# PERCEPTUAL INVESTIGATION OF IMAGE PLACEMENT WITH AMBISONICS FOR NON-CENTRED LISTENERS

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## ABSTRACT

Ambisonics is a scalable spatial audio technique that attempts to present a sound scene to listeners over as large an area as possible. A localisation experiment was carried out to investigate the performance of a first and third order system at three listening positions - one in the centre and two off-centre. The test used a reverse target-pointer adjustment method to determine the error, both signed and absolute, for each combination of listening position and system. The signed error was used to indicate the direction and magnitude of the shifts in panning angle introduced for the off-centre listening positions. The absolute error was used as a measure of the performance of the listening position and systems combinations for a comparison of their overall performance. A comparison was made between the degree of image shifting between the two systems and the robustness of their off-centre performance.

## 1. INTRODUCTION

Michael Gerzon [1] first proposed the theory behind Ambisonics in the 1970s as an alternative to the then prevalent quadraphonic systems. It is a multichannel reproduction technique that attempts to recreate a physical sound field over as large a listening area as possible. It is scalable and higher orders allow a larger listening area, but an increase in order also requires more loudspeakers to recreate the sound field [2].

In its most basic form, Ambisonics is used to reconstruct a plane wave by decomposing the sound field using spherical harmonic functions. This process is known as the encoding stage. In theory an infinite number of spherical harmonics must be used to recreate the sound field but in practice the series must be limited to a finite order $N$. An ambisonic reconstruction of order $N > 1$ is referred to as Higher Order Ambisonics (HOA) [2].

The encoded channels must be decoded to an appropriate loudspeaker array if the sound scene is to be presented to a listener. Ideally the array should have a regular layout, although decoding is possible to arrays that are irregular [3, 4]. The decoding process calculates the appropriate loudspeaker gains needed to recreate the sound field and the minimum number of loudspeakers required depends on the order of the reproduction. There are different weightings for decoding, such as basic, max $r_E$ [5] and in-phase [6], which are appropriate for different situations and different weightings can be used over different frequency ranges.

In-phase decoding was proposed in [6] for situations where a large number of the listeners cannot be in the sweet spot, such as the presentation of a sound scene to an audience. This is a compromise between the accuracy for a listener at the centre and for those outside the sweet-spot. However, max $r_E$ decoding [5] focusses the energy of the loudspeaker array toward the region of the recreated source. Its has been shown to give better localisation performance (ability to place an image using a loudspeaker array) for an off-centre listener than in-phase [7].

Due to the limited ambisonic order of the reproduction the sound field is only physically well reproduced up to a certain limit frequency. For a listening position at 0.6 m from the centre of the array (approximately one seat outside the centre) the signal is only well reproduced with basic decoding up to approximately 80 Hz and 230 Hz at first and third order respectively. This was calculated using the D-error [8] and defining the well reproduced frequency as being that which has less that -14 dB of error when compared to the ideal physical field. However, it is not clear how these indications compare to subjective performance that can be achieved when listening outside the sweet spot.

Previous off-centre tests into localisation have been carried out in rooms with moderately long reverberation times with irregular loudspeaker arrangements [7, 9]. In [7] the localisation performance of three decoding weightings was tested for orders 1, 3 and 5, along with a subjective rating of the localisation accuracy. In [9] the localisation performance was tested for a number of spatial audio systems at nine listening positions inside the array. This study also had multiple listeners inside the array who would block direct sound to other listeners. However, in both cases the test environments were somewhat reverberant. It therefore becomes difficult to disentangle the influence of the room, the irregularity of the reproduction array and the off-centre listening positions.

The experiment presented in this paper was intended to isolate the influence of sitting off-centre from that of the irregularity of the arrays and relatively long reverberation times present in the test conditions for these previous studies. It was specifically designed to investigate the localisation performance of ambisonic reproduction of two different orders (first and third) at three listening positions, including the centre as reference.

## 2. EXPERIMENT PROCEDURE

### 2.1. Experiment Overview

The experiment was designed to test the localisation performance for three listening positions using two ambisonic systems. The listening positions were at $(0, 0)$ m, $(0, -0.6)$ m and $(-0.42, 0.52)$ m, where the origin is the centre of the loudspeaker array, the x-axis is to the front and y-axis is to the left. The listening positions are called centre, right and back-left respectively throughout this

paper and are indicated in figure 1.

The two ambisonic systems were 1st order with a square loudspeaker layout (denoted o1spk4) and 3rd order with an octagonal loudspeakers with a vertex at the front (o3spk8). Both used the max $r_E$ decoding weighting. This was chosen over a basic decode because it was shown to give better localisation results for off-centre listeners [7].

## 2.2. Experiment Environment

### 2.2.1. Experiment Room

The experiment was performed in a listening studio in the Sonic Arts Research Centre with additional acoustic damping on the walls to reduce the reflections as much as possible. The room has dimensions 6.45 m $\times$ 5.44 m $\times$ 2.53 m. The broadband $t_{30}$ reverberation time was 0.095 s.

### 2.2.2. Loudspeaker Array

The array had a radius of 2.2m and consisted of eight equalised Genelec 1030a loudspeakers. They were placed at $0°$, $45°$, $90°$, $135°$, $180°$, $225°$, $270°$ and $315°$ and the loudspeakers used for the two ambisonic arrays and as targets are indicated in figure 1. All eight were used for the o3spk8 system. Those at $45°$, $135°$, $225°$ and $315°$ were used for the o1spk4 system. Two calibrated Genelec 1029a loudspeakers were placed at $30°$ and $240°$ and were not part of the ambisonic arrays. The base of the loudspeakers were 1.05 m from the ground and were at ear level when the subjects were seated in the test positions.

## 2.3. Experiment Design

### 2.3.1. Stimuli

The experiment was designed using the reverse acoustic-pointer method [10, 11, 12]. This procedure uses a static target sound recreated by a single loudspeaker and a dynamic, ambisonic pointer. The target and pointer sounds were amplitude modulated white noise with frequency range 20-20 kHz and duration of 206 ms, each with different modulation frequencies (7 Hz and 21 Hz respectively). They were presented alternately, starting with the target stimulus followed by a silence of 150 ms and then the pointer stimulus.

### 2.3.2. Experiment Procedure

The eight targets (shown in figure 1) were presented in a random order and were repeated 3 times for each of the two systems. This process was repeated at each of the three listening positions.

Listeners were provided with a dial and button interface. The dial moved the pointer sound around the listener with a resolution of $\pm 0.08°$ and the button allowed the subject to indicate that they had finished the current run and wished to move on to the next. The initial pointer panning angle was randomised such that

$$20° \leq |\text{initial pointer angle - target angle}| \leq 60°$$

The subjects' task was to use the dial to move the pointer sound so that it appeared to be arriving from the same direction as the target sound. The subjects were given a maximum of 25 target-pointer stimuli trials to complete the task. If the subject was satisfied that they had lined up the target and pointer before the 25
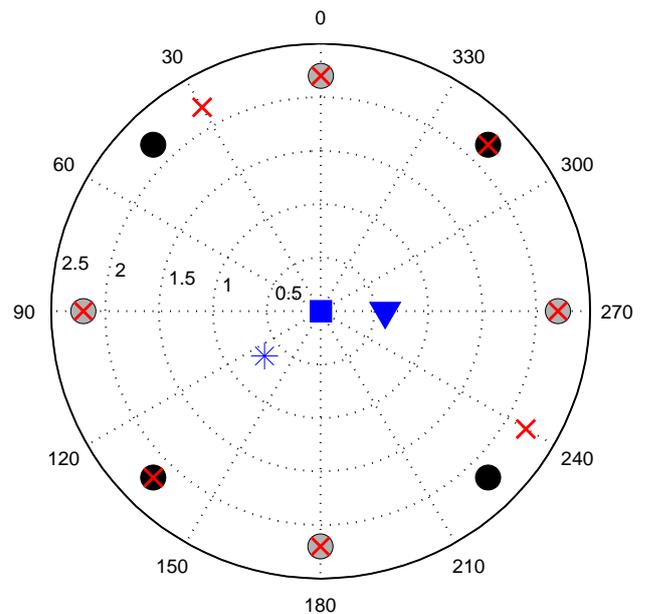


Figure 1: *The 10 loudspeaker positions used for the ambisonic arrays, the targets and the three listening positions. The eight loudspeakers used for the third order HOA array are circles and the four that were also used for the first order array are coloured black. Those used as targets are indicated by red crosses. The listening positions are shown as blue shapes around the centre.*

trials were completed they could press the button on the interface to move on to the next run. There was a 1 second silence upon pressing the button before the next run began.

The test was carried out at three listening positions, shown in figure 1 - centre, right and back-left. The order of the listening positions each subject took the test in was randomised to reduce the effect of any learning bias. Between each listening position the subjects were given the opportunity to have a short break to avoid them becoming fatigued.

Listeners were seated and instructed to keep their head still while they were performing the experiment and asked to avoid using spectral matching by comparing the spectra of the two stimuli for similarity when aligning the target and pointer stimuli.

The total number of conditions for each subject was 8 (target directions) $\times$ 2 (systems) $\times$ 3 (listening positions) = 48 and each condition was repeated 3 times giving a total of 144 runs. The whole experiment took between a minimum of 30 minutes and a maximum of 1 hour, including a short session to give the experiment instructions and training. The total time was dependent on how quickly the subject moved through the runs.

### 2.3.3. Training

The training was in two stages. Initially the subjects were given the opportunity to move the pointer sound using the dial. This was to allow them to adjust to the sensitivity of the dial. Secondly, they were given a practice of the main test procedure. Each of the targets was presented once and the system was randomly assigned, with four of the targets using o1spk4 and the others with o3spk8. The training was performed at the centre listening position for all

of the subjects. After the training they were moved to their randomly assigned position and carried out the main test.

## 2.4. Test Subjects

There was a total of 18 subjects who took part in the experiment, 3 women and 15 men, with an age range from 19 to 45. 11 of the subjects self reported as experienced at listening to spatial audio rendering. All three of the paper authors took the test. None of the subjects reported any hearing loss but no formal test was carried out before the experiment.

## 3. RESULTS

### 3.1. Influence of Parameters

A non-parametic analysis of variance (ANOVA) was performed on the absolute error (defined here as the magnitude of the difference between the ambisonic pointer angle and the target angle relative to the centre) was performed on the following factors 1) the system (o1spk4 or o3spk8), 2) repetition (1 to 3), 3) listening position. The results of each is given in the appropriate section. These tests were run for three groups: the three authors, subjects who reported as experienced listeners and the remaining, non-expert listeners. A non-parametric ANOVA was performed on the absolute error. No significant difference was found between these three groups ($\chi^2(2)$ = 2.03, p = 0.3617). Therefore the results of the authors have been included in the results presented here.

#### 3.1.1. Number of Target-Pointer Trials Taken

Given that the number of trials of target-pointer pairs during each run was limited to 25 (see section 2.3) it is worth considering the proportion of target-pointer runs during which the user was still moving the pointer on the final trial. Over the whole experiment and all three listening positions, 7.8% of the runs had the pointer still moving on the final trial, which is significantly lower than the 23.6% found by Bertet et al [10] when evaluating ambisonic microphones using a white noise pointer stimulus without amplitude modulation. The percentage of runs with the pointer still moving on the 25th trial at each seat was 7.3%, 9.0% and 7.1% at the centre, right and back-left listening positions. Therefore roughly the same proportion of runs required the maximum number of trials.

The total number of trials needed (from 1 to 25) during each run follows the same trend across all three listening positions for both systems. There does not seem to have been a large change depending on the listening position on how many trials were taken. There is a much larger difference in the distribution between the two different systems. For o1spk4 the most frequency number of trials taken was the maximum of 25. In contrast, the o3spk8 systems appears much less difficult as the modal values lie between 8 and 11 trials for the three seats. A total of 73.7% of the runs which took a full 25 trials were with the o1spk4 system and the remainder were for o3spk8.

Further investigation into each of these individual runs shows which runs people were converging on a result and which were still making large movements when the scene ended. A run was deemed to be converging if the standard deviation of the pointer angle was less than 10° over the final 3 pointer trials and diverging if it was larger. It was found that 97% of the runs that used all 25 trials were diverging. This seems to indicate that if a subject had not begun to converge on a response by the 25th pointer trial there
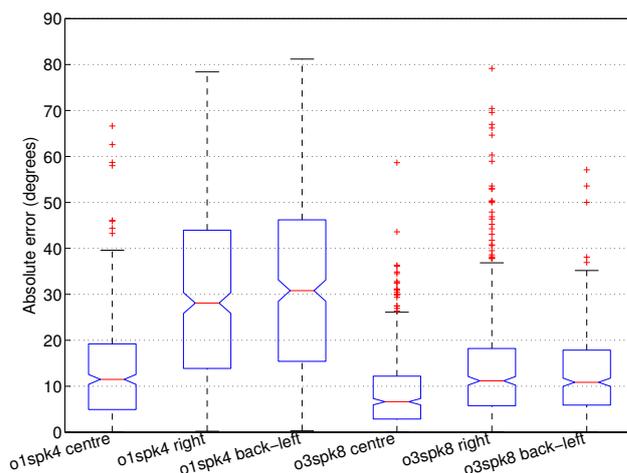


Figure 2: *The median, interquartile and 95% values of the total absolute error for the two ambisonic systems at the three listening positions. The red crosses are the outlier values. For clarity some of these values were truncated for the o1spk4 right (5 points), o1spk4 back-left (1 point) and o3spk8 centre (1 point).*

was too large an ambiguity about the pointer direction to complete the task in the limited time.

#### 3.1.2. Effect of Target Repetitions

Since each target was tested three times with each system and at each listening position the effect of these repetitions was tested to see if there was a learning effect. Using non-parametric analysis of variance it was found that there was no statistical difference in the absolute error over each of the three repetitions ($\chi^2(2)$ = 0.35, p = 0.8412). This suggests that there was no fatigue or learning effects over the three repetitions of each condition.

### 3.2. Total Absolute Error

#### 3.2.1. Influence of the System

Using a non-parametric analysis of variance on the absolute error across all of the targets and listening positions, the first order and third order systems were found to be statistically different ($\chi^2(1)$ = 344.3, p<0.01). The median absolute error was larger for the first order system than the third order system (20.3° and 9.3° respectively), as was the interquartile range (30° and 12°). The smaller interquartile range for the higher order system, combined with the distribution of pointer trials needed, shows the increased ease and consistency with which the subjects are able to perform the task compared with the first order system.

#### 3.2.2. Influence of the Listening Position

The absolute error at each of the different listening positions for all of the targets is higher for both the off-centre positions than it is for the centre, as shown in figure 2. This is true for both systems but the effect is much smaller with the o3spk8 system, as would be expected of the higher order system. A non-parametric analysis of variance on the absolute error and listening position shows that there is statistical difference between the three positions
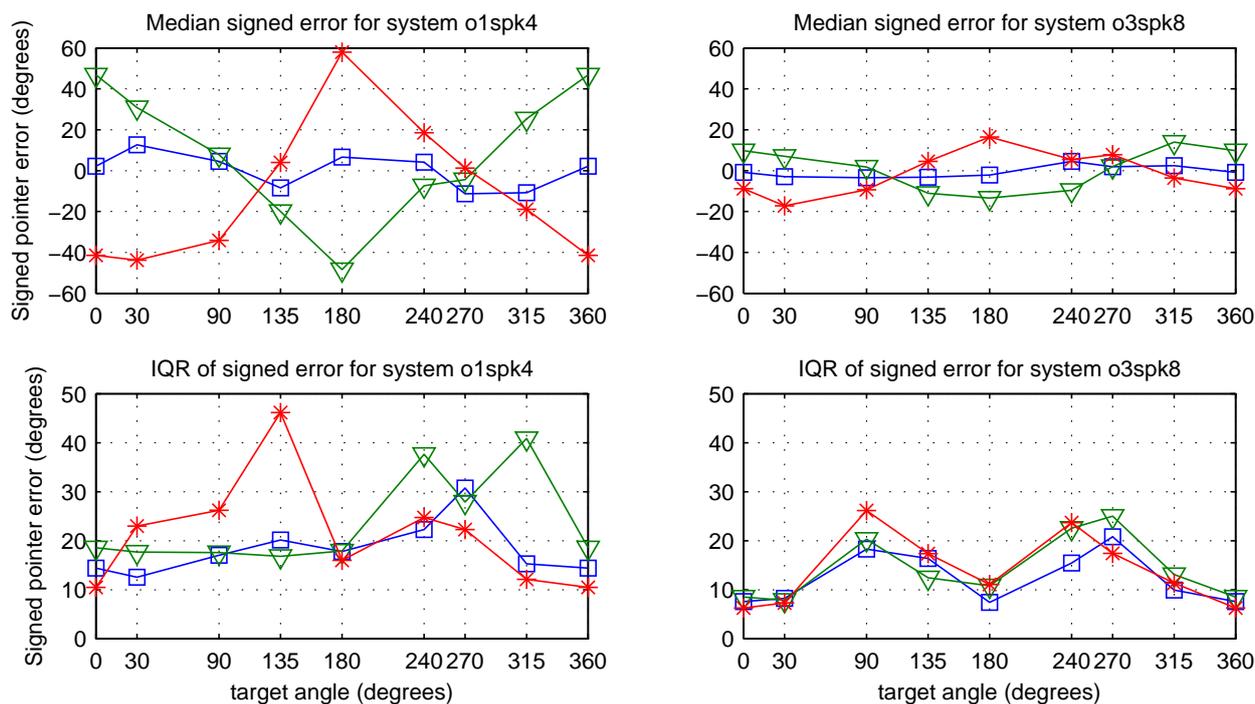
Figure 3: *(Top) The median signed error for all three listening positions and the two ambisonic systems. Positive error indicates the pointer was shifted in an anti-clockwise direction from the target angle and negative error indicates a clockwise shift. (Bottom) The interquartile range for all three listening positions and the two ambisonic systems. Results for the centre are blue squares, for the right are green triangles and for the back-left are red stars.*

($\chi^2(2)$ = 206.38, p<0.01). Further analysis showed no significant difference between the two off-centre positions so the difference is only between the centre and off-centre positions. The similar amount of error for each of the off-centre positions is consistent with the fact that both listening positions are a similar distance from the centre of the array.

Comparing the o1spk4 results for the centre and o3spk8 for the two off-centre seats in figure 2 shows that there is a comparable amount of overall error in all three. The median absolute error is 11.48°, 11.17° and 10.86° with an interquartile range of 14.30°, 12.44° and 11.96° for o1spk4 (centre), o3spk8 (right) and o3spk8 (back-left) respectively. From this, it appears that o3spk8 actually performs marginally better at the off-centre positions than o1spk4 does at the centre. However, there is no significant statistical difference so the global performance of these three system/listening position combinations can be said to be equivalent.

If the perceptual sweet spot is defined as the region over which there is equal or better performance than for a listener at the centre for o1spk4 then o3spk8 has a sweet spot of at least 0.6m radius for the setup used in this experiment. Further investigation is needed to determine whether this would increase proportionately with an increase in array radius or if it would be limited to the absolute distance from the centre.

### 3.3. Analysis of Pointer Error for Off-Centre Listeners

The signed error at each of the three listening positions indicates the magnitude and direction of the pointer results from the target angle. This is shown in figure 3 where a positive error indicates the pointer was shifted in an anti-clockwise direction from the target angle and negative error indicates a clockwise shift. For the off-centre listening positions the smallest shifts are for the targets that lie on or close to the line which passes through the listening position and the centre off the array. The largest shift is for the targets that are close to perpendicular with this line. The sign of the error depends on which side of this line the target lies and they are shifted in a direction such that the pointer angle moves to the more distant side of the loudspeaker array. The errors for the two off-centre listening positions are mirrored in the x-axis since one of the listening positions is moved to the left and the other to the right. The target angle with minimum error is also shifted slightly due to the listening position to the left also being shifted backward from the centre of the array.

At the off-centre positions the pointer's angular direction was moved to compensate for the proximity to the nearest loudspeakers. For the right listening position all of the results are shifted further to the left side of the array (except the 90° and 270° targets) presumably to compensate for the proximity to the loudspeakers on the right side of the array. Similarly, for the back-left listening position the pointer is shifted toward the front-right quadrant.

The spread, indicated by the interquartile range, is also shown in figure 3. For the off-centre o1spk4 system the spread is largest for the targets that are nearest to the listening position and also part of the reproduction array, suggesting the proximity to the loudspeakers meant a large range of pointer angles are likely to be perceived as coming from one direction closer to the listener. For

*o1spk4*

*o3spk8*
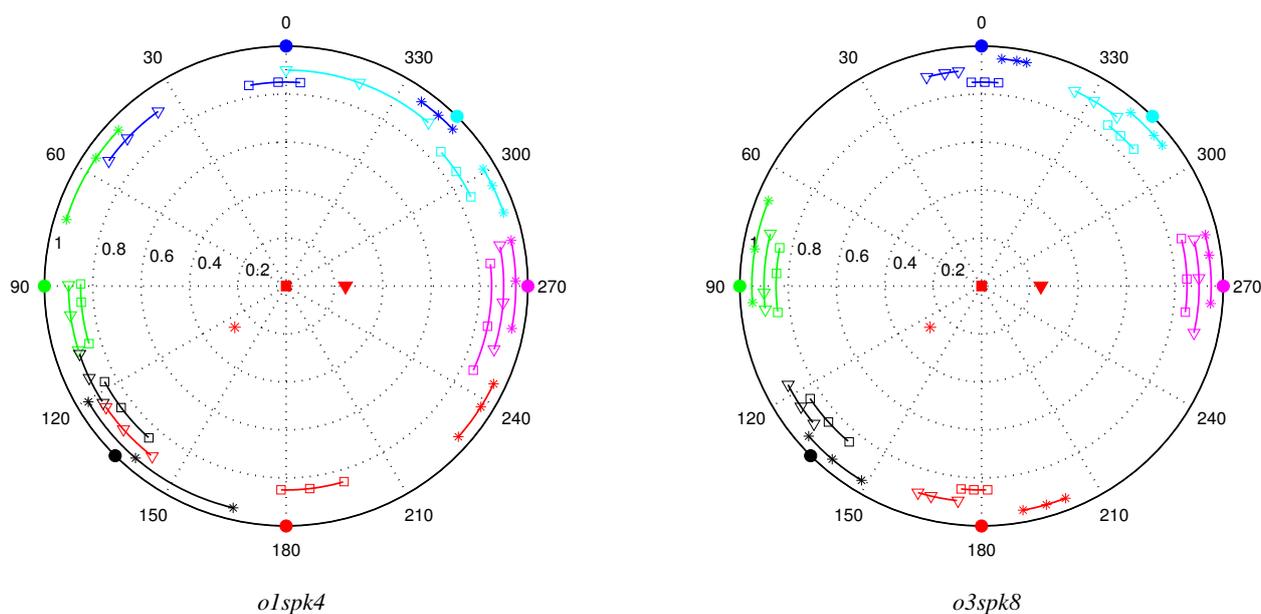
Figure 4: *The median and interquartile values of the pointer positions for all 18 listeners with (left) the first order system using 4 loud-speakers in a square array (right) third order system using 8 loudspeakers in an octagonal array. The results for all three of the listening positions are shown for targets at angles $0°$, $90°$, $135°$, $180°$, $270°$ and $315°$ relative to the centre of the array. Results for the centre are represented by a square, results for the listening position represented by a triangle and those for the back-left are a star. The colour of the results matches the colour for each of the targets, shown as circles on the circumference of the plots. The results for the targets at $30°$ and $240°$ have been omitted for visual clarity.*

the o3spk8 system there is a very strong pattern where the highest spread is generally at the $\pm90°$ targets and lowest at $0°$ and $180°$. This is similar to results from previous ambisonics localisation experiments [10, 13] and also what would be expected for normal human localisation [14] which has increased blur for sources at lateral directions.

The spread of pointer angles for o3spk8 off-centre is actually lower for certain target positions (those nearest to the front and back) than o1spk4 at the centre. This will allow certain pointer positions to be more sharply defined for o3spk8 off-centre than o1spk4 can even manage at the centre. Coupled with the fact that the overall performance is equal (see figure 2) this shows an effective increase in the size of the listening area from first to third order.

To highlight the biggest difference, figure 4 shows the median, 25% and 75% values for six selected targets for all three listening positions - front and back and those that lie on or close to a line between the centre of the array and the off-centre listening positions. The same trends are present for o1spk4 and o3spk8, but the displacement of the pointer angle from the target angle at off-centre positions is much smaller for o3spk8. For example, for the target at $0°$ the o1spk4 results for the right listening position are shifted anti-clockwise from the target angle, clockwise for the back-left position. o3spk8 shows the results shifted in the same directions but the magnitude of the shift is much smaller.

### 3.4. Informal Comments and Thoughts

Several subjects reported that the pointer was elevated above the loudspeakers with o1spk4, although this seemed to be highly in-

dividualised. Some reported elevation when the source was at the front position, others when it was to the sides and some either experienced no elevation or did not notice it while they were doing the test. Illusion of elevation has been noted before with Ambisonics [2]. It is also possible that the frequency content of the stimulus caused such an elevation illusion.

There were no large changes in coloration with changes in listening position for the o3spk8 system. With the o1spk4 system there was a change of colour that was associated more with the pointer position that the listening position. The pointer colour when the source was on the nearer side to an off-centre listener was different to that on the far side of the array. The change in colour was also associated with change in pointer diffuseness when moved around the array.

Two subjects reported occasionally being able to hear two signals when sitting in the off-centre position, one in the pointer direction and another from a nearby loudspeaker. This could have been caused by the nature of the stimulus used for the pointer. Perhaps if a program material such as a vocal recording had been used then this splitting might not have occurred. Informal testing by the lead author has found this image splitting to have a strong frequency dependence, with higher frequency sounds splitting more easily than low. It is also more prevalent for first order than third order. However, further investigation is needed.

### 4. DISCUSSION

As would be expected, the o1spk4 system had lower performance than the o3spk8 system and the task was more difficult to achieve. This was evident from the error at all three listening positions, but

the difficulty was also highlighted by the fact that even at the centre a greater number of subjects took the full 25 trials to find the source with the o1spk4 system. At the centre position the performance of o3spk8 is comparable to the performance of a mixed basic/max $r_E$ 4th order system in [10]. In terms of spread in the results all three listening positions for o3spk8 are approaching that of actual human hearing [14], where the largest blur is for lateral sources.

For o1spk4 the loudspeaker gains on the opposite side to the recreated sound source are still relatively high for most image positions. This led to some very large shifts in the pointer position and a very large absolute error for many of the targets. This was likely an attempt to use the loudspeaker gains to compensate for the earlier arrival times pulling the pointer into the nearest loudspeaker via the precedence effect [15, 16]. Several subjects reported that when the source was on the far side of the array it would become very diffuse or became "like a cloud" where the sound had no well defined direction. The same large deviation in the pointer position from the target angle is not present in o3spk8 at off-centre positions. This may be because the loudspeakers on the opposite side to the source tend to have a much lower gain than at first order and this means the subject does not need to adjust the pointer position so much to compensate for the earlier arrival time of signals from the nearer loudspeakers. Even though there is some signal arriving from the nearer loudspeakers the gain will be much larger from the source direction and therefore the direction with highest gain override the image shift due to the earlier arriving signals.

Several subjects reported very large, sudden jumps in the image position "from one side of the array to the other" with very small movements of the dial when in the off-centre positions (this seemed only to be for one system which was presumably o1spk4). Given that the off-centre listening positions were only really one seat outside the centre sweet-spot this represents quite a large instability effect on the localisation of the image. The signed error for o1spk4 right (figure 3) shows that the median pointer angles for the $0°$ and $180°$ targets are shifted by at least $45°$ to the left of the array. This means that the pointer angles lie within a $90°$ arc of each other but are perceived over a $180°$ arc on the array circumference. This demonstrates how a small shift in panning angle on the far side of the array can lead to a relatively large shift in the perceived direction i.e. a $90°$ change in panning angle corresponds to a $180°$ change in perceived position on the array circumference.

Several theoretical studies have defined errors based on the physical soundfield and a comparison with that of a real source [2] such as the D-error [8] and the relative intensity [17]. Each of these measures of error shows that at a given radius from the centre the signal is only objectively well reproduced up a limit frequency. This frequency increases with reproduction order and decreases with increasing radius. At the off-centre positions in this experiment the maximum well reproduced frequency is approximately 80Hz and 230Hz for first and third order respectively. While these limits are quite low the results in the previous section demonstrate that, at least for o3spk8, good performance can still be obtained even when the theoretical reproduction limit is low.

The results here are presented for an array of 2.2m radius but further investigation is required to determine the effect of a change in array radius on the error. Consider the case where the array radius is doubled and the off-centre listener remain the same absolute distance from the centre. The time delay between loudspeakers would remain fixed but the loudspeaker gain changes due to proximity or distance would be reduced. In this case we might expect the results to be better than for a small array since the relative loud-speaker gains are close to that of the centre position and the time delays do not change. Conversely, if the listener was to be placed a distance from the centre that is proportional to the increase in array size we might expect inferior results than for the smaller array. This is because the relative loudspeaker gains would be the same for both arrays but the arrival time delays for the larger array will be greater. If this was the case then it would not be predicted by investigation of the physical error since the well reproduced region is largely independent of the array size, except at very low frequencies.

## 5. CONCLUSIONS

The listening experiment presented in this paper investigated the error introduced to an ambisonic pointer's angle when matching a single source target. It tested first and third order ambisonic systems at one central and two off-centre listening positions.

The listening position was found to have a large influence on the total error for the two tested systems. The minimum error was for targets close to or along the line connecting the listener and the array centre. The maximum error was for the targets perpendicular to it. Conversely, the number of trials taken to complete the task was not found to depend on the listening position. Instead, the order of the ambisonic reproduction was a more important factor, with third order requiring fewer trials than first order, regardless of the listening position.

In addition, the third order system was found to perform as well off-centre as the first order system did in the centre, showing the same trend of increasing accuracy with increased order as in [10, 7, 9]. An argument could be made that even in the off-centre positions the third order system performed better than central first order because it was able to reproduce images in certain directions with less variance in the pointer angles, indicating that the third order system succeeded in increasing the size of the listening area to include the off-centre listening positions..

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