LOCALISATION OF ELEVATED VIRTUAL SOURCES IN HIGHER ORDER AMBISONIC SOUND FIELDS

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1 ABSTRACT

Ambisonics allows the reproduction of 3D sound-fields. Higher-order Ambisonics provides improved resolution, and the promise of enhanced localisation at the expense of higher channel counts, and increased broadcast bandwidth, and storage requirements. Due to the resolution of human hearing it is possible that lower-order reproduction is sufficient for the vertical plane, resulting in mixed-order Ambisonic renderings. To investigate, we report the results of subjective localisation tests for virtual sources placed in the vertical plane at different elevations and azimuths, for 1st, 2nd and 3rd order Ambisonic reproduction over a 16 loudspeaker system. The results provide insights into the requirements of higher-order Ambisonics for broadcast and domestic reproduction.

2 INTRODUCTION

The current broadcast and consumer audio formats for spatial audio reproduction are limited to 2D reproduction, limiting the experience for the user. Expanding current systems to include height reproduction creating a 3D system may lead to improved listener experience. The use of higher order Ambisonics is one method of recording, storing, and transmitting 3D sound. There are already several other systems available like the 22.2 NHK system, and the IOSONO system based on wavefield synthesis.

Ambisonics is essentially a two stage system. This means that sound scenes can be recorded or synthetically encoded without the knowledge of the reproduction setup. Further to this Ambisonics resolution of reproduction is based on the order and as such can be tailored to the resolution required by using a higher or lower order reproduction. This could be advantageous especially when considering 3D systems since it is well known that human hearing in the vertical plane is not good. So it may be possible to reduce the vertical order compared to the horizontal. This leads to a mixed order system which may yield optimal reproduced quality for a given bandwidth or storage limit.

The ability of panning methods utilised in 3D systems has been studied by Capra *et al* [1], Morrell and Reiss [2], Keiler and Batke [3] however these have featured one type of Ambisonic order compared to other methods. In this study three different Ambisonic orders have been investigated to determine the difference between each order at localising an elevated virtual source. Two different sound sources have been used, and it has been found that there were significant differences between 1st and 3rd order in terms of sound source used.

3 AMBISONIC REPRODUCTION

Ambisonics was invented in1969 by Michael Gerzon [4], and is based around different resolutions of reproduction starting at zero order which only accounts for the pressure component (W),adding the directional components (X, Y, Z) provides directional information in three dimensions up to 1st order. This provides limited sound field resolution, although adding further components up to 2nd or 3rd order provides greater spatial resolution. However with each increasing order the minimum number of speakers required also increases, thus a third order system will be the highest order investigated in this study, since this will require a minimum of 16 speakers. See equation1 where M is the Ambisonic order. Ambisonic reproduction also assumes a regular layout of speakers, this being achieved easily for horizontal sources since the speakers only have to be equally spaced, however for sources with height this is more difficult because there are only five shapes that provide a regular array, these being the platonic solids [5]

$$(M+1)^\wedge 2 \qquad (1)$$

In order to reproduce a soundfield using Ambisonics there are a few steps necessary. Firstly the signal has to be encoded to the desired location, and then decoded to the speaker array. In order to encode the signal to the desired location the Furse-Mahlam equation set was used using the SN3D normalisation [6]. Where W through to Z are the first order components, R to V are the second order components and K through to Q are the 3rd order components, θ is the source azimuth, and φ is the source elevation. See Equation 2

$$\begin{gathered}
W = 1 \\
X = \cos(\theta) \times \cos(\varphi) \\
Y = \sin(\theta) \times \cos(\varphi) \\
Z = \sin(\varphi) \\
R = (3\sin{}^\wedge 2\varphi - 1)/2 \\
S = \sqrt{3/2}\ \cos(\theta)\sin(2\varphi) \\
T = \sqrt{3/2}\ \sin(\theta)\sin(2\varphi) \\
U = \sqrt{3/2}\ \cos(2\,\theta)\cos(\varphi)^\wedge 2 \\
V = \sqrt{3/2}\ \sin(2\theta)\cos(\varphi)^\wedge 2 \\
K = \sin(\varphi)(5\sin{}^\wedge 2 - 3)/2 \\
L = \sqrt{3/8}\ \cos(\theta)\cos(\varphi)(5\sin{}^\wedge 2\varphi - 1) \\
M = \sqrt{3/8}\ \sin(\theta)\cos(\varphi)(5\sin{}^\wedge 2\ \varphi - 1) \\
N = \sqrt{15/2}\ \cos(2\theta)\sin(\varphi)\cos{}^\wedge 2\,\varphi \\
O = \sqrt{15/2}\ \sin(2\theta)\sin(\varphi)\cos{}^\wedge 2\ \varphi \\
P = \sqrt{5/8}\ \cos(3\theta)\cos{}^\wedge 3\ \varphi \\
Q = \sqrt{5/8}\ \sin(3\theta)\cos{}^\wedge 3\varphi
\end{gathered} \qquad (2)$$

A matrix of ‘C’ speaker directions based on spherical coordinates is created with each speaker also being multiplied by the corresponding spherical harmonic. The pseudo inverted speaker matrix ‘D’ is finally multiplied by the encoded signal direction $\vec{B}$ which provides the final gains required to reconstruct the sound field. See equation 3

$$C^{-1} \cdot \vec{B} = D \cdot \vec{B} \tag{3}$$

It is also explained by Moreau *et al* [7] that in higher order Ambisonics more selective use of the loudspeakers means that higher directivities for sound sources are achieved. In addition further optimisation of a decoder can be realised by using weighting coefficients per order, for example the 'max rE' (maximum energy) coefficients, which aims at concentrating panned sources to the desired location. This was a feature of the decoding used in these listening tests.

4 LISTENING TEST

A listening test has been carried out to investigate the localisation accuracy of three different Ambisonic orders there has been a small amount of work in this area. For example a triple stereo dipole system, using a transaural method is compared to a sixteen channel 3D Ambisonic system by [1]. A first order decode was used which was optimized for the speaker array. It was found that there were no significant differences between either of the systems, and elevated sources were hard to localise. A number of localisation confusions were also prevalent, especially where sources were placed below the participant, since they tended to be localised in the upper hemisphere.

A comparison of different panning methods was investigated by [2] amongst other methods such as VBAP (Vector Based Amplitude Panning), inter aural time delay, and 3rd order Ambisonics to find which method using manipulation of distance, and position, places the sound source at the desired location with least error around a 3D 16 channel speaker array. A variety of audio samples were used which were panned using the different methods. Four positions were tested, and it was found that overall the 3rd order Ambisonic method performed better than the ITD method, however the VBAP methods having similar performance to that of 3rd order Ambisonics, unfortunately there was no breakdown regarding the performance using the different audio samples.

The same speaker array was used by [3] as Capra *et al*, however two different methods of Ambisonics decoding were tested. The first was a basic 3rd order decode (mode matching), the second was VBAP, and finally their proposed method which is based on the work of Kirkeby [8]. In their test only two positions were used, and instead of directional estimates from participants a modified MUSHRA test regime was used using preference scores. It was found that their proposed panning method received the highest preference scores.

4.1 PHYSICAL SET UP

Three different resolutions of Ambisonic decoding were utilised which were prepared to be played back over 16 speakers, using a similar set up as [1],[3]. Active Genelec 8030A speakers were arranged with 8 placed on the horizontal plane at the listeners ear height starting at $0°$ and equally spaced at $45°$angles, another 8 speakers were displaced four above the listener in a square and four below, offset at +- $35°$ elevation, an additional five speakers were also placed at a further five positions in order to playback real sound sources. The first speaker in the square started at $45°$ and was spaced at $90°$ angle. The array radius was 1.35m, with the listening position in the centre of the array (See Figure 1). The semi anechoic chamber within the school of Computing Science and Engineering at the University of Salford was utilised for the tests, this chamber conforms to ISO 3744, ISO 3745, and BS 4196 standards. The working dimensions of the chamber are 4.2x3.3x3.0m.

Figure 1- Speaker Array Used in Experiment

4.2 HUMAN HEARING IN THE VERTICAL DIMENSION

It has already been stated that the resolution of human hearing in the vertical dimension is not as good compared with the horizontal. There have been many studies to support this, early studies by Roffler and Butler [9] into the spatial location of different high and low tones. It was found that sound sources were judged in terms of their respective pitch not the sources actual location, further to this it is stated that in order to localise a sound displaced vertically the sound must have frequency content above 7 kHz and the pinna must be present. Further to this Blauert [10] also characterised what is termed “directional bands” where a sounds energy content at a specific frequency would dictate the perceived elevation of that sound not the actual location, these factors outline the peculiarities of human hearing with sources in the vertical dimension.

4.3 SOUND SOURCES

It is critical in listening tests to select the appropriate audio samples since this can have a large bearing on the final results. It has been noted that pink noise and speech have been used extensively in localisation tests by Liebetrau *et al* [11],Barbour [12],Keiler and Batke [3],Naoe *et al* [13] due to factors explained by Carlile [14] that for accurate localisation spectral information across a wide range of frequencies is required, however it has been explained by Wightman and Kistler [15] that localising the direction of a broadband sound source the inter-aural time differences dominate. It has also been reported by Liebetrau *et al* [11] in terms of speech, that humans are very sensitive to speech and as such should assist localisation. Contrary to this it was found by Davis and Stephens [16] that the use of noise and male speech in their tests that noise could be localised better than the speech sample in vertical localisation.

It would seem from previous research that in terms of localisation there are advantages to using pink noise or speech but no compelling case to use one over another. In order to try and determine the optimal stimuli, it was decided to use both full bandwidth pink noise bursts, and a female speech sample. The speech sample was taken from the music test CD for Archimedes [17]. Each of the samples was made to be two seconds long, and was 44.1kHz 16bit.

4.4 EXPERIMENTAL DESIGN

The sound samples were replayed from a computer software package, interfaced to a multichannel digital to analogue converter via MADI (Multichannel Audio Digital Interface). The audio samples were arranged in a random order for each participant. A feature of the software allowed cue points to be assigned, allowing instant switching of playback between samples this was controlled by the experimenter.

An acoustically transparent curtain was hung within the semi anechoic chamber, however participants could see the rear loudspeakers on entering the chamber. None were visible whilst seated at the listening position. The two sound samples were processed using 1st, 2nd, and 3rd order Ambisonics, with eight virtual sources for each order, and five real sources, this made a total of fifty eight sound sources for each test. See Table 1

Virtual Sources	Azimuth	Elevation	**Real Sources**	Azimuth	Elevation
Pink Noise, Speech	20	35	Pink Noise, Speech	20	35
Pink Noise, Speech	20	-35			
Pink Noise, Speech	70	20			
Pink Noise, Speech	70	35	Pink Noise, Speech	70	35
Pink Noise, Speech	90	35	Pink Noise, Speech	90	35
Pink Noise, Speech	300	0	Pink Noise, Speech	300	0
Pink Noise, Speech	330	-35			
Pink Noise, Speech	330	35	Pink Noise, Speech	330	35

Table 1- Real and Virtual Source Positions

Each of the active monitors were adjusted in level to produce 70dB(A) at the listening position using pink noise. Further level alignment was made for each order by comparing each system 1st, 2nd, and 3rd order to the centre channel of the horizontal array, which was fed pink noise output from the computer at 0dB, this was due to anti phase components from other speakers not allowing conventional calibration with a sound level meter. The levels for each order output from the computer relative to the centre channel at 0dB were: 1st and 2nd order -9.8dB and 3rd order- 5.2dB. The levels for each of the real sources replayed from the individual speaker were adjusted to give 70dB (A) at the listening position.

4.5 RECORDING PARTICIPANT RESPONSES

Collecting participant’s judgements in terms of 3D space is not a trivial matter. Several methods have been used by others for example Pernaux *et al* [18] evaluated different methods of reporting 3D sound source positioning, and found that finger pointing with a 3D visual interface provided the least error. In a study conducted by Wightman and Kistler [19] they used a method of verbally reporting the azimuth and elevation of sources in spherical coordinates, and also using a clock face method, however there were no differences in the results between using either. Other methods were also explored by Evans [20] however they stated that allowing subjects to report verbally the position of the sound source can yield an accuracy of up to $1°$. It was decided in terms of available resources to use the method of reporting verbally the position of the sound source in spherical coordinates, this was achieved using an intercom system that allowed communication between the operator and the participants. To assist the participant in their judgement of the sound source position, a vertical scale was created on the curtain hung in front of them. The scale had tick marks in $5°$ increments, with $0°$ being directly straight ahead, in line with the tweeter of the centre speaker, and the scale spanning up to $55°$ up and down, measured using an inclinometer. The radius of the curtain did not allow the creation of an azimuth scale, so a sheet of paper with azimuths marked on it was used. Participants were told that the two second audio samples would be played a total of three times, however they could ask for it to be played again if needed. After the participants had been given instructions and had time to ask questions the test was started.

Eleven participants took part, and were either staff or postgraduate researchers of the Acoustic Research Centre at the University of Salford. Since all of the participants either taught or were researching audio technology they were classed as a selected assessors [21]

5 Results

A large amount of data was collected so only the highlights of the results will be presented in this paper. The elevation error was calculated by comparing the participant's unsigned response from the intended panned location to obtain the localisation error. Two responses were gathered for each participant, the azimuth position, and the elevation.

In order to evaluate the participant's performance before assessing the virtual sources, it was necessary to inspect the performance with regards to the real sources. It has been explained by Strybel and Fujimoto [22] that the minimum audible vertical angle is approximately $4 – 5°$ inspecting the errors for the real positions it can be seen that the real sources are on average just slightly higher than this amount, using a different reporting method could have achieved more accuracy. It could be said owing to the relatively small confidence limits that the group of participants were able to localise the sources with some accuracy, and so were deemed to give reliable judgements. See Figure 2

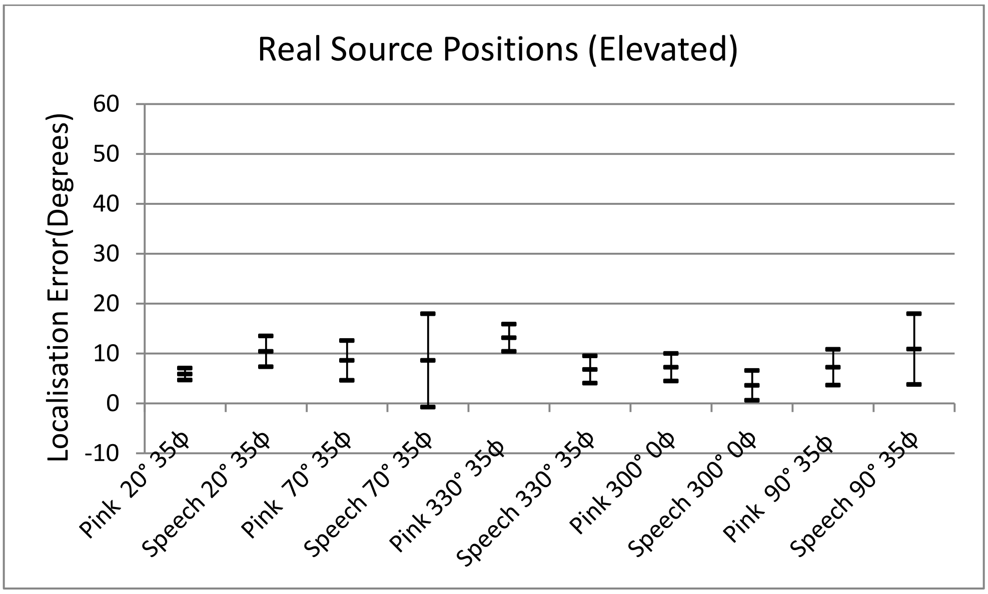

Figure 2-Mean and 95% Confidence Intervals for real Source Positions

Looking at the differences between orders for each of the elevated positions it was interesting to note the degree of variation for the 1st and 2nd order whilst the 3rd order showed more consistency in the participant's responses over all of the positions. See figures 3, 4, and 5

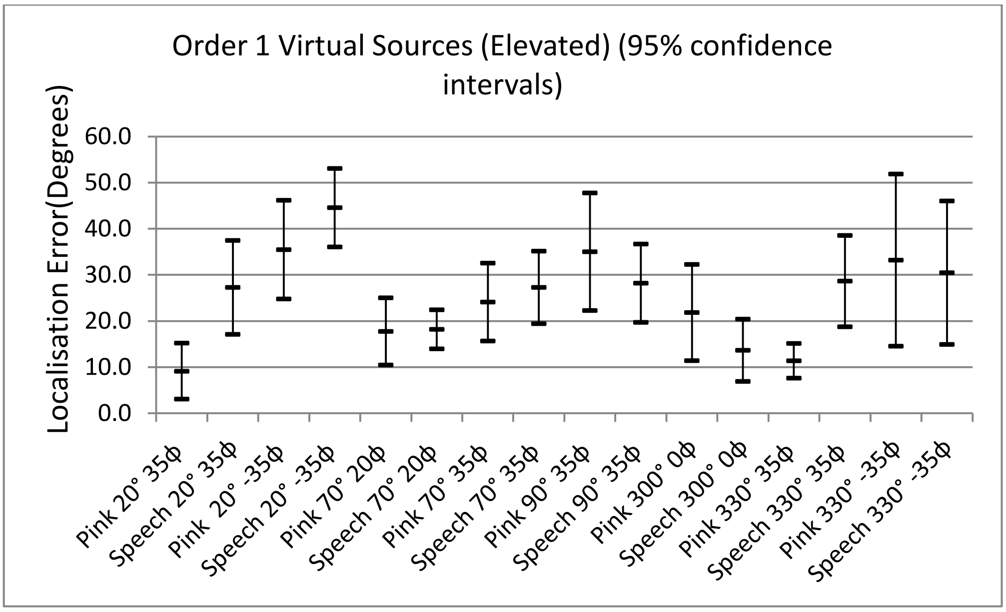

Figure 3- Mean and 95% Confidence Intervals for Elevated 1st Order Virtual Sources (Pink Noise, Speech)

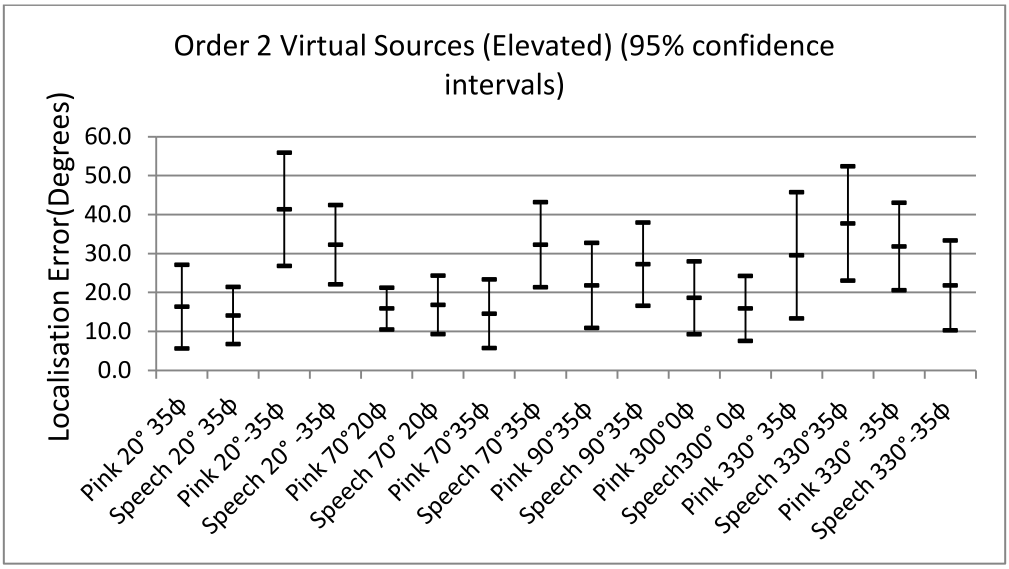

Figure 4- Mean and 95% Confidence Intervals for Elevated 2nd Order Virtual Sources (Pink Noise, Speech)

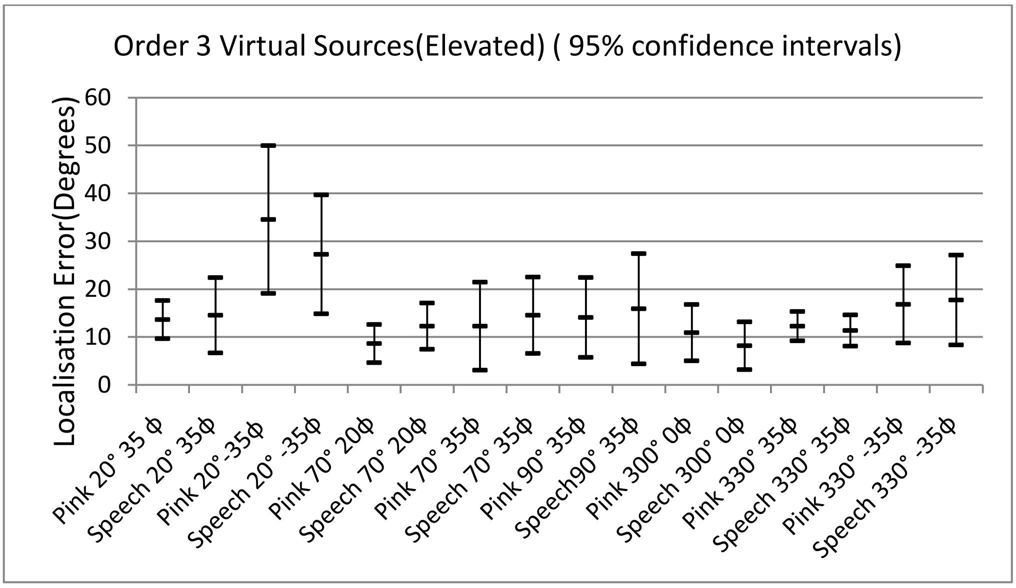

Figure 5- Mean and 95% Confidence Intervals for Elevated 3rd Order Virtual Sources (Pink Noise, Speech)

It can be seen however from the large confidence intervals that the sources placed below the participant especially at $20° - 35\varphi$ caused down with up confusions for all orders, these were also in combination with front back errors. However in terms of 3rd order, the number of confusions for this position was much lower. See Figure 6

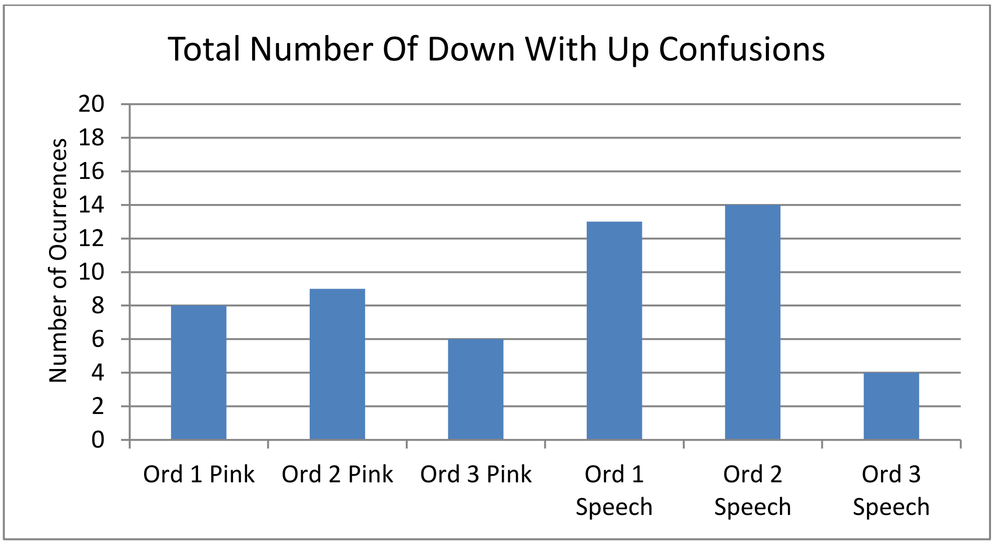

Figure 6- Total Number of Down With Up Confusions for Ambisonic order and Sound Source

The down with up confusions also caused some participants to have front back confusions, again with these being more prevalent for the sources placed below the participant rather than above. See Table 2

Female Speech	$20° \, 35\varphi$	$20° - 35\varphi$	$300° \, 0\varphi$	$330° \, 35\varphi$	$330° - 35\varphi$	TOTAL
Order 1	3	3	0	4	2	12
Order 2	1	4	1	2	2	10
Order 3	0	3	0	0	1	4
Pink Noise						
Order 1	1	4	0	1	4	10
Order 2	2	2	5	2	4	15
Order 3	0	3	0	0	0	3

Table 2- Number of Front/Back Confusions for Ambisonic Order Position and Sound Source

In order to determine which order performed with the least error the total mean error collapsed over all elevated positions was examined, it can be seen that the 3rd order has less total average error compared to 1st and 2nd order for the speech item. A similar trend was also noticed for the pink noise item, however the difference was not statistically significant. See Figure 7

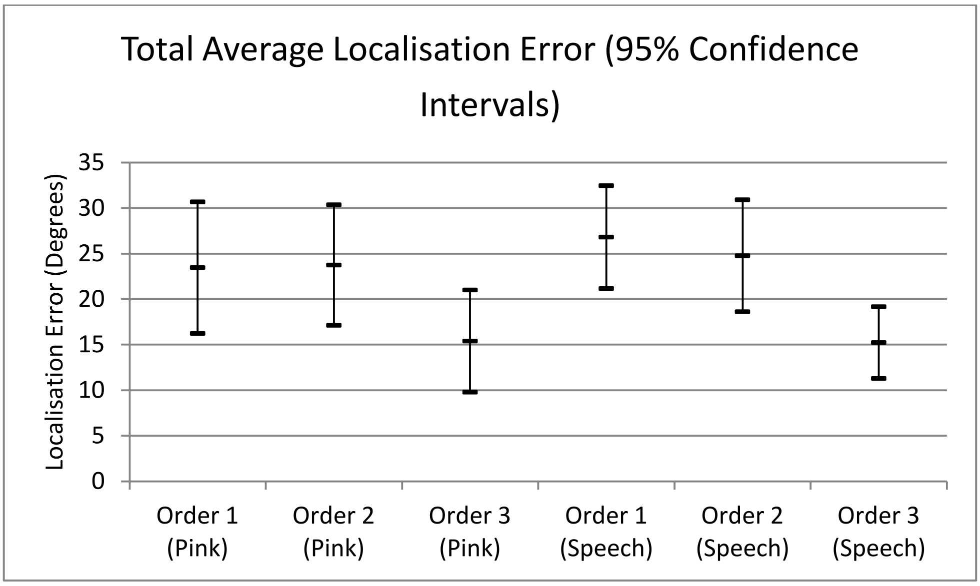

Figure 7- Mean and 95% Confidence Intervals for Total Average Elevation Error for Ambisonic Order and Sound Source

In order to determine if the performance of the 3rd order rendering was significantly different to that of the other renderings for speech or pink noise a one way ANOVA was carried out at the 0.5% significance level [23].

It was found that for the pink noise item no significant difference could be found between orders for elevated virtual sources $F(2,21) = 2.032, p > 0.05$

However carrying out a one way ANOVA of the elevated positions for the speech sample it was found that there were significant differences between orders $F(2,21) = 5.17, p < 0.05$.

In order to determine where the specific differences were between the orders a Bonferroni post hoc test was carried out, this showed that there was a significant difference between 1st and 3rd in terms of overall mean localisation error with 3rd order having a significantly smaller error, however there was no significant difference between 2nd and 3rd order, although this was a borderline case. See Table 2

(I) order	(J) order	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
order 1	order 2	2.04500	3.84654	1.000	-7.9612	12.0512
	order 3	11.59000*	3.84654	.020	1.5838	21.5962
order 2	order 1	-2.04500	3.84654	1.000	-12.0512	7.9612
	order 3	9.54500	3.84654	.065	-.4612	19.5512
order 3	order 1	-11.59000*	3.84654	.020	-21.5962	-1.5838
	order 2	-9.54500	3.84654	.065	-19.5512	.4612

*. The mean difference is significant at the 0.05 level.

Table 3- Bonferroni Multiple Comparisons for Total Average Elevation Error for Ambisonic Order

6 Discussion

It was noticeable from the initial inspection of the data, the inconsistency of the 1st and 2nd order compared to the 3rd order which placed sources with the least error and with similar localisation to that of real sources, this was also found for azimuth judgements. A factor that could have caused larger azimuth errors could be due to angular dispersion at higher frequencies as a function of order explained by Daniel [24]. Looking at the errors for elevated sources using pink noise this was not statistically significant. One reasonable explanation could be that the large amount of localisation cues provided by pink noise meant that participants were provided with a larger amount of cues to assist localisation, even when the order used was not able to place the source with much accuracy. Contrary to the case where significant differences were found between orders for the speech item which has a more limited frequency range. It was also documented by [11] that in terms of speech human hearing is very sensitive to speech, this could have made the participants more critical with the panned sources. It was also noticed that for the position constrained to the horizontal participants tended to place this off the horizontal, this was also evident for the real sources, and was also more pronounced for the 1st order rendering. Larger offsets were more evident for the pink noise source than speech, possibly due to more high frequency content, overestimation of elevated sound sources was also found by [11]

It was thought that the down with up confusions could have been caused by the close proximity of the lower speaker ring to the listener, however the 3rd order material did not suffer badly from this. So it is thought that due to the large number of speakers working in the 1st and 2nd order case this could have caused confusion for the listeners, contrary to the 3rd order case where fewer speakers are being used to place the virtual source.

It should be acknowledged there were a number of non ideal situations within the test design. Firstly the way the subject reported their answers which could have inflated the localisation errors, secondly and most notably the speaker array used was not a regular array. Due to factors previously explained, because of the distribution of speakers eight on the horizontal and only four above and below it could be said that for sources placed on the horizontal there would be an unfair advantage to third order, contrary to this elevated sources would only have four speakers thus disadvantaging second and third order. It is striking that the 3rd order system did perform reasonably in light of the rules regarding Ambisonic reproduction, and regular 3D rigs. Not surprisingly 1st order is particularly bad at placing sources, this could also be said for 2nd order however with less confidence since the difference overall is not significant when compared to 3rd order. The previous statement is only valid for the speech item since using the pink noise sample no difference could be found between orders, which to a certain extent answers the question regarding localisation accuracy and sound source, certainly in this case, and under semi anechoic conditions. However in general the results indicate that 3rd order Ambisonics is more effective at accurately localising panned sources than lower order systems, although localisation accuracy remains below the limit set by the human hearing and indicated by the results for the real sources. It is possible that 4th or higher order reproduction may be required to achieve vertical localisation accuracy as good as human hearing. However in terms of requirement for mixed order systems it should be noted that the results presented above were obtained under semi anechoic conditions, and in real world reverberant environments the highest Ambisonic order required for the vertical plane might be considerably lower.

Providing recommendations on which order performs best remains difficult. Elevated sound sources with limited bandwidth may require more accuracy to allow accurate localisation, while more diffuse material could make use of lower order reproduction, a clue to this can be found in the work conducted by Baume and Churnside [25] using 1st order recordings, it was found that for speakers above and below participants there was a clear preference for atmospheric non directional content, whereas for music where sources are mainly in the horizontal plane, there was no clear preference for high and low speakers. It does seem that elevated sources placed towards the front of a listener are harder to localise than sources placed to the side, which seems counterintuitive, however sound sources placed to the side of the listener would generate larger level differences between the ears compared with a sound source placed in front [26]

7 Conclusions

Three different orders of Ambisonic decoding have been evaluated in terms of localisation using a 3D speaker array in semi anechoic conditions using 2 different sound sources. It has been found that localisation accuracy is not consistent for 1st and 2nd order with 3rd order providing more consistent results overall. Significant differences were found between 1st and 3rd order for the speech sample, although no difference was found between orders for the pink noise sample, suggesting that the use of order for elevated sound sources may be dependent on the desired accuracy of localisation and the frequency content of the sound source.

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