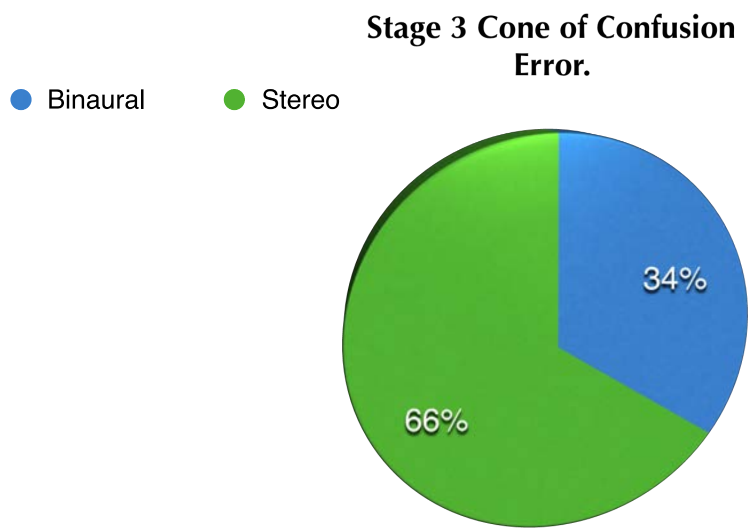

Figure 29. Stage 3. Cones of confusion

Stereo vs Binaural Results

Stage 4

In Stage 4, subjects were presented with guitar and organ samples, which were recorded in the room position of -45 degrees elevation and at a close microphone position. The results, with perhaps the exception of question 1 in which subjects exposed to binaural scored 55%, (Figure 30) show low overall performance in both microphones. This is arguably the consequence of changing the elevation of the sound source, in which the reader will recall in the Literature Review, that elevation works most efficiently when on the horizontal plane.

Binaural	Elevation	Azimuth	Far / Close	Instrument	A	B	C	D	E	F	G	H	I	J	K	TOTAL MARKS	TOTAL PERCENT
STAGE 4																	
Question 1 State location	-45 Degrees	90 Degrees	Close.	Guitar	0	0	0	1	1	1	0	1	0	1	1	6 Points	55%
Question 2 State location	-45 Degrees	180 Degrees	Close.	Organ	0	0	0	0	1	0	0	0	0	0	0	1 Point	9%
Stage 4 Total					0	0	0	1	2	1	0	1	0	1	1	7 Points / 22 Points	32%

Figure 30. Table Results with Data Reference. Stage 4

Stereo	Elevation	Azimuth	Far / Close	Instrument	A	B	C	D	E	F	G	H	I	J	K	TOTAL MARKS	TOTAL PERCENTAGE
STAGE 4																	
Question 1 State location	-45 Degrees	225 Degrees	Close.	Guitar	0	0	1	0	0	0	0	1	0	1	0	3 Points	27%
Question 2 State location	-45 Degrees	90 Degrees	Close.	Organ	0	1	0	0	0	0	0	0	0	0	0	1 Point	9%
Stage 4 Total					0	1	1	0	0	0	0	1	0	1	0	4 Points out of 22	18%

Figure 31. Table Results with Data Reference. Stage 4

In terms of enhanced performance, subjects using the binaural recording still perform with better accuracy then stereo, but as can be noted from Figure 32, the overall gains in comparison to Stages 1 - 3 are smaller, with some loss in performance for Subjects A & B.

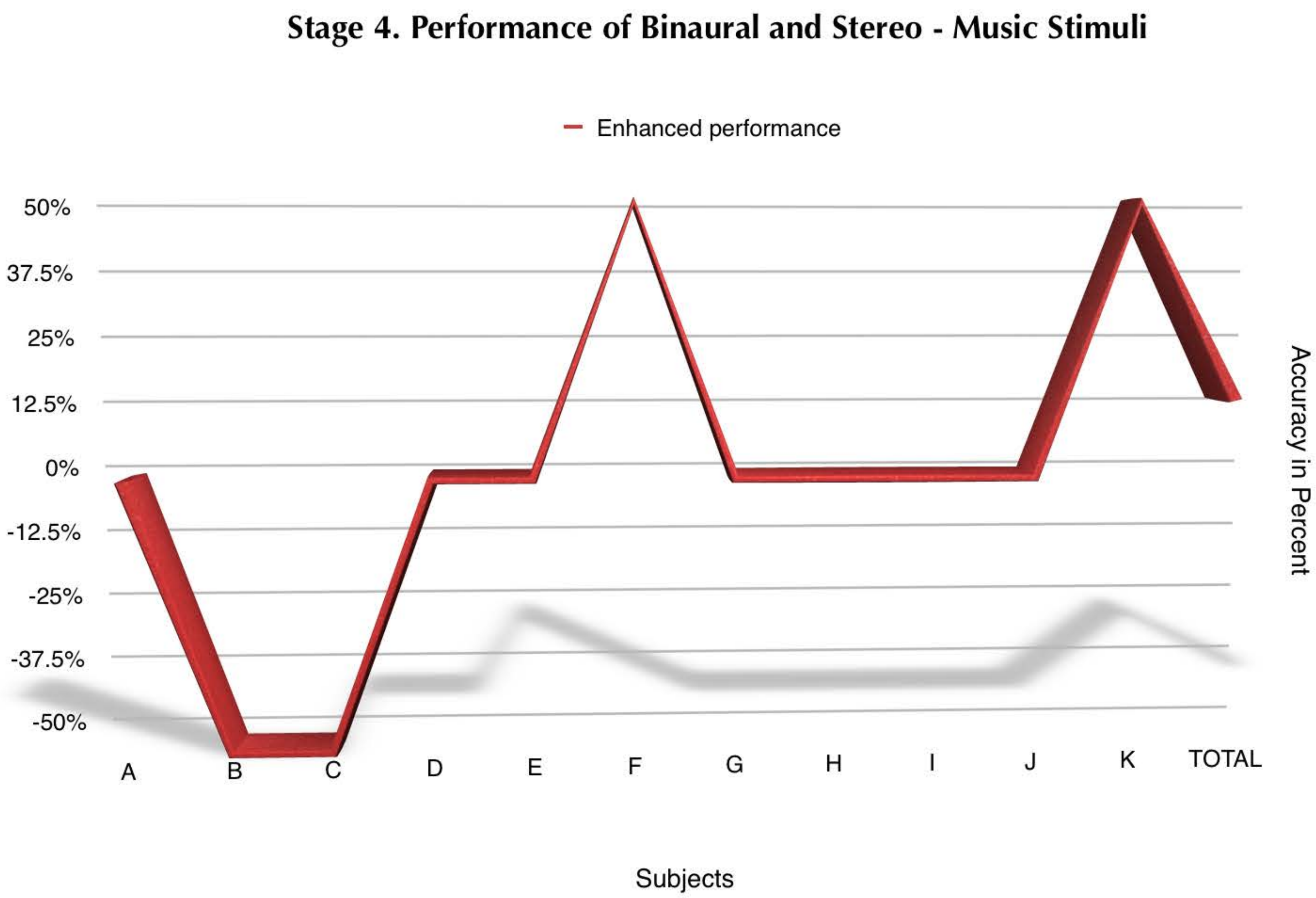

Figure 32. Performance Enhancement Chart for subjects using binaural.

Stereo vs Binaural Results

Stage 5

In Stage 5, both microphones fall in performance slightly, with binaural enjoying only a lower margin of improvement over stereo. Subjects who answered correctly when binaural recordings were used, scored 23%, whilst those listening to stereo recordings scored 14%. Instruments included bass and drums, with samples recorded at -66 degrees elevation and at a far microphone room distance. Note the repeated loss of performance in subjects A & B.

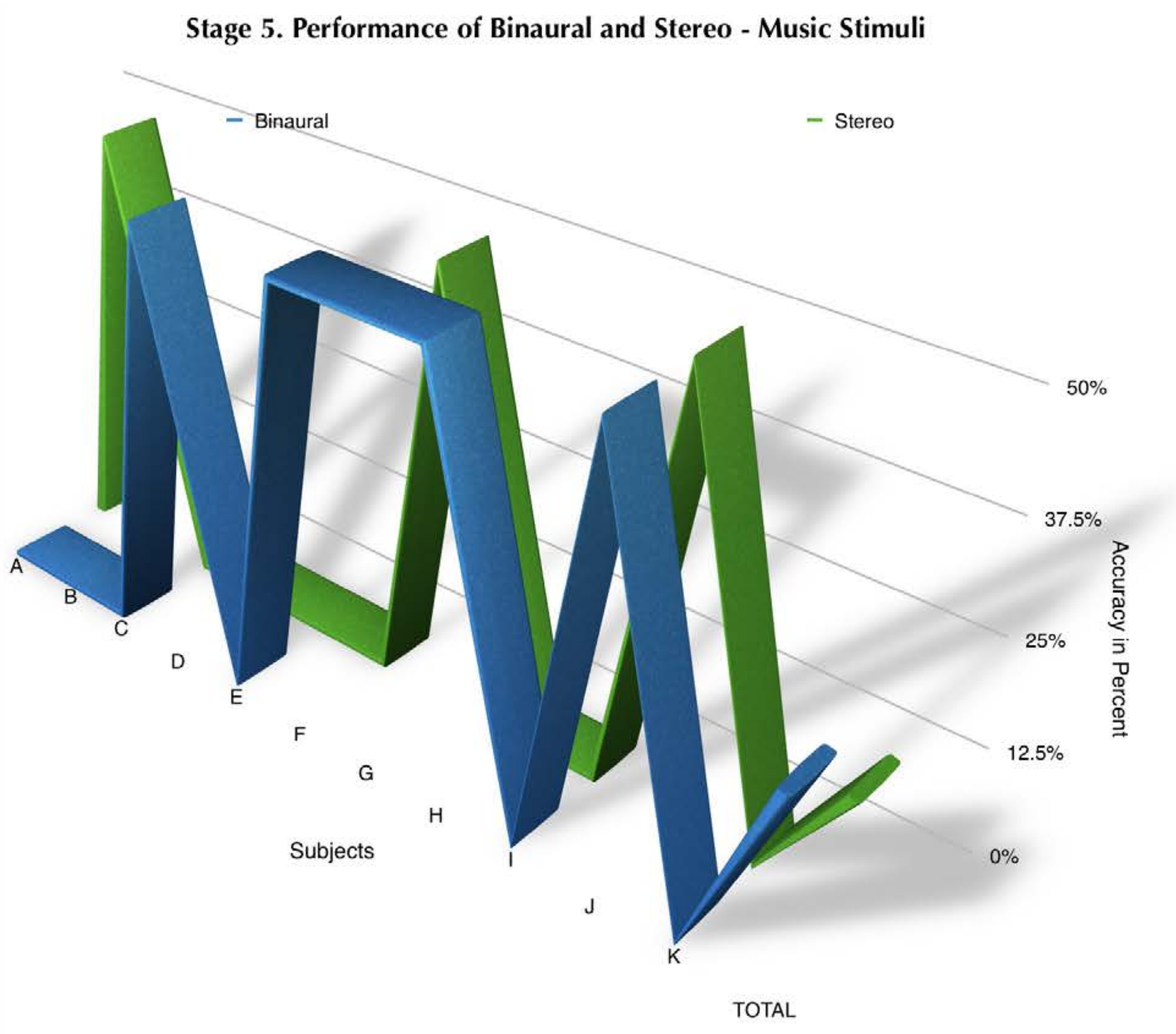

Figure 33. Results Stage 3. Stereo vs Binaural

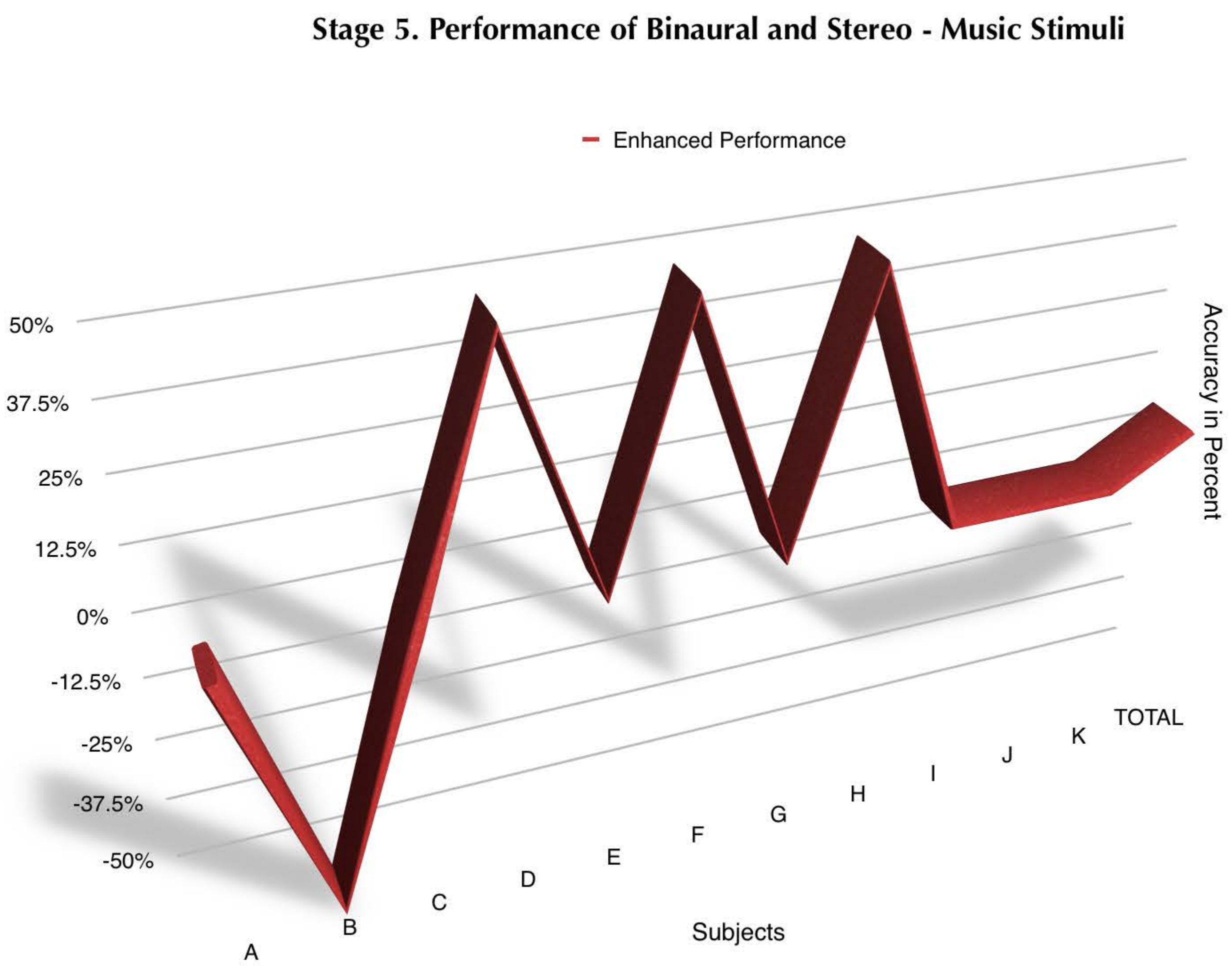

Figure 34. Performance Enhancement Chart for subjects using binaural.

	Subject	A	B	C	D	E	F	G	H	I	J	K	TOTAL MARKS	TOTAL PERCENTAGE
Binaural	Total Stages 1 - 5	4	4	5	6	5	6	6	6	4	6	4	56 out of 154	36%
Stereo	Total Stages 1 - 5	4	5	4	3	3	2	5	3	2	6	1	38 out of 154	25%

Figure 35. Table Results. Stages 1 - 5.

Stereo vs Binaural Results

Accuracy by instrument

To conclude with the results of Stages 1 - 5, it may be useful to look at how subjects performed in localising the recordings by instrument. The purpose of this is to gauge the influence of frequency, and bandwidth on auditory hearing. Do sounds using inter-aural time delays (low frequencies) perform better than instruments using inter-aural level differences (high frequencies) and how do the binaural recordings compare to stereo in this respect ?

Accuracy by instrument. Binaural. **Accuracy by instrument. Stereo.**

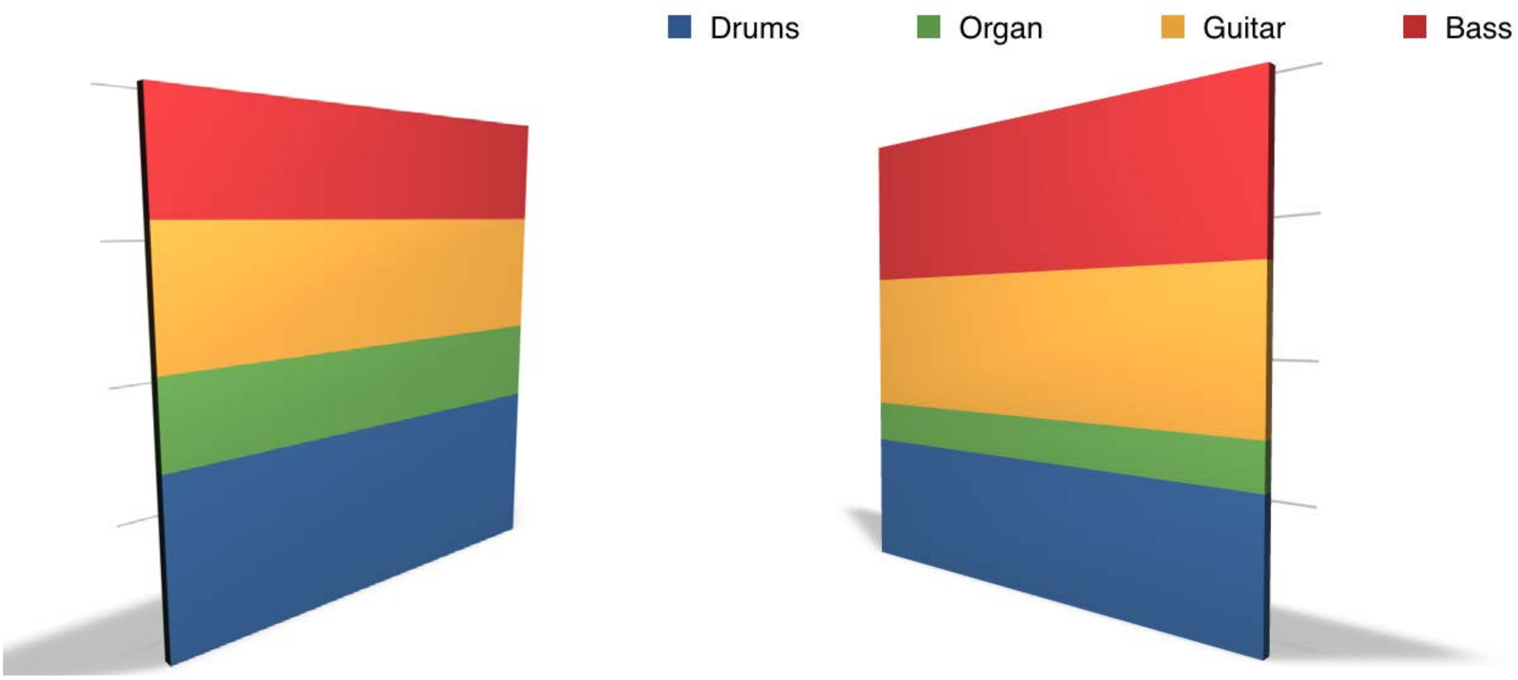

Figure 36. Accuracy by instrument. A comparison of stereo and binaural data.

Results show broadly similar higher accuracy rates in both binaural and stereo recordings with drums (full bandwidth), bass (low frequency) and guitar (low to midrange) whilst the organ (mid to high) appeared to be the most frequent instrument in which subjects struggled to localise.

Stereo vs Binaural Results

Stage 6 - Pink Noise

Binaural	Elevation	Azimuth	Far / Close	Bandwith	A	B	C	D	E	F	G	H	I	J	K	TOTAL MARKS	TOTAL PERCENTAGE
STAGE 6																	
Question 1 State location	0 Degrees	90 Degrees	Close.	Full Band	0	1	1	1	1	1	1	1	0	1	1	9 Points	82%
Question 2 State location	-45 Degrees	135 Degrees	Close	Mid Band	0	0	0	1	1	0	0	0	0	0	1	3 Points	27%
Question 3 State location	-45 Degrees	180 Degrees	Close	High Band	1	0	0	1	0	0	0	1	0	0	1	4 Points	36%
Question 4 State location	-45 Degrees	225 Degrees	Close	High Band	1	0	0	1	0	1	1	0	0	0	1	5 Points	45%
Question 5 State location	0 Degrees	135 Degrees	Far	Mid Band	1	1	1	0	1	0	0	0	0	0	1	5 Points	45%
Question 6 State location	0 Degrees	180 Degrees	Far	Low Pass	0	0	0	1	0	0	0	1	0	0	0	2 Points	18%
Question 7 State location	0 Degrees	225 Degrees	Far	High Pass	0	1	0	0	0	0	0	0	0	0	1	2 Points	18%
Total Stage 6					3	3	2	5	3	2	2	3	0	1	6	30 out of 77	39%

Figure 37. Table Results with Data Reference. Stage 6. Binaural - Pink Noise.

Stereo	Elevation	Azimuth	Far / Close	Bandwith	A	B	C	D	E	F	G	H	I	J	K	TOTAL MARKS	TOTAL PERCENTAGE
STAGE 6																	
Question 1 State location	0 Degrees	90 Degrees	Close	Mid Band	0	0	0	0	0	0	0	0	0	0	0	0 Points	0%
Question 2 State location	45 Degrees	90 Degrees	Close	Full Band	0	0	1	0	1	0	1	0	0	0	0	3 Points	27%
Question 3 State location	-45 Degrees	45 Degrees	Close	Low Pass	0	0	0	0	0	0	0	0	0	0	0	0 Points	0%
Question 2 State location	-45 Degrees	225 Degrees	Close	High Pass	0	1	0	0	0	0	1	0	0	0	0	2 Points	18%
Question 5 State location	0 Degrees	0 Degrees	Far	Low Pass	0	0	0	0	0	0	0	0	0	0	1	1 Point	9%
Question 6 State location	0 Degrees	90 Degrees	Far	Mid Band	1	0	0	0	0	0	0	1	0	0	0	2 Points	18%
Question 7 State location	- 66 Degrees	135 Degrees	Far	Mid Band	0	0	0	0	0	0	0	1	0	0	0	1 Points	9%
Total Stage 6					1	1	1	0	1	0	2	2	0	0	1	9 out of 77	12%

Figure 38. Table Results with Data Reference. Stage 6. Stereo - Pink Noise.

Binaural Results. Pink Noise

TOTAL CORRECT RESPONSE	FREQUENCY	ACTUAL LOCATION	DISTANCE	ELEVATION
82%	Full Band	90 Degrees	Close.	0 Degrees
27%	Mid Band	135 Degrees	Close	-45 Degrees
36%	High Band	180 Degrees	Close	-45 Degrees
45%	High Band	225 Degrees	Close	-45 Degrees
45%	Mid Band	135 Degrees	Far	0 Degrees
18%	Low Pass	180 Degrees	Far	0 Degrees
18%	High Pass	225 Degrees	Far	0 Degrees

Figure 39. Table Results with Data Reference. Stage 6. Binaural - Pink Noise.

Stereo Results. Pink Noise

TOTAL CORRECT RESPONSE	FREQUENCY	ACTUAL LOCATION	DISTANCE	ELEVATION
27%	Full Band	90 Degrees	Close	0 Degrees
0%	Mid Band	90 Degrees	Close	0 Degrees
9%	High Pass	225 Degrees	Close	-45 Degrees
0%	Low Pass	45 Degrees	Close	-45 Degrees
0%	Low Pass	90 Degrees	Close	-45 Degrees
9%	Low Pass	0 Degrees	Far	0 Degrees
18%	Mid Band	90 Degrees	Far	0 Degrees
18%	Mid Band	135 Degrees	Far	- 66 Degrees

Figure 40. Table Results with Data Reference. Stage 6. Stereo - Pink Noise.

Critical Observations from Pink Noise Results.

- Errors in accuracy increase when elevation is negative . Supports NASA research of Begault 2000.
- Errors in accuracy decrease when microphone position is close.
- Subjects using both binaural and stereo, respond more accurately when using full bandwidth noise.
- High and mid band appears more favourable then low.
- Highest percentage of accuracy (82%) amongst subjects when binaural recordings were presented.
- A possible correlation between full bandwidth and the drums, which also has a broad frequency range, being amongst subjects ability to successfully localise the test sounds.
- Overall higher performance in binaural.

Chapter 8 Conclusion

Through analysis of the results, one can see quite clearly that subjects using binaural, appear to perform better than when using stereo in localising sound. The results mirror the findings of Batteau, (Gerzon, 1975) who found that when pinnae were added to microphones, subject's ability to localise sounds improved, with less front and back confusion.

As predicted in the literature review, binaural gave better performance than stereo with regards to successfully localising musical sounds, on account of the Head Related Transfer Function, with its implications for phase and amplitude.

In somewhat of a u-turn from the literature review, the inclusion of pink noise was entered into the experiment. This arose from studies made in the methodology of sound localisation tests, in which pink noise was a common feature. Also influencing this decision was the discovery of results from previous tests which used musical stimuli, in which binaural fared badly. The inclusion of pink noise, in which binaural also performed better in, aimed to give a more objective overall picture, but did so, in sacrificing some of the original, intended aims of the literature review.

This included an investigation into the harmonic series as an auditory cue. With affirmed evidence, that phase plays an essential role in the auditory system, does this therefore imply that harmonic intervals with simple ratio structures are easier to locate than dissonant structures with complex ratios ? What is the parallel between inter aural time delays, in which phase plays a part, and harmonic tones, in which phase in dissonant tones, creates the audible sound of amplitude beating ? Are consonant sounds easier to localise ? These questions bare the welcoming fruit of further investigation.

How-ever, the core of the question posed by the Literature Review - does binaural perform better than stereo, was indeed addressed and kept true to its path.

The overall performance of both stereo and binaural, the reader will have noted, leaves some room for improvement. One possible reason for this was the difficulty of the test, which many subjects, particularly in Stages 3 - 6, confided was challenging. Had the task given to the subjects been over-estimated ? In trying to explain this objectively, there are a few variables one might consider. Firstly, and perhaps the most obvious, is the allowance of error in the design and procedure of the experiment. Would subjects have scored better points in accuracy if more practise questions had been set at the beginning of Stages 1 - 5 (music stimuli) and Stage 6 (noise stimuli) ?.

Another factor to consider might be the precision of the sound source (mono speaker), with regards to the microphone. The reader will recall from the Methodology Chapter, that the mono speaker was used independently for each azimuth and elevation co-ordinate, with regards to the binaural and stereo microphone. Some deviation between the two placements appears reasonably likely and this too, will have influenced the results. Recall that even a small delay of 0.5ms results in total phase cancellation of frequencies surmounting to 1kHz. Senior (2008). With this in mind, its worth considering that any deviation the mono speaker made in terms of co-ordinates of the room, may reflect in longer or shorter delay arrival times from the closest microphone to the furthest. With any deviation in error from the true mono speaker placement, one might also expect a certain change in frequency content - if frequencies are cancelled out unintentionally, this may influence, to a degree, the ability of the subject to discern the overall sound.

Asides error, the unexpected results may have been down to the absence of vision, head tracking equipment or inaccurate HRTF information shared between the subject and binaural microphone. If a subject’s head varies too much from the dimension of the microphone (distance of ears etc), the HRTF effect becomes somewhat diminished. Individualised HRTFs is a possible solution, and references will be given for this in the further reading section.

Further Reading

As a starting point and reference, attention is drawn to two possible surrounding areas, in which binaural can be improved and so may be worthwhile for the reader to further investigate. The first is the idea of an individualised HRTF, which comprised of ILDs, ITDs and spectral coloration, helps the listener better localise a sound in 3D space. (Fitzpatrick, Semwal and Wickert, n.d.)

A second area which may be useful for further research, is that of head tracking devices, which as Fitzpatrick, Semwal and Wickert state, (n.d, p 2) can aid in fine tuning the source's location, by means of turning the head to '*resolve any remaining ambiguities*'. The reader may also wish to reference the previously mentioned work of Paukner, Rothbucher and Diepold , (2014, p29), who state the enhanced impact of head tracking on decreasing front / back ambiguity.

In addition to this, and for a more general enquiry into the nature of 3D sound, readers may find the BBC website, a quick, useful point of reference, in which developments and updates are accessible.

Academic routes in 3D sound, at postgraduate level, are offered by institutions such as the University of Salford (2017). I was advised that in supporting an application for the PhD course, an A-level in Mathematics would be an advantageous asset. This was unsurprising and welcoming, as mathematical principles have surfaced frequently in my own research over the last 6 months or so and a close fondness of the subject has gradually developed. Arguably then, if the reader wishes to truly solidify an understanding of 3D sound, Mathematics may well pose, a useful ally.

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