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A Comparative Approach to Sound Localisation within a 3D Sound Field

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ABSTRACT

In this paper we compare different methods for sound localisation around and within a 3D sound field. The first objective is to determine which form of panning is consistently preferred for panning sources around the speaker array. The second objective and main focus of the paper is localising sources within the speaker array. We seek to determine if the sound sources can be located without movement or a secondary reference source. The authors compare various techniques based on ambisonics, vector base amplitude panning and time delay based panning. We report on subjective listening tests that show which method of panning is preferred by listeners, and rate the success of panning within a 3D speaker array.

1. INTRODUCTION

Sound localisation is a natural process carried out by humans on a day to day basis. This localisation process helps us to determine where a sound is coming from. We can determine the azimuth and elevation as well as distance of the source object. In natural hearing, two of the main properties that are used to locate a sound source are the interaural amplitude difference and the interaural time difference (later referred to as IAD and ITD). Most panning techniques of sound are based on the amplitude differences of sources to place a sound between two or more loudspeakers.

It is the authors' objective in this paper to determine whether or not a listener can perceive the relative distance between his or herself and the placement of a source in a loudspeaker array. A relative distance is used because mixes for music, film and games are created for loudspeaker arrays where angles of displacement are given, but there is no distance for each speaker. It is common that all loudspeakers should be equidistant from the user.

The focus of the paper is to compare various localisation techniques used to place a point source within a three dimensional (3D) speaker array. It is an ability in most digital audio workstation software

(DAWs) for the user to place a source inside the speaker array when working with consumer surround formats such as 5.1 and 7.1 as examples. Thus, to recommend for a 3D localisation technique, it must have the ability to pan inside the speaker array. To this effect listening tests will be carried out to determine if the listeners perceive a sense of a source being closer to them than the speakers are when there is no other reference source to help indicate this and when the sound source is not moving.

The overall objective is to provide a recommendation for a panning technique to be used if the sound source is positioned anywhere inside or around the speaker array. If this is not possible, we aim to suggest different preferred techniques that provide the most accurate results around the array or inside the array, dependant on the end users' intent of source positioning.

2. LOCALISATION TECHNIQUES

In this paper we compare five localisation techniques that are used to pan sources in a 3D speaker array. As most methods do not pan a source within the speaker array an 'opposite source' approach is taken. The opposite source uses a 2nd panned source that is opposite the intended azimuth and elevations angles to give the sense of the sound being placed within the speaker array. The two sources use a sine/cosine rule to keep the sound energy constant; this is in essence a stereo pan between the two sources. All the methods compared have been presented as academic research and some have been implemented into end user software. The different methods to be tested all use a different amount of speakers to place a point source. To place a source within the speaker array the two Ambisonics methods would use up to 16 speakers whilst the Vector Base Amplitude Panning (VBAP) and Interaural Time Delay methods would use a maximum of 6 speakers at once. The methods being compared are as follows:

- 3rd Order Ambisonics using Furse-Malham Weightings
- B Format Inside Panner
- Interaural Time Delay
- Vector Base Amplitude Panning
- Vector Base Amplitude Panning with Interaural Time Delay

2.1. 3rd Order Ambisonics using Furse-Malham Weightings

Ambisonics is based on the theory of spherical harmonics originally introduced by Michael Gerzon [1]. In this technique a sound source is split into directional components that represent the sound based on a given azimuth and elevation angle. This localisation technique represents the traditional use of Ambisonics with the Furse-Malham (FuMa) weightings [2] as seen in equation (1). For this method the opposite source approach is used to pan inside the speaker array as seen in equation (2).

In equation (1), S_i is the input signal, W is the omnidirectional zeroth order component, X, Y and Z are the first order directional components, R through V are the second order directional components and K through Q are the third order directional components. The inputted azimuth is given as θ, and the elevation angle as ϕ. The azimuth goes from 0° in front of the listener clockwise to 360° and the elevation starts at 0° to be on level with the listener to 90° for directly above and -90° for directly below.

$$
\begin{aligned}
&W = S_i/\sqrt{2},\ X = S_i\cos\theta\cos\phi,\ Y = S_i\sin\theta\cos\phi,\ Z = S_i\sin\phi \\
&R = S_i(3\sin^2\phi - 1)/2,\ S = 2S_i\cos\theta\sin(2\phi)/\sqrt{3} \\
&T = 2S_i\sin\theta\sin(2\phi)/\sqrt{3},\ U = 2S_i\sin(2\theta)\cos^2\phi/\sqrt{3} \\
&V = 2S_i\sin(2\theta)\cos^2\phi/\sqrt{3},\ K = S_i\sin\phi(5\sin^2\phi - 3)/2 \\
&L = \sqrt{\frac{45}{32}}S_i\cos\theta\cos\phi(5\sin^2\phi - 1) \\
&M = \sqrt{\frac{45}{32}}S_i\sin\theta\cos\phi(5\sin^2\phi - 1) \\
&N = 3S_i\cos(2\theta)\sin\phi\cos^2\phi/\sqrt{5},\ O = 3S_i\sin(2\theta)\sin\phi\cos^2\phi/\sqrt{5} \\
&P = \sqrt{\frac{8}{5}}\cos(3\theta)\cos^3\phi S_i,\ Q = \sqrt{\frac{8}{5}}\sin(3\theta)\cos^3\phi S_i
\end{aligned}
\tag{1}
$$

Equation (2) shows the sine/cosine method for panning within the speaker array. S_1 is the original panning position with S_2 being the opposite location. The user control when panning is σ, which gives a relative value between 0 for the central position to 1 for the speaker array and is given to three decimal places. This value is multiplied by 45° to work on the sine/cosine scale to provide equal energy.

$$S_1 = \cos(45\sigma), S_2 = \sin(45\sigma) \quad (2)$$
$$0.000 \le \sigma \le 1.000$$

2.2. B Format Inside Panner

The B Format Inside Panner [3] is a first order method of Ambisonics that is designed to pan inside the speaker array. This technique can be categorized alongside Penha's [4] and Menzies [5] techniques for inside panning. These three methods work on the principal of increasing the *W* omnidirectional component whilst decreasing *X*, *Y* and *Z* directional components. As shown in equation (3), the B Format Inside Panner uses a linear variable *a* to increase/decrease the *W* value whilst decreasing/increasing the *X*, *Y* and *Z* values. In this case $S_i / 2$ is used so that the *W* channel does not exceed its intended maximum value.

$$W = \frac{(1+a)}{\sqrt{2}} S_i / 2, X = (1-a)\cos\theta\cos\phi S_i / 2$$
$$Y = (1-a)\sin\theta\cos\phi S_i / 2, Z = (1-a)\sin\phi S_i / 2 \quad (3)$$
$$0 \le a \le 1$$

2.3. Interaural Time Delay

Interaural time delays are an integral part of human hearing. When measuring head related transfer functions (HRTFs) from a dummy head or using HRTFs for binaural reproduction, ITD is automatically included as well as IAD, since without it the result would not be as natural to the listener as possible. Panning between two loudspeakers can be achieved by delaying the signal by 1.0ms in the right speaker to pan to the left speaker and by delaying the signal by 1.0ms in the left speaker to pan to the right speaker. In a 3D implementation, a triplet of speakers is fed the same signal and time delays are calculated for each speaker to position the sound source anywhere inside the triplet. Equation (3) shows the formula used to calculate *delay*$_n$, the delay for a speaker in the triplet. This equation approximates the curve shown by Zölzer [6]. This method also uses the opposite source approach as given in equation (2).

$$delay_n = 10^{\delta/20} / 30 \quad (3)$$
$$-30^\circ \le \delta \le 30^\circ$$

In the implementation of the ITD panner provided in this paper, gain values from VBAP are converted to ITD values and gain of 1.0 is applied to all speakers within the triplet. To calculate the conversion, the implementation did the following:

- $\sin^{-1}(\sum g_{\neq n}{}^2)$ is found, where g_n is the gain of the speaker being calculated
- if greater than 45 then calculate delay, else apply no time delay
- subtract 45
- multiply by $30/45$
- answer is δ, substitute into equation (3)

2.4. Vector Base Amplitude Panning

Vector Base Amplitude Panning was introduced by Pulkki [7][8]. This technique uses a triplet of speakers with gain weightings to pan a point source in a 3D speaker array. In a 2D case VBAP gives the same results as the tangent law for amplitude panning. Vectors are calculated for the point source using equation (7), which is identical to the first order Ambisonics equations for X, Y and Z found in equation (1).

$$p_x = \cos\theta\cos\phi, p_y = \sin\theta\cos\phi, p_z = \sin\phi \quad (7)$$

The gain coefficients for the triplet of speakers is then calculated using equation (8).

$$g_{123} = p^T L_{123}{}^{-1} = \left[p_x p_y p_z \right] \begin{pmatrix} l_{1x} & l_{1y} & l_{1z} \\ l_{2x} & l_{2y} & l_{2z} \\ l_{3x} & l_{3y} & l_{3z} \end{pmatrix}^{-1} \quad (8)$$

Where g_{123} is the gains for speakers 1, 2 and 3, p^T is the transpose of the point source vector and L_{123} is the inverse matrix of the loudspeaker triplet.

The gain coefficients are then normalized using equation (9) to keep constant energy when panning around the speaker array.

$$\sqrt{g_1{}^2 + g_2{}^2 + g_3{}^2} = 1 \quad (9)$$

This method uses the opposite source approach as stated in equation (2).

2.5. Vector Base Amplitude Panning with Interaural Time Delay

The authors decided to implement VBAP and ITD so that there was a method being compared that included both IAD and ITD. Using both techniques together means that there are two cues given to the listener to locate a source. This could provide the listener with more location information for the hearing mechanism to locate the source. As with both the IAD and VBAP implementation, the opposite source approach is applied to pan inside the speaker array.

3. TESTING

For performing the test, four different stationary source positions were chosen within the 3D speaker array. The positions were chosen to include varying azimuths, elevations and inside values. The listening test was performed by 8 candidates, at Queen Mary University of London all with previous experience of research in the audio field. The speaker array, configured in the Centre for Digital Music at Queen Mary University of London's Listening Room, used features 16 speakers over 3 tiers that are position as listed in table 1.

All candidates took an initial three question test to determine their audio spatial awareness. The candidates heard the same music three times, coming from an individual speaker each time. The candidates had to select which speaker the music was coming from. All candidates were able to locate sound effectively under those conditions.

For the listening tests, there were a total of 20 questions, each of the 4 positions was tested using each of the 5 techniques discussed in Section 2. Twenty different sound clips were used, 5 of a band, 5 of a solo vocalist, 5 of saxophone and 5 of acoustic guitar and vocals. Each listener never heard the same sound sample for more than 1 question, the order of questions was randomized and the playlist used was also randomized. The music type was easy to listen to; popular song/jazz standard with simple tonal harmony. This was chosen over sounds such as noise bursts or pink noise as the authors felt this was a more natural comparison to the sounds people are used to listening to and represented an end use of the techniques. Sound clips were approximately 20-25 seconds long and listeners played them 2-3 times each with the total testing last no more than 30minutes. Each listener took the tests individually and were stood in the centre of the speaker array.

3.1. Test 1

In the first test, a stationary source was placed on the speaker array in front and to the right of the listener with a slight elevation $\theta = 35.0, \phi = 15.0, \sigma = 1.000$ where θ is the source azimuth, ϕ the source elevation and σ the relative inside value.

Speaker	Azimuth Angle	Elevation Angle
1	0.0	90.0
2	0.0	0.0
3	41.9	0.0
4	94.6	0.0
5	150.6	0.0
6	-152.4	0.0
7	-94.5	0.0
8	-44.0	0.0
9	0.0	28.3
10	90.0	27.2
11	180.0	26.7
12	-90.0	27.5
13	-45.0	-29.0
14	45.0	-30.0
15	135.0	-25.9
16	-135.0	-27.8

Table 1 Speaker Positions

This test was used to determine which source localises best on the speaker array. The use of a forward angle with little height places the sound in an easy to localize position. The results of this test can be seen in table 2, where Δ is used to refer to the distance between the intended position or angle, and the position or angle as perceived by the listener. ΔX, ΔY and ΔZ represent front-back, right-left and up-down respectively to stay with convention as shown in [7].

The results of this test show that the 3rd Order Ambisonics method has the least average azimuth and elevation angle away from the source location and also the lowest standard deviation. The ITD approximation has the largest average azimuth difference, whilst for elevation angle, 3rd Order Ambisonics and VBAP have similar results even though for azimuth angle VBAP had the largest average difference. When comparing the average Euclidean distance both the 3rd Order Ambisonics and VBAP methods have very similar results.

3.2. Test 2

The second position was used to find out if listeners could tell where a sound source was coming from when it was set just under half the distance between the listener and the speaker array. The values used were $\theta = -55.0, \phi = 0.0, \sigma = 0.450$.

The results from table 3 reveal that there was overall a higher average distance when comparing position 2 with position 1. In this test VBAP with ITD had the lowest average azimuth and elevation difference as well as the lowest average Euclidian distance. 3rd Order Ambisonics had the lowest average for the inside position. The 3rd Order Ambisonics method uses more speakers than any other method to locate a source inside the speaker array. The diffuseness of 3rd Order Ambisonics explains the higher perceived inside values and explains also why the location of the source was not perceived as well as any other methods.

Figure 1 depicts the perceived locations of the source, as well as the intended location and the location of the listener. The plot is oriented such that the listener is facing towards the top (front is straight ahead of the listener), bottom represents behind the listener, and left/ right are left/right of listener). Thus, the listeners' selected X values are on the graph's Y axis and vice versa in accordance to Ambisonic and VBAP coordinates [2][7]. Elevation was ignored as the source position had an elevation of 0°. The figure indicates that users could generally locate the source correctly as being ahead and to the left of the listener, though ITD was consistently perceived as having less forward positioning. for the most part, however, sources were localised closer to the front position than intended.

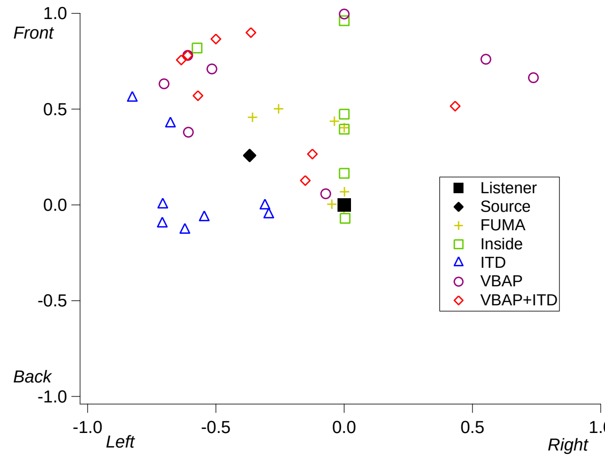

Figure 1 Perceived source positions for all evaluations in Test 2. The intended source was placed 55 conterclockwise from the listener, and at a radial distance of 0.45, where 1 represents placement on the speaker array.

3.3. Test 3

The third test was used to determine if listeners could tell when a sound that was behind and below them was perceived at the intended position when it was moved just inside the speaker array. The values used were $\theta = -165.0, \phi = -20.0, \sigma = 0.800$.

The results of this test are given in table 4. It can be seen that the listeners did think the source had moved off the speaker array for all but the ITD method. The 3rd Order Ambisonics outperformed the other methods for this position in all aspects but when considering the Euclidean distance the VBAP and VBAP with ITD methods gave reasonable results.

3.4. Test 4

The final position used was as follows $\theta = 90.0, \phi = 45.0, \sigma = 0.100$.

The results as given in table 5 show that when the source is very close to the listener's head, 3rd Order Ambisonics gave the best results. This method had the lowest azimuth and elevation difference averages as well as having the smallest Euclidean distance from the intended source. The two VBAP based methods also gave consistent results compared to the other positions and were not significantly worse than the 3rd Order Ambisonics results.

4. CONCLUSIONS

The preliminary results obtained by the authors indicate that when placing sounds on or inside the speaker array, using 3rd Order Ambisonics gives the best intended results. The results show that listeners do perceive sounds closer to them than the speaker array without the source moving or there being a secondary source for comparison. The Vector Base Amplitude Panning methods also performed very well and in one test placed the sound inside the array better than 3rd Order Ambisonics. The results also indicate that using a localization method based on ITD alone yields poor localization results and the common use of amplitude based panning is justified.

5. FURTHER WORK

The authors regard this work as ongoing and realise that the use of only four source positions and eight listeners does not give authorative results. Further work will be based on these preliminary results to build solid conclusions on spatial localisation. It can be seen that perceived angles and intended angles do not always coincide even when the source is on the speaker array, this can lead to further investigation and this behaviour has been documented by Griesinger [9].

The authors would like to further investigate VBAP techniques and carry out tests using different ITD models in conjunction with VBAP. Investigations are ongoing into the possibility to extend VBAP. For instance, features such as rotate, tilt and tumble, which are part of Ambisonics, may be incorporated into a VBAP model alongside any other features found in common DAW applications. Future work will include listening tests with more localisation positions and could move the listener away from the sweet spot for testing of localisation throughout the listening space.

6. ACKNOWLEDGEMENTS

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	Listener	1	2	3	4	5	6	7	8	**Average**	**Std Dev**
Δ Azimuth	Fuma	-9	-29	-2	-23	-49	-8	5	2	14.11	18.334
	Inside	-26	-25	-19	-29	35	12	-32	7	20.56	24.506
	ITD	-17	-47	-23	-5	-78	-103	-34	-19	36.22	33.759
	VBAP	35	27	35	-1	0	-145	35	-19	33.00	60.539
	VBAP+ITD	35	35	35	-2	35	35	35	-57	29.89	33.280
Δ Elevation	Fuma	-17	-32	-50	45	-61	20	15	23	29.22	38.372
	Inside	-33	-20	-47	-52	-75	-51	-5	27	34.44	32.049
	ITD	-7	-69	-44	81	-62	-14	0	15	32.44	48.288
	VBAP	-45	-21	-12	15	15	-75	15	-69	29.67	37.330
	VBAP+ITD	-14	-37	15	55	-61	-52	-75	-68	41.89	45.463
Δ Inside	Fuma	0.087	0.787	0.000	0.330	0.092	0.121	0.398	0.378	0.244	0.256
	Inside	0.049	0.646	0.000	0.252	0.169	0.879	0.033	0.068	0.233	0.325
	ITD	0.000	0.621	0.432	0.325	0.559	0.179	0.719	0.000	0.315	0.276
	VBAP	0.082	0.000	0.000	0.389	0.277	0.859	1.000	0.582	0.354	0.385
	VBAP+ITD	0.374	0.155	0.000	0.213	0.091	0.700	0.427	0.943	0.323	0.322
Δ X	Fuma	0.234	0.728	0.454	0.484	0.768	0.151	0.270	0.275	0.374	0.230
	Inside	0.483	0.646	0.515	0.663	0.791	0.746	0.436	-0.014	0.477	0.254
	ITD	0.220	0.786	0.636	0.581	0.830	1.325	0.694	0.203	0.586	0.358
	VBAP	0.332	-0.010	-0.100	0.297	0.199	0.791	0.791	0.766	0.365	0.361
	VBAP+ITD	0.244	0.271	-0.209	0.310	0.571	0.674	0.791	0.791	0.429	0.343
Δ Y	Fuma	0.016	0.423	0.300	0.062	0.336	-0.043	0.253	0.219	0.184	0.166
	Inside	-0.003	0.303	0.174	0.291	0.554	0.535	-0.282	0.126	0.252	0.276
	ITD	-0.177	0.515	0.306	0.378	0.463	0.074	0.301	-0.255	0.274	0.289
	VBAP	0.554	0.441	0.554	0.195	0.139	0.554	0.554	0.519	0.390	0.173
	VBAP+ITD	0.554	0.554	0.554	0.191	0.554	0.554	0.554	0.547	0.451	0.128
Δ Z	Fuma	-0.225	0.103	-0.647	0.594	-0.622	0.335	0.259	0.345	0.348	0.465
	Inside	-0.448	0.056	-0.624	-0.430	-0.572	0.148	-0.072	0.453	0.311	0.389
	ITD	-0.116	-0.118	-0.228	0.875	-0.171	-0.139	0.186	0.259	0.232	0.370
	VBAP	-0.536	-0.329	-0.195	0.259	0.259	0.118	0.259	-0.157	0.235	0.307
	VBAP+ITD	-0.045	-0.407	0.259	0.765	-0.623	-0.017	-0.314	0.202	0.292	0.438
Source-Answer	Fuma	0.325	0.848	0.846	0.768	1.044	0.370	0.452	0.492	0.572	0.266
Distance	Inside	0.659	0.716	0.828	0.842	1.123	0.930	0.525	0.470	0.677	0.215
	ITD	0.305	0.947	0.742	1.116	0.966	1.334	0.779	0.416	0.734	0.343
	VBAP	0.840	0.551	0.596	0.439	0.355	0.973	1.000	0.938	0.632	0.256
	VBAP+ITD	0.607	0.739	0.646	0.847	1.011	0.873	1.016	0.983	0.747	0.162

Table 2 Test 1 Results

	Listener	1	2	3	4	5	6	7	8	**Average**	**Std Dev**
ΔAzimuth	Fuma	-56	-55	-50	-17	-28	123	-55	31	46.11	62.585
	Inside	-55	-55	-55	-55	-20	125	-55	128	60.89	82.214
	ITD	36	42	35	45	1	47	3	43	28.00	18.670
	VBAP	-91	-19	-17	-4	-55	-103	-7	3	33.22	41.245
	VBAP+ITD	-25	-10	-15	-95	-33	-5	-30	-17	25.56	28.449
ΔElevation	Fuma	-83	-90	-64	30	-10	-85	0	-85	49.667	47.530
	Inside	-60	-32	-16	0	0	-90	-90	-51	37.667	36.481
	ITD	-72	-45	-45	-60	5	-45	-37	-35	38.222	22.467
	VBAP	-20	-15	-8	25	-5	-7	7	-14	11.222	14.451
	VBAP+ITD	0	0	-9	30	-14	-14	19	-8	10.444	16.018
Δ Inside	Fuma	-0.113	0.368	-0.55	-0.22	-0.122	0.193	0.047	-0.103	0.191	0.276
	Inside	-0.497	-0.016	-0.55	0.285	-0.550	-0.448	0.212	0.338	0.322	0.397
	ITD	-0.550	-0.327	-0.55	-0.147	-0.550	-0.448	-0.550	-0.424	0.394	0.145
	VBAP	-0.550	-0.458	-0.55	0.348	-0.550	-0.550	-0.502	-0.288	0.422	0.310
	VBAP+ITD	-0.550	-0.356	-0.55	-0.327	-0.550	0.246	0.140	-0.550	0.363	0.326
Δ X	Fuma	0.190	0.258	-0.179	-0.199	-0.244	0.280	-0.145	0.255	0.194	0.237
	Inside	-0.215	-0.137	-0.703	0.093	-0.561	0.258	0.258	0.328	0.284	0.390
	ITD	0.264	0.325	0.258	0.310	-0.299	0.390	-0.165	0.358	0.263	0.261
	VBAP	-0.502	-0.451	-0.522	0.200	-0.738	-0.406	-0.374	-0.121	0.368	0.285
	VBAP+ITD	-0.608	-0.312	-0.499	-0.257	-0.642	0.131	-0.008	-0.522	0.331	0.283
ΔY	Fuma	-0.370	-0.369	-0.330	-0.011	-0.113	-0.368	-0.369	-0.321	0.250	0.139
	Inside	-0.369	-0.369	-0.369	-0.369	0.205	-0.369	-0.369	-0.372	0.310	0.203
	ITD	-0.060	0.177	0.338	-0.075	0.457	0.252	0.309	0.340	0.223	0.193
	VBAP	-0.921	0.147	0.241	-0.297	-0.369	-1.106	0.334	0.239	0.406	0.557
	VBAP+ITD	0.131	0.201	0.266	0.064	-0.005	-0.217	-0.245	0.241	0.152	0.198
Δ Z	Fuma	-0.559	-0.082	-0.899	0.335	-0.099	-0.256	0.000	-0.551	0.309	0.389
	Inside	-0.820	-0.247	-0.276	0.000	0.000	-0.898	-0.238	-0.087	0.285	0.350
	ITD	-0.951	-0.549	-0.707	-0.517	0.087	-0.635	-0.602	-0.501	0.506	0.294
	VBAP	-0.342	-0.235	-0.139	0.043	-0.087	-0.122	0.116	-0.179	0.140	0.146
	VBAP+ITD	0.000	0.000	-0.156	0.389	-0.242	-0.049	0.101	-0.139	0.120	0.194
Source-Answer	Fuma	0.696	0.457	0.974	0.390	0.286	0.529	0.396	0.686	0.491	0.223
Distance	Inside	0.925	0.464	0.840	0.380	0.597	1.004	0.509	0.504	0.580	0.236
	ITD	0.989	0.662	0.825	0.607	0.553	0.787	0.696	0.704	0.647	0.137
	VBAP	1.103	0.530	0.592	0.360	0.830	1.185	0.515	0.322	0.604	0.326
	VBAP+ITD	0.622	0.371	0.586	0.470	0.686	0.258	0.265	0.592	0.428	0.166

Table 3 Test 2 Results

	Listener	1	2	3	4	5	6	7	8	Average	Std Dev
Δ Azimuth	Fuma	-1	-28	14	-45	15	14	-7	-3	14.11	21.630
	Inside	-165	-165	14	-15	-165	7	15	-122	74.22	86.892
	ITD	-165	-165	-165	-30	-165	-165	-165	-165	131.67	47.730
	VBAP	15	-10	-34	-30	-165	-26	-11	5	32.89	56.361
	VBAP+ITD	154	-6	-4	-34	15	-15	14	1	27.00	58.086
Δ Elevation	Fuma	-38	-20	-36	-20	-2	-17	10	-24	18.556	16.071
	Inside	-58	-78	-54	-79	-59	-69	-92	-16	56.111	22.956
	ITD	-79	-56	-65	-20	-64	-76	-92	-32	53.778	24.142
	VBAP	20	35	-29	-70	-26	-11	39	18	27.556	37.675
	VBAP+ITD	-32	36	-20	-48	27	2	37	43	27.222	35.298
Δ Inside	Fuma	-0.20	0.543	-0.20	0.626	-0.2	-0.20	-0.142	0.096	0.245	0.351
	Inside	-0.143	0.587	-0.20	-0.069	-0.079	0.47	-0.113	-0.20	0.207	0.312
	ITD	-0.20	-0.20	-0.20	0.16	-0.20	0.014	-0.20	-0.20	0.153	0.138
	VBAP	-0.20	-0.035	-0.20	0.208	0.047	0.057	-0.20	0.198	0.127	0.172
	VBAP+ITD	-0.20	0.115	-0.20	-0.181	0.066	-0.084	-0.20	-0.094	0.127	0.126
Δ X	Fuma	0.188	-0.538	0.235	-0.639	0.225	0.272	0.030	-0.058	0.243	0.360
	Inside	-1.469	-0.839	0.103	-0.339	-1.409	-0.512	-0.444	-1.456	0.730	0.596
	ITD	-1.241	-1.535	-1.433	-0.274	-1.445	-1.166	-1.035	-1.704	1.093	0.441
	VBAP	0.040	-0.292	-0.078	-0.457	-1.475	-0.172	-0.263	-0.259	0.337	0.471
	VBAP+ITD	-1.464	-0.369	0.219	-0.158	-0.226	-0.016	-0.182	-0.332	0.330	0.500
Δ Y	Fuma	0.068	-0.019	-0.178	-0.044	-0.195	-0.177	0.111	0.022	0.090	0.119
	Inside	-0.195	-0.195	-0.180	0.029	-0.195	-0.164	-0.195	0.486	0.182	0.240
	ITD	-0.195	-0.195	-0.195	0.258	-0.195	-0.195	-0.195	-0.195	0.180	0.160
	VBAP	-0.195	0.008	0.551	0.075	-0.195	0.287	0.031	-0.112	0.161	0.255
	VBAP+ITD	-0.836	-0.057	0.131	0.459	-0.195	0.215	-0.185	-0.096	0.242	0.381
Δ Z	Fuma	-0.583	-0.274	-0.549	-0.274	0.035	-0.221	0.197	-0.323	0.273	0.264
	Inside	-0.854	-0.454	-0.833	-1.018	-0.827	-0.523	-1.142	-0.204	0.651	0.313
	ITD	-1.131	-0.861	-0.981	-0.274	-0.968	-0.925	-1.225	-0.482	0.761	0.322
	VBAP	0.369	0.410	-0.430	-0.727	-0.352	-0.157	0.584	0.097	0.347	0.465
	VBAP+ITD	-0.482	0.294	-0.274	-0.734	0.263	0.058	0.565	0.523	0.355	0.477
Source-Answer	Fuma	0.616	0.604	0.623	0.697	0.299	0.393	0.228	0.329	0.421	0.180
Distance	Inside	1.711	0.974	0.858	1.074	1.645	0.750	1.241	1.548	1.089	0.371
	ITD	1.690	1.771	1.748	0.465	1.751	1.501	1.615	1.782	1.369	0.445
	VBAP	0.419	0.504	0.703	0.862	1.529	0.370	0.641	0.298	0.592	0.396
	VBAP+ITD	1.754	0.475	0.374	0.880	0.397	0.223	0.622	0.627	0.595	0.481

Table 4 Test 3 Results

	Listener	1	2	3	4	5	6	7	8	**Average**	**Std Dev**
Δ Azimuth	Fuma	1	16	-1	-22	42	-36	0	0	13.11	23.305
	Inside	84	90	90	30	90	-91	90	91	72.89	64.180
	ITD	0	-3	25	-20	64	0	0	72	20.44	33.665
	VBAP	0	30	-3	-38	58	42	-1	-75	27.44	43.237
	VBAP+ITD	0	2	0	-85	-91	55	33	-59	36.11	54.086
Δ Elevation	Fuma	28	-2	6	9	45	1	0	-38	14.33	24.127
	Inside	-40	-23	45	-35	-37	19	-15	45	28.78	36.152
	ITD	34	29	21	-32	45	-25	14	49	27.67	30.310
	VBAP	-8	19	28	-45	36	-7	19	19	20.11	26.284
	VBAP+ITD	-12	-5	12	25	63	-16	45	20	22.00	27.800
Δ Inside	Fuma	0.000	0.651	0.000	0.665	0.836	0.510	0.233	0.597	0.388	0.319
	Inside	0.019	0.000	1.000	0.330	0.083	0.976	0.267	0.612	0.365	0.408
	ITD	0.000	0.111	0.000	0.165	0.000	0.480	0.354	0.082	0.132	0.179
	VBAP	0.000	0.490	0.000	0.442	0.000	0.427	0.364	0.971	0.299	0.335
	VBAP+ITD	0.000	0.334	0.000	0.840	0.389	0.291	0.427	0.660	0.327	0.290
Δ X	Fuma	-0.017	-0.066	0.014	0.102	-0.110	0.207	0.000	0.000	0.057	0.099
	Inside	-0.085	-0.375	0.000	-0.058	-0.128	0.022	-0.367	-0.388	0.158	0.175
	ITD	0.000	0.045	-0.386	0.064	-0.899	0.000	0.000	-0.871	0.252	0.414
	VBAP	0.000	-0.229	0.050	0.000	-0.838	-0.236	0.010	0.025	0.154	0.299
	VBAP+ITD	0.000	-0.015	0.000	0.150	0.581	-0.282	-0.312	0.264	0.178	0.290
Δ Y	Fuma	-0.249	0.478	-0.070	0.456	0.585	0.422	0.165	0.658	0.343	0.324
	Inside	0.698	0.707	0.707	0.606	0.707	0.707	0.707	0.714	0.617	0.036
	ITD	-0.275	-0.146	-0.121	0.531	0.269	0.529	0.153	0.424	0.272	0.320
	VBAP	0.105	0.310	-0.248	0.707	0.184	0.445	0.136	0.700	0.315	0.322
	VBAP+ITD	0.162	0.279	-0.132	0.694	0.717	0.510	0.227	0.548	0.363	0.293
Δ Z	Fuma	0.415	0.452	0.078	0.510	0.707	0.367	0.165	0.307	0.333	0.198
	Inside	-0.270	-0.220	0.707	0.047	-0.201	0.697	0.072	0.707	0.325	0.441
	ITD	0.516	0.462	0.300	-0.106	0.707	0.218	0.374	0.771	0.384	0.280
	VBAP	-0.092	0.484	0.415	0.149	0.551	0.256	0.428	0.694	0.341	0.248
	VBAP+ITD	-0.132	0.197	0.162	0.652	0.896	0.087	0.707	0.563	0.377	0.360
Source-Answer	Fuma	0.484	0.661	0.105	0.692	0.924	0.596	0.233	0.726	0.491	0.269
Distance	Inside	0.753	0.830	1.000	0.611	0.746	0.993	0.800	1.077	0.757	0.158
	ITD	0.585	0.487	0.504	0.545	1.175	0.573	0.405	1.238	0.612	0.325
	VBAP	0.140	0.618	0.486	0.723	1.019	0.565	0.449	0.987	0.554	0.289
	VBAP+ITD	0.209	0.342	0.209	0.964	1.286	0.589	0.805	0.829	0.582	0.387

Table 5 Test 4 Results