EFFECT OF EARLY REFLECTIONS IN BINAURAL SYSTEMS WITH LOUDSPEAKER REPRODUCTION

Asbjørn Sæbø

Acoustics Group
Department of telecommunications
Norwegian University of Science and Technology (NTNU)
7491 GLØSHAUGEN, NORWAY
saeboe@tele.ntnu.no

ABSTRACT

Systems for 3D sound reproduction are often implemented with binaural technology where signals are played back over loudspeakers. This paper reports preliminary results from an investigation on how reflected sound in the listening room influences horisontal localisation in such systems. An experiment, consisting of listening tests, was done. Results from the experiment showed that reflections as late as 5ms and 10ms did influence localisation in such systems. The probability for reversals between front and back localisation increased, and the ability to localise to the back was degraded. Localisation was clustered towards the direction of the reflections.

1. INTRODUCTION

The use of various kinds of 3D-audio is getting common. A much used technique is to present binaural signals over loudspeakers with the help of suitable crosstalk-cancelling filtering [1] - [3]. The base for the cross-talk cancelling filters is a set of Head-Related Transfer Functions (HRTFs) [4], [5]. HRTFs include the effect of the ears, head and torso of the listener. In applications of this kind, they may also include the effect of the room in which the playback is to take place. They are then not pure HRTFs in the strict sense, but a combination of HRTFs and room transfer functions.

Previous research indicates that such systems may be sensitive to reflections from surrounding surfaces, dependent upon their strength and how early they arrive. These reflections are typically caused by the walls, floor and ceiling in the listening room. However, it seems that the effect of the room and its reflections has not been fully investigated.

Anechoic or largely anechoic conditions were first thought necessary to obtain good results [6], [4] (pp 287 and 360), [2]. However, this has later been found not to be the case. Cooper and Bauch report that "The integrity of the crosstalk paths from loudspeakers to ears can be compromised by competing reflected paths that differ in delay from the primary paths by amounts of less than 1 (or perhaps 2) ms. Substantial contributions from such paths can begin to impair side imaging and allow some appearance of front-back ambiguity." [1]. They also report in [3] that "Our experience with transaural demonstrations has shown that as long as strong reflections arriving somewhat sooner than 2-3ms after the direct sound are avoided, the room does not substantially spoil the imaging." Practical experience also shows that such playback systems tend to work "fairly well" under non-freefield conditions, provided the reflections are "not too early and too strong", but that the room indeed does influence the auditory image and how it is perceived.

It is the aim of the present investigation to try to reach more specific conclusions about the effect of early reflections on sound presentation of this kind.

2. EXPERIMENT

An experiment consisting of listening tests was devised. The purpose of the experiment was to compare localisation in a playback system based on binaural recordings and cross-talk cancellation under free-field conditions to localisation in the same system with reflections present. The case of a reverberant room was simplified to one or two reflecting walls in an anechoic room. The experiment was further limited to localisation in the horizontal plane only.

2.1. Setup

The setup for the listening tests is shown in figure 1. Five cases

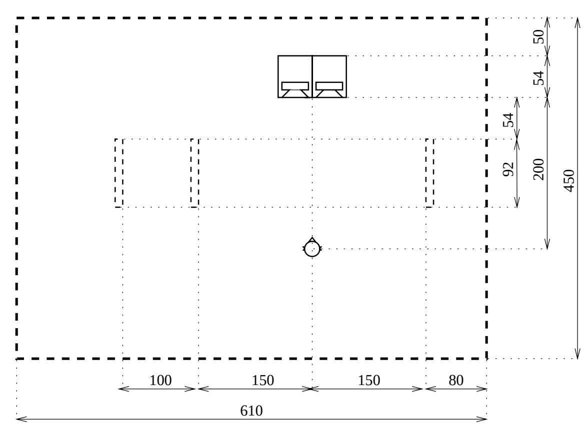

Figure 1: *Experimental setup in the anechoic room. The loudspeakers and the listener position are shown. The locations used for the reflecting wall(s) are shown with dashed lines. All measures are in centimetres. The height of the room is 450 cm, the height of the reflecting walls is 200 cm. The thick dashed line marks the inner boundary of the room.*

were tested:

- Anechoic

- One wall 150 cm to the left
- One wall 150 cm to the left, compensated for in the filtering
- One wall 250 cm to the left
- Two walls, one at each side, at 150 cm distance

The anechoic case was repeated once.

The reference system used for directions is angles in the interval from -180° (inclusive) to 180°. The forward direction, as seen from the listening position, is zero degrees. Angles increase clockwise, so negative angles are to the left, positive to the right. The directions to the walls are -68°, -56° and 56°. The reflections from the walls are delayed ca 5ms and 10ms with respect to the direct sound.

Nine paid volunteers participated as listeners in this test. They were all male, 22 to 26 years old. All of them had normal hearing. None of them had participated in listening tests before. At the start of the experiment, the listeners did two training sessions. Both training sessions were given using the same setup and equipment as for the rest of the experiment.

2.2. Filters and signals

The design of the cross-talk cancelling filters and the filtering of the test signals were done with a more developed version of the software described in [7]. For all tests but one, the filtering was based upon measurements of HRTFs for the anechoic setup. The exception was one test were the filtering was based upon measurements of the setup including a reflecting wall. This was done in order to cancel out the reflection from the wall by having the filtering compensate for it.

The signals used for the test were binaural recordings of a talking person. The recordings were done in a largely anechoic room, with the talking person placed on every 22.5 degrees on a circle around the recording position. Several recordings were done for each direction. From these recordings, a set of 20 randomised sequences of directions were produced. The sequences were prefiltered with the crosstalk cancelling filters, and burnt to CDs, which were subsequently used as the playback source during the tests. The HRTF measurements and the binaural recordings were done with the same artificial head, a Neumann KU81i.

2.3. The tests

For each test, the listeners were presented with eight sequences of sound, each presenting twelve directions. (No direction was presented more than two times during a given sequence.) They were instructed to mark the apparent direction of the sound sources on a form. The answers were afterwards converted to a digital format, and rounded to the nearest degree. A total of 5180 valid answers were collected during the tests.

3. RESULTS AND DISCUSSION

The results are presented in figures 2 - 6. Here, all answers have been rounded to the nearest presented direction. Perceived directions are then plotted against presented directions. The area of the filled circles correspond to the number of answers for that combination of presented and perceived direction[1].

[1]The number of answers is normalised to the number of times that direction was presented, to compensate for the fact that not all directions have been presented equally many times.

3.1. Reversals, per test

As can be seen from the figures, there are many front-back reversals, especially from back to front. This is a well known effect, cf. [6] and [8]. Every direction in the frontal half-plane has a mirrored direction in the backplane, and vice versa. One of the questions studied was whether the number of reversals is influenced by the presence of reflections.

A simple algorithm for deciding whether an answer is “reversed” or not is to compare it to the presented direction and to the mirrored presented direction. If it is closer to the mirrored one, it is counted as reversed. Using this technique on the answers for each test, we get the results shown in table 1.

Setup	Mirrored	Total	Fraction
Anechoic	559	1728	0.32
One wall	285	864	0.33
One wall, far	303	863	0.35
One wall, compensated	330	862	0.38
Two walls	364	863	0.42

Table 1: Percentage of reversals for the various setups. Setup, number of reversed answers, total number of answers and number of reversed answers divided by total number of answers. Ordered by increasing reversal percentage.

The fact that the anechoic case has the lowest percentage of reversals is to be expected. This is the reference setup, for which the crosstalk-cancelling filters were designed, so it is reasonable to belive that any disturbances in the playback chain with respect to this will lead to degraded performance. It should be noted, however, that the difference between the case with the most reversals and the anechoic setup is only 31%.

For the two cases with one uncompensated wall, the setup with the wall farthest away have the most reversals. This is contrary to what one might expect. The closer wall causes an reflection that is both stronger and earlier, and therefore should have a greater impact. An explanation may be that the more delayed reflection gives rise to a secondary source more distinguished from the direct sound. This may have caused the listeners to report the direction of this secondary source instead.

The setup where the wall was compensated for has the second most reversals. This may indicate that the compensation has not worked, but instead made things worse. Due to a lack of suitable measuring equipment, the compensation has only been tested by simulation. It is possible that slight misplacements of the listener, temperature changes (causing the speed of sound to change) and so on may have caused the inverse filtering to fail. This setup is more fragile to such factors than the other cases, as it involves a more complex inverse filtering where also the transmission path for the reflected sound is taken into account.

The setup with two walls has the most reversals. This is also the setup where the room differs the most different from the anechoic situation.

3.2. Reversals, per direction

If we divide the answers by presented direction and then count reversals, we get the results shown in table 2. These results are discussed below.

For directions in the back half plane, the anechoic case has the lowest number of reversals. This is except for the directions straight backwards (-180°) and -157.5°. For the second of those it is 0.01 from being the minimum value. This would seem to suggest that the ability to localise back is degraded by the reflecting walls.

Angle	An-echoic	One wall	One wall, comp.	One wall, far	Two walls
-180.0	0.81	**0.65**	0.82	0.75	0.86
-157.5	0.47	0.78	0.71	**0.46**	0.70
-135.0	**0.31**	0.56	0.51	0.44	0.71
-112.5	**0.40**	0.63	0.51	0.63	0.67
-90.0	0	0	0	0	0
-67.5	0.34	**0.11**	0.28	0.13	0.17
-45.0	0.17	**0.05**	0.13	0.15	0.11
-22.5	0.20	**0.11**	0.13	0.15	0.13
0.0	0.09	0.16	**0.07**	0.20	0.11
22.5	0.13	**0.07**	0.11	0.16	0.11
45.0	0.26	0.22	0.29	**0.11**	0.13
67.5	0.31	0.42	0.26	0.30	**0.07**
90.0	0	0	0	0	0
112.5	**0.53**	0.59	0.62	0.64	0.76
135.0	**0.44**	0.53	0.63	0.60	0.78
157.5	**0.53**	0.67	0.85	0.75	0.81

Table 2: Percentage of reversals for the various presented angles, for each kind of setup. Minimum values are marked by printing them in bold.

Further, we see that the test with one wall close to the left has the fewest reversals in the left frontal quarter-plane, where the wall was placed. This may suggest that the early reflection from nearly the same direction (at least in the same quarter-plane) as the presented sound have reinforced the localisation to the virtual sound source.

For the right frontal quarter-plane, no pattern can be observed, except that the anechoic case never has the fewest reversals. This may be explained similarly to above, that the walls cause localisation to collapse towards the front. I.e.: There is, for all tests, a probability for reversals to happen. If the walls give a greater probability for localisation to the front, then there is also a lower probability for incorrect localisation to the back for frontal directions.

3.3. Clustering

From the figures we can see that for all setups including walls, there is a clustering of perceived directions towards the direction(s) of the wall(s) which is not present for the anechoic case[2].

[2] Due to the rounding of answers, the clustering in the figures is towards the direction closest to the direction of the wall.

4. CONCLUSIONS

A listening test experiment has been carried out for a system for playback of binaural sound over loudspeakers. The influence of reflections delayed 5ms and 10ms, produced by placing walls in an anechoic room, was investigated and compared to the anechoic case. The following conclusions may be drawn with respect to the presence of walls/reflections:

- The playback situation is influenced in a way that alters the localisation
- The probability for reversals between front and back is increased
- The ability to localise to the back half plane is degraded.
- Localisation is clustered towards the reflecting walls.

5. REFERENCES

[1] Duane H. Cooper and Jerald L. Bauck, “Prospects for Transaural Recording”, J. Audio Eng. Soc. 37:3-19, 1989

[2] Henrik Møller, “Fundamentals of Binaural Technology”, Applied Acoustics 36:171-218, 1992

[3] Jerry Bauck and Duane H. Cooper, “Generalized Transaural Stereo and Applications”, J. Audio Eng. Soc. 44:683-705, 1996

[4] Jens Blauert, “Spatial Hearing”, Revised Edition, MIT Press 1997

[5] Henrik Møller and Michael Friis Sørensen and Dorte Hammershøi and Clemen Boje Jensen, “Head-Related Transfer Functions of Human Subjects”, J. Audio Eng. Soc. 43:300-321, 1995

[6] P. Damaske, “Head-Related Two-Channel Stereophony with Loudspeaker Reproduction”, J. Acoust. Soc. Amer., 50:1109-1115, 1971

[7] Asbjørn Sæbø “Implementation of Transaural Systems in Software on a PC”, Preprint 4799, 105th Conv. of the Audio Eng. Soc., September 1998

[8] Kelvin C. K. Foo and Malcolm O.J. Hawksford and Michael P. Hoolier, “Optimization of Virtual Sound Reproduced Using Two Loudspeakers”, Proc. Audio Eng. Soc. 16th Int. Conf. Spatial Sound Reproduction, April 1999

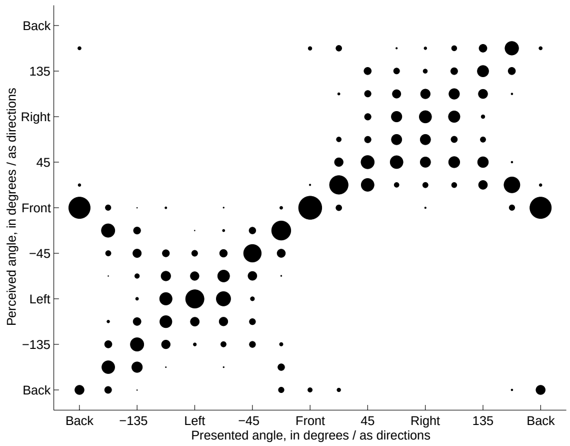

Figure 2: *Anechoic*

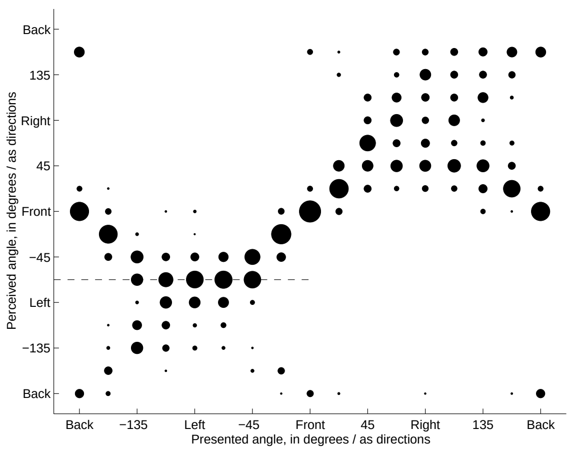

Figure 3: *One wall*

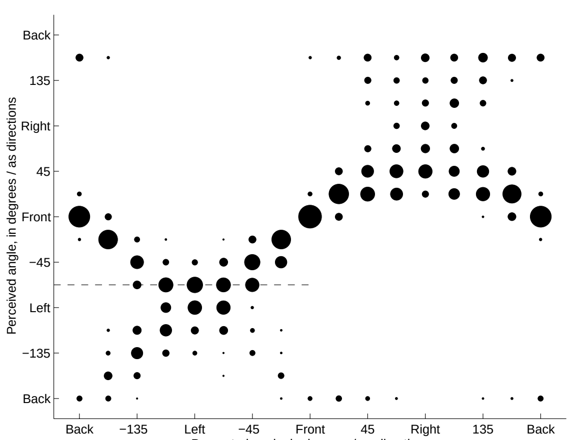

Figure 4: *One wall, compensated for*

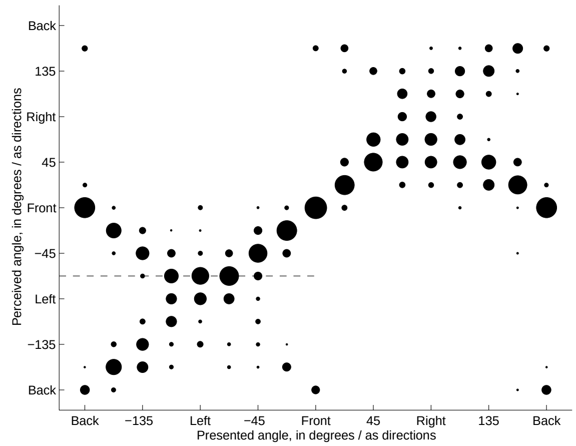

Figure 5: *One wall, farther away*

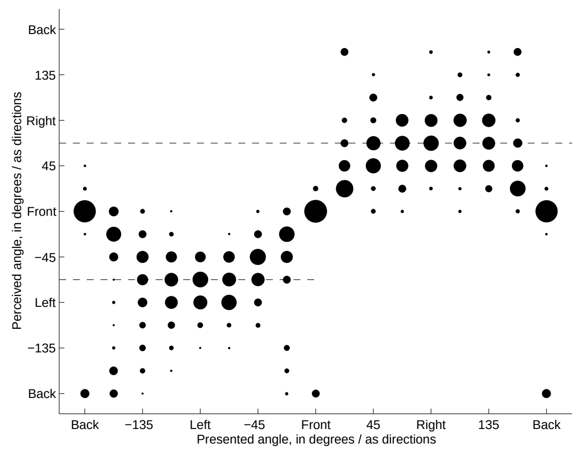

Figure 6: *Two walls*