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Wave Field Synthesis in the Real World: Part 1 – In the Living Room

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ABSTRACT

In anechoic rooms the concept of Wave Field Synthesis (WFS) has already proven to provide superior spatial sound over a large part of the room. The progress in microelectronics enables WFS to become available in commercial products at reasonable price. In the next future it will be installed in different acoustical environments. In anechoic space WFS needs a huge number of loudspeakers. In “normal” listening conditions simulated and real acoustics interfere with each other making the generated wave field less exact.

This paper describes listening tests conducted to evaluate WFS in common living room conditions. Parameters under test are the number of loudspeakers, the distance between loudspeakers, the position of the simulated source and the position of listeners relative to the loudspeakers.

1. Introduction

The concept of Wave Field Synthesis (WFS) has been promoted for more than 20 years by the Technical University of Delft. Under ideal conditions in anechoic rooms WFS provides better spatial sound than all multi-channel systems widely in use today. WFS is able to enlarge the sweet-spot to fill the whole listening room. However the huge computational costs prevented WFS from wide use until today. With the recent progress in microelectronics WFS will be available for commercial products at reasonable prize very soon. Ten partners in the European project CARROUSO are currently developing the necessary technical solutions. Examples of applications where WFS is adequate are sound reproduction in the home, in museums, for multimedia installations and in cinemas. Most of these applications will be in rooms where special acoustic treatment is not possible and which are not anechoic at all.

This paper is the first in a series of papers to evaluate the perceptual performance of WFS in real world environments. The listening tests described here were conducted in a normal living room.

2. Experimental Design and Parameters

2.1. Listening room

The listening room used for the test is located in a former East-German apartment building. However the size of the room was increased to be more in line of living rooms common in Germany today: The room is not rectangular (see figure 1). The longest wall has several windows equipped with curtains. Furniture includes a three-seated sofa, a two-seated sofa, an armchair, a small table, a desk and normal chair. In contrast to ordinary listening rooms no cupboard is in the room. The walls are of concrete covered with wood-chip wall paper, some posters in glass framing decorate the room. The carpeting is needled felt.

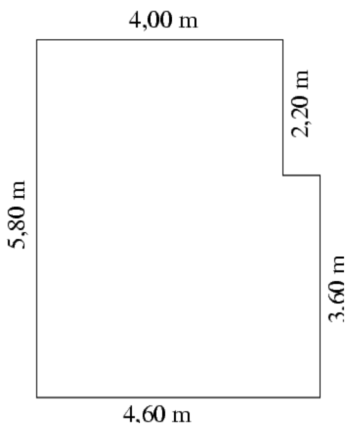

Figure 1: The listening room

2.2. Loudspeaker Arrangement

The loudspeakers are arranged in nine panels with eight speakers each, placed along the walls of the listening room, five of them in the front and four in the rear. The distance between two speakers in an array is 17 cm. The loudspeaker array does not encircle the listening space completely: the entrance of the room and the door to the balcony are forcing gaps in the array. The height of the panels was adjusted to fit the position of the average listener while sitting on the armchair in the listening test. Due to the limitations of the sound cards used only 48 different output signals could be reproduced at the same time. Therefore at the sides and in the back two speakers are reproducing the same signal. Figure 2 shows the overall configuration.

2.3. Test Data

Two different audio samples are used to study the influence of the test parameters on different programme material: An excerpt from Suzan Vega Tom´s Dinner and Castanets from the EBU SQAM disc. The first has been selected because it is known that localization is most sensitive with speech and singing voice and that human voice is very critical in sense of audio quality. The later has been chosen to incorporate a more transient signal. It is important to be noted that both signals are not recorded in the anechoic room and that both signals contain some spatial information about the recording room.
The mono test sequences are rendered as virtual sources at different fixed or moving positions according to the test procedure explained later. No room simulation is applied.

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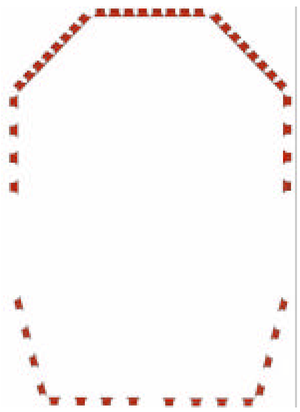

Figure 2: Loudspeaker Arrangement

2.4. Test Panel

The test subjects are stuff member of Fraunhofer AEMT, of the Technical University Ilmenau and students. All of them are trained for listening tests and have either a background as active musicians or are doing recordings.

2.5. Test Parameters

The test parameters are:

- listener position
- distance and angle of incidence of the virtual source
- loudspeaker configuration.

By varying the spacing between the loudspeakers for a loudspeaker array, different loudspeaker configurations with appropriate filters have been applied. The speaker spacing is increased indirectly by leaving out one, two, three or pairs of two or four loudspeakers from the array, therefore only each other, third, fourth loudspeaker or pairs per two or four loudspeakers are active. To simulate arrays with closer spacing modules are stacked with an horizontal offset of half the distance of the loudspeakers within one panel resulting in a “W”-shaped configuration.

2.6. Test Method

2.6.1. Overall Audio Quality

The test method applied to evaluate the overall audio quality has been derived from the ITU-R BS.1534 (MUSHRA) test.: The signals of all loudspeaker configurations are simultaneously offered to the subjects on a graphical display and they are allowed to listen to all signals in arbitrary order as often as they want. The listeners were asked to rate the sound quality according to the ITU-R quality scale. Neither a reference nor anchors are presented to the subjects. This is in contrast to original MUSHRA test where an open reference, a hidden reference and at least one anchors is mandatory.

2.6.2. Localization

For localization experiments the listeners are asked to place a point on a computer screen indicating the position of the perceived sound. As hints to the subject the shape of the listening room is indicated on the screen.

2.6.3. Localization with Simulated Head Movements

It is known from psychoacoustics that head movements improve the performance in localization experiments. To evaluate the stability of the reproduced sound-image against movements by the listener’s head an additional experiment has been conducted. To make the results more reproducible instead of allowing the listeners to move their head the sound source was moving simulating small head movements at reasonable speed. In this experiment listeners were asked to rate the timbral changes of the sound.

2.7. Experiments

2.7.1. Experiment 1

This first experiment evaluates the audio quality by comparison of several loudspeaker configurations. The source position was constant at x=0, y=10 meters. The listener position always was in the center.

Experiment 1a compares the configuration “all loudspeakers active”, “blocks of two loudspeakers active” and “blocks of four loudspeakers active”.

In experiment 1b configurations with all loudspeakers active as well as spatial sub-sampled versions where only every second, every third, every fourth channel is active are evaluated.

2.7.2. Experiment 2

This second experiment evaluates the influence of different listener positions as shown in figure 3 respectively in table 1. The loudspeaker configurations are the same as in experiment 1b.

Position no.	x	Y
1	0	0
2	0	1.5
3	-0.5	0
4	-0.5	1.0
5	-0.5	1.5

Table 1: Listener positions evaluated in experiment 2

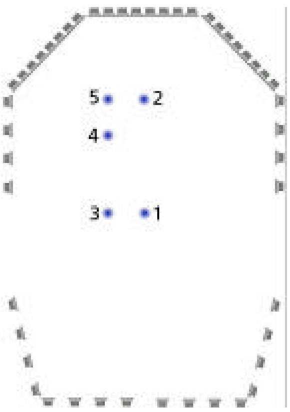

Figure 3: Listening positions evaluated in experiment 2

2.7.3. Experiment 3

This experiment evaluates the precision of spatial imaging. In experiment 3a the virtual sources are positioned at different angles of incidence but at a constant distance of 3m. All virtual sources are behind the loudspeaker array. The angles of the virtual source are -10°, 20°, 30°, -45°, -60°, 70°, -80°.

In experiment 3b the virtual sources are located at different distances (3, 5, 8, 10 meters) from the center of the array at the same angle of 0°.

Both in 3a and 3b the test subjects are not informed that only one parameter (angle respectively distance) is varied.

2.7.4. Experiment 4

This experiment assesses the effect of spatial aliasing especially in the presence of head movements. In this test only Castanets is used as test item. The test subjects are asked to rate changes in timbre. They were educated to focus on the annoyance of the differences. Only one loudspeaker panel with 8 speakers is used. The listeners are located either at a distance of 2.7 meters or of 1.5 meters from the loudspeaker array. All virtual sources are placed at a distance of 3 meters behind the array and disposed at the angles of -20°, 0°, 10°, 20°, 30°, 40°, 50°, 60° as shown in figure 4. Instead of allowing head movements to the listeners the virtual sources are moved automatically. The excursion of the sources is 0.5 meters to each side parallel to the panel.

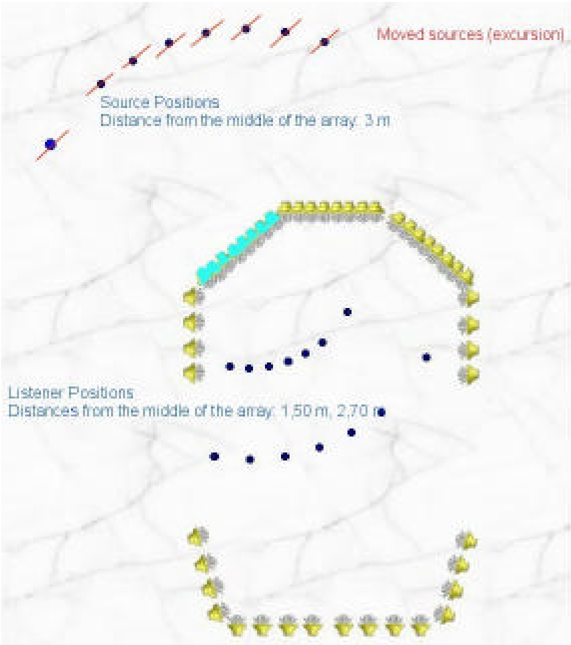

Figure 4: listener and source positions evaluated in experiment 4

2.7.5. Experiment 5

This test evaluates the properties of non horizontal aligned loudspeakers. Four different loudspeaker configurations are used:

- one loudspeaker panel using all 8 speakers
- two panels shifted one upon the other (so the spacing between the loudspeakers is reduced by a factor of two)
- every second loudspeaker active and every third loudspeaker active (as in experiment 1b).

The listener positions are at the angles 0° and 30° and at a distance from the panel of 2.7 meters. The virtual sources were positioned at the same distance of 3 meters behind the array at the angles of -20°, 0°, 10°, 30°, 50° as shown in figure 5.

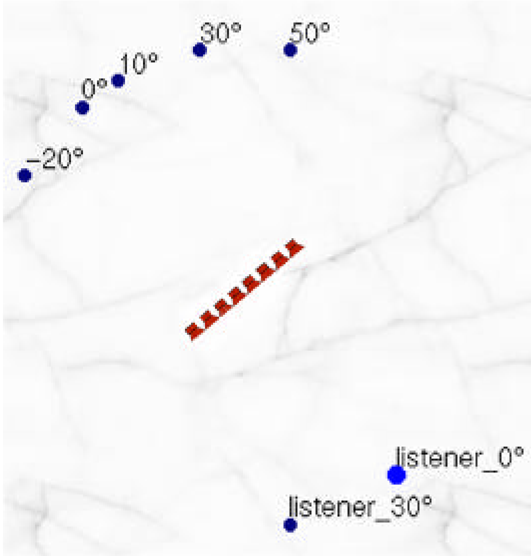

Figure 5: listener and source positions evaluated in experiment 5

3. Results

3.1. Experiment 1

Figures 6 to 7 show the results of experiment 1. It can be seen from figure 6 that feeding the same signal to more than one speaker impairs the overall audio quality. There is a similar but less pronounced effect with spatial sub-sampling as reported in figure 7.

3.2. Experiment 2

Depending on the listener position the different configuration are scored differently as shown in figures 8 to12. It is important to note that not always the full array scored best. However it should be mentioned that the deviation between the results of different subjects are very large. Only a few configurations differ statistically significant.

3.3. Experiment 3

In this experiment different results were obtained for the two different test items. While Suzan Vega was localized rather exact both in respect of angle and distance in experiment 3a (figures 13 and 14) Castanets are in generally located to far away. In the distance experiment 3b (figures 15 and 16) the subjects were not able to distinct between different distances for Suzan Vega, but could do this pretty well for Castanets.

A reason for this effect can be that the Castanets recording already contains some spatial information. These experiments should be repeated with other test sequences and with proper room simulation.

3.4. Experiment 4

As shown in figures 17 to 23 the artifacts of spatial aliasing are worst, if the listener is closer than 10 degrees from the line through virtual source and middle of loudspeaker array. At other angles this effect fades out. The overall sound quality is related to the place in the listening room.

3.5. Experiment 5

It can be seen from figure 24 that decreasing the distance between loudspeakers by displacing them horizontally does cause more distortions. This W-shaped configuration sounds even worse than a configuration were the number of speakers is reduced by a factor of two compared to the full array.

4. Conclusions

It has been shown that wave field synthesis in listening room environments does provide a good quality. The effect of spatial aliasing due to the limited sampling of the room is less pronounced than expected. However the effect of changes in timbre with head movements needs further investigation. Adding a second row of speakers with a horizontal displacement does not improve the sound quality.

5. Acknowledgments

The authors want to thank all volunteers which have donated their time and ear to take part in the listening tests. The work on spatial audio was partly funded by the Thuringian Ministery of Science, Research and Culture, and by the European Commission in the context of the CARROUSO project.

6. REFERENCES

Berkhout, A.J.; de Vries, D.; "Acoustic Holography for Sound Control" presented at the AES86th convention, 1989 March, preprint 2801.

De Vries, D.; Vogel, P., "Experience with a Sound Enhancement System Based on Wavefront Synthesis" presented at the AES05th convention, 1993 October, preprint 3748.

Sporer, T.; Plogsties, J.; Brix, S.; "CARROUSO - An European Approach to 3D-Audio" presented at the AES110th convention, Amsterdam, The Netherlands, 2001 May, preprint 5314.

ITU-R Recommendation BS.1534, "Method for the subjective assessment of intermediate quality level of coding systems"; approved in 2001-06

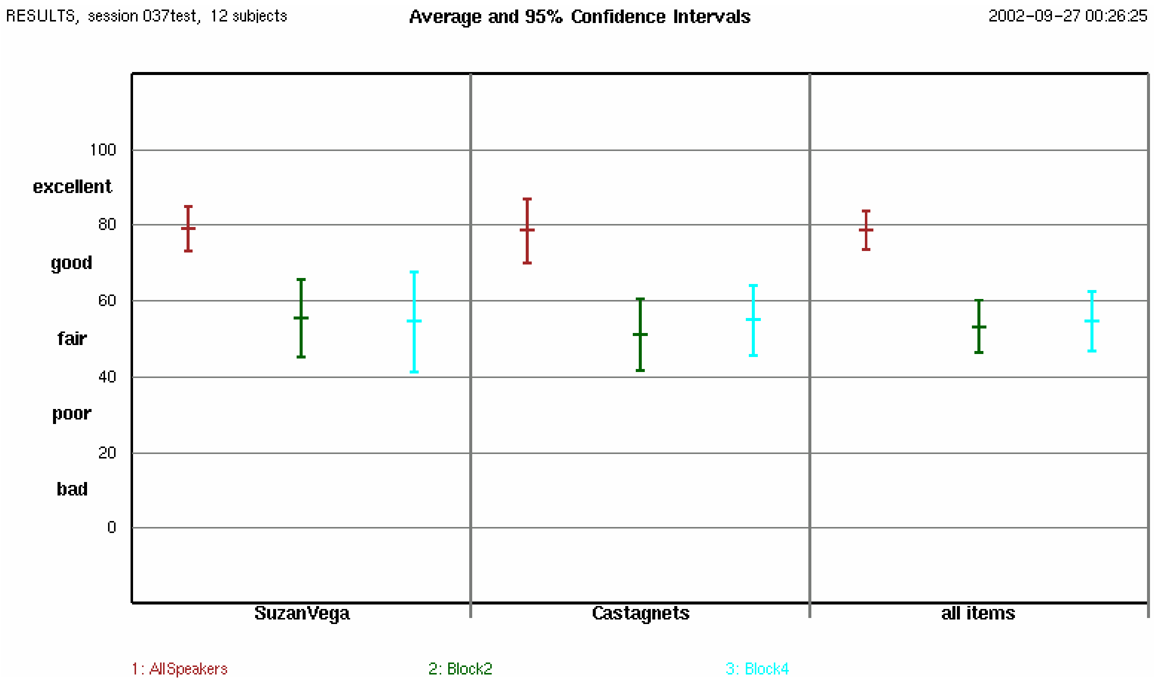

Figure 6: Experiment 1a - audio quality – blocks of loudspeakers

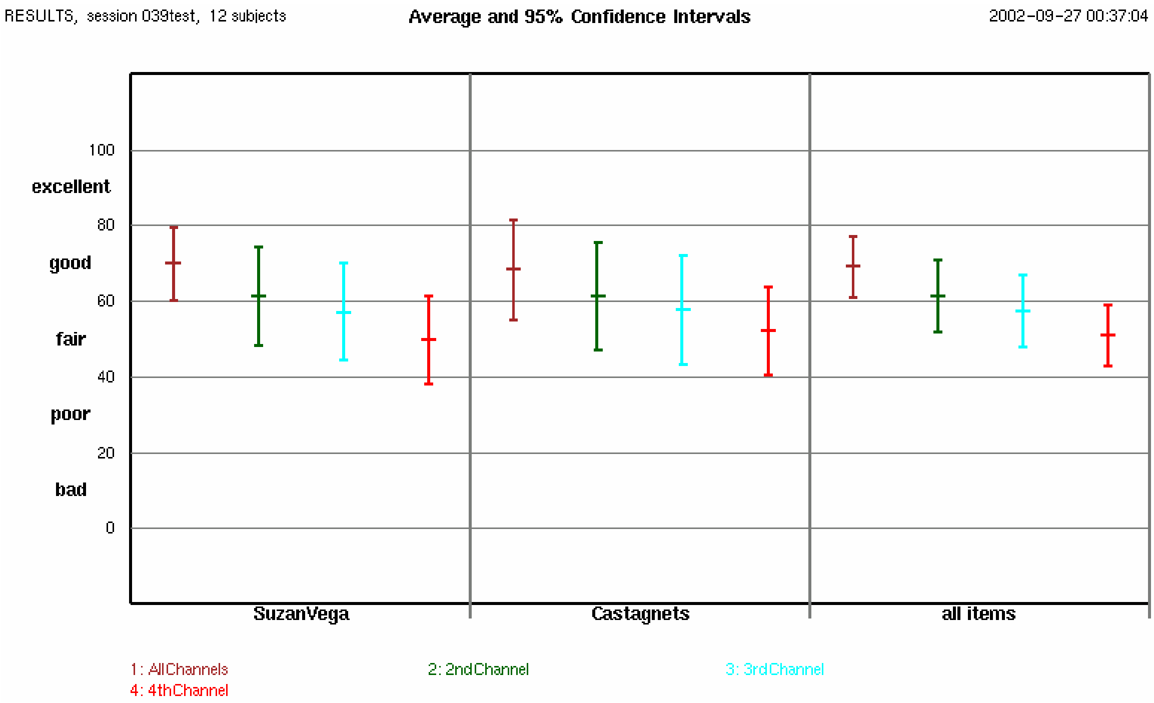

Figure 7: Experiment 1b - audio quality – spatial sub-sampling

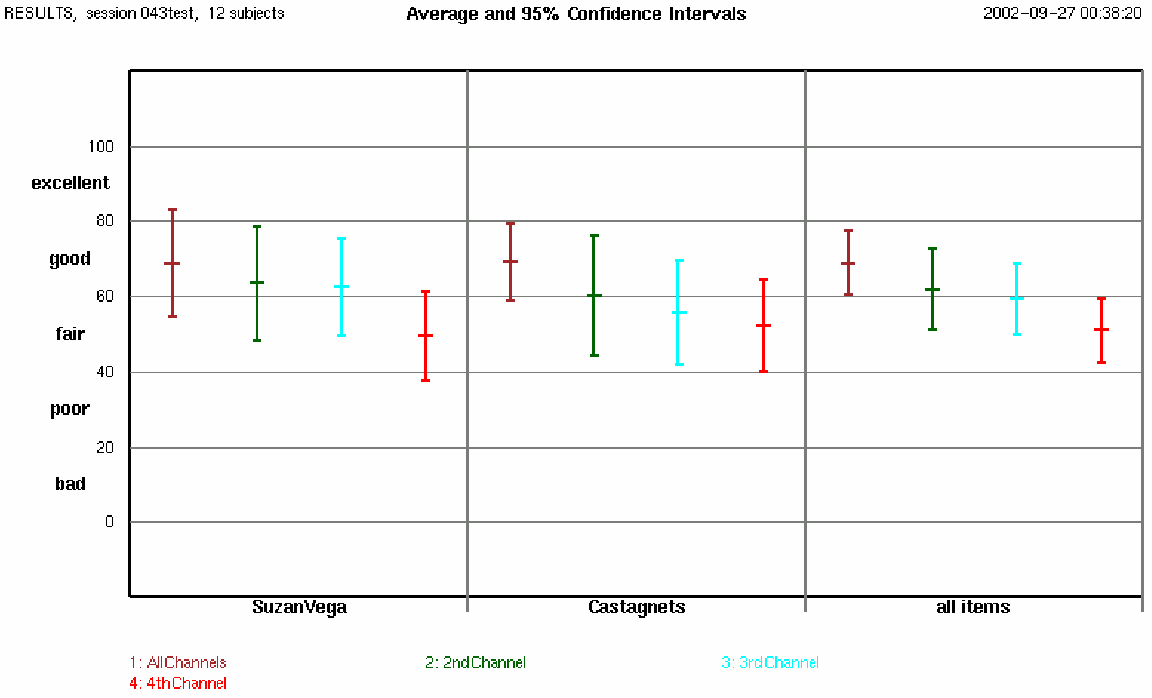

Figure 8: Experiment 2a - audio quality at listener position 1

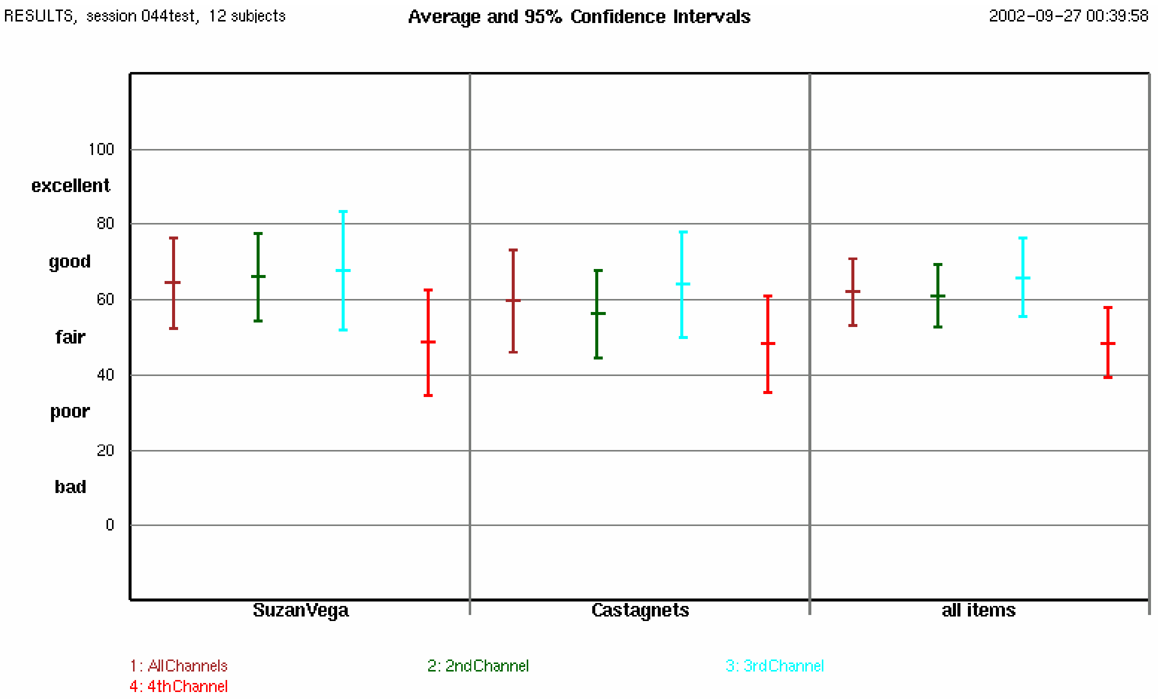

Figure 9: Experiment 2b - audio quality at listener position 2

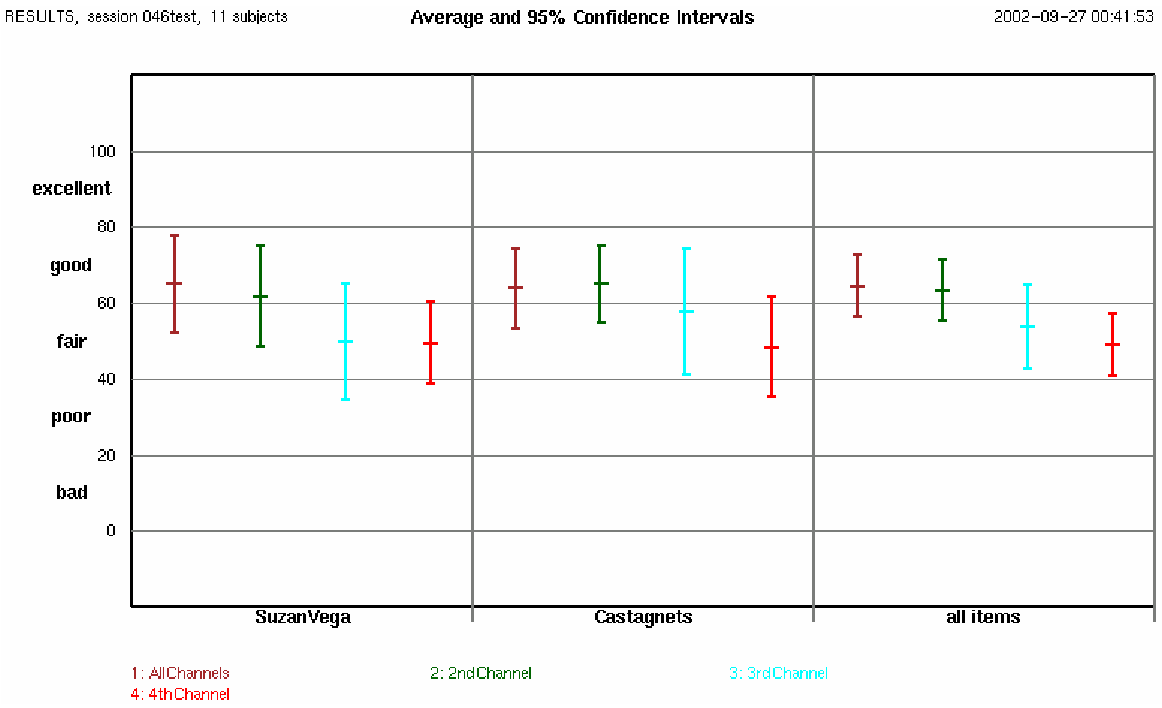

Figure 10: Experiment 2c - audio quality at listener position 3

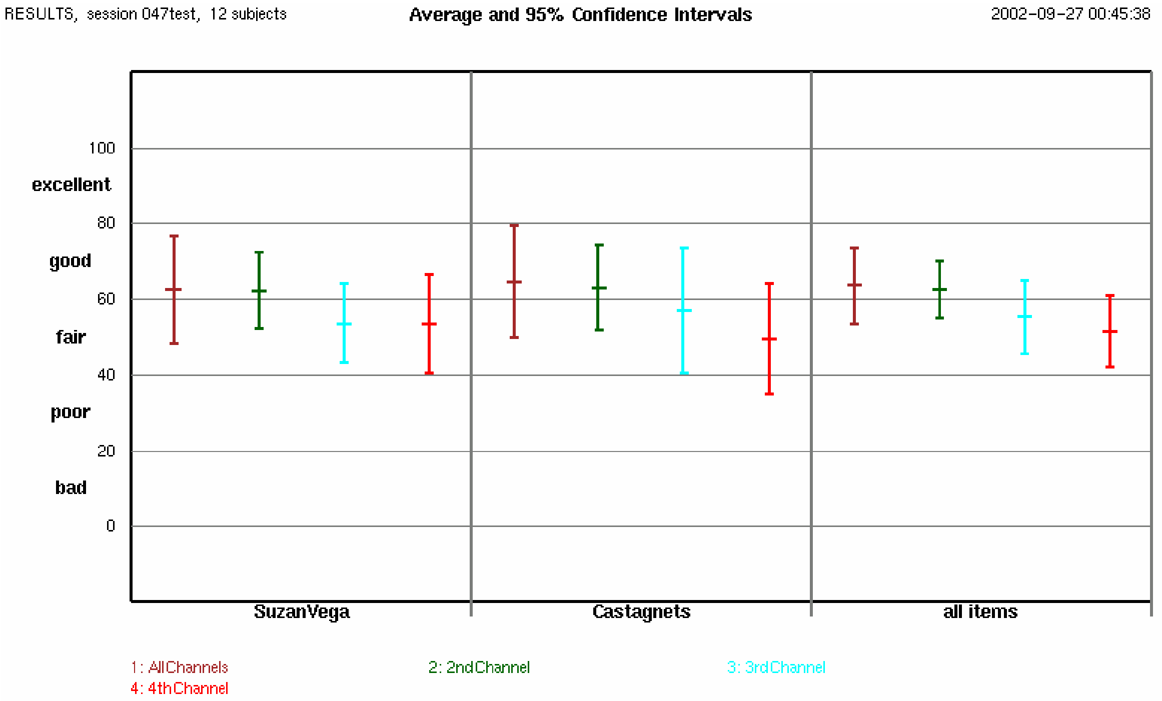

Figure 11: Experiment 2d - audio quality at listener position 4

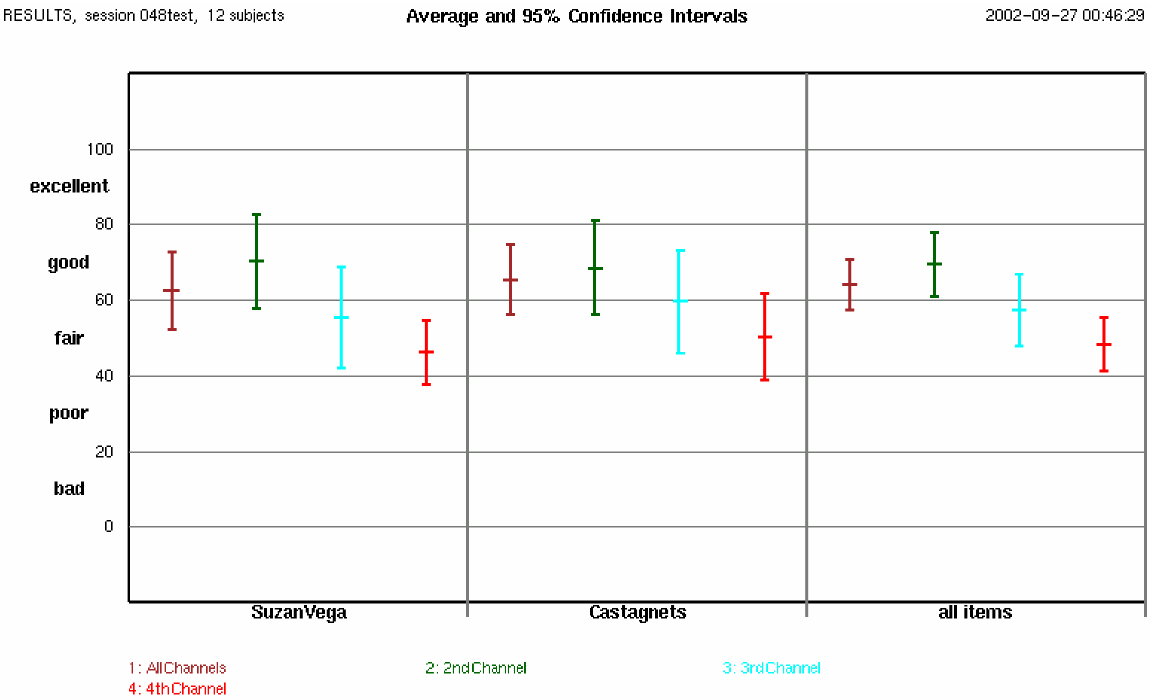

Figure 12: Experiment 2e – audio quality at listener position 5

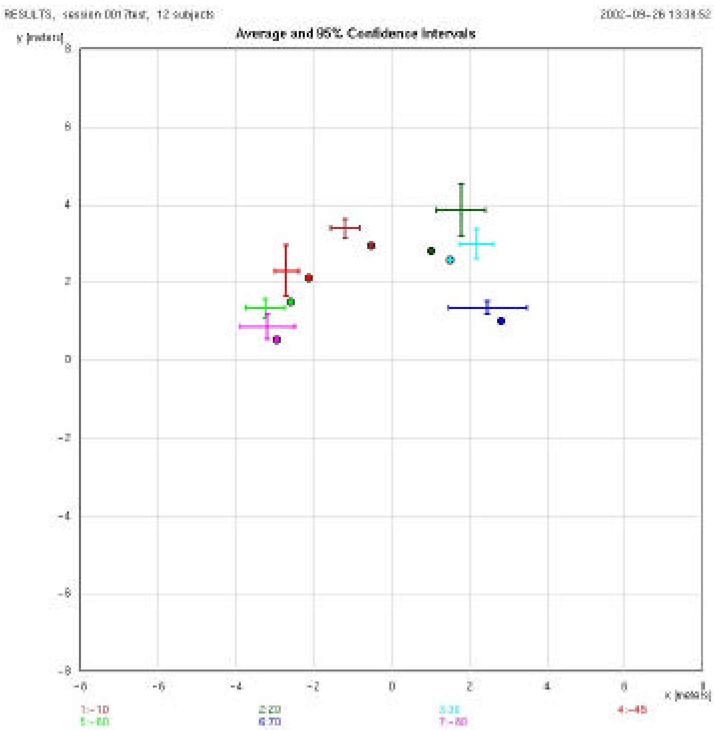

Figure 13: Experiment 3a – Localization – correct position indicated with circles (Item: Suzan Vega)

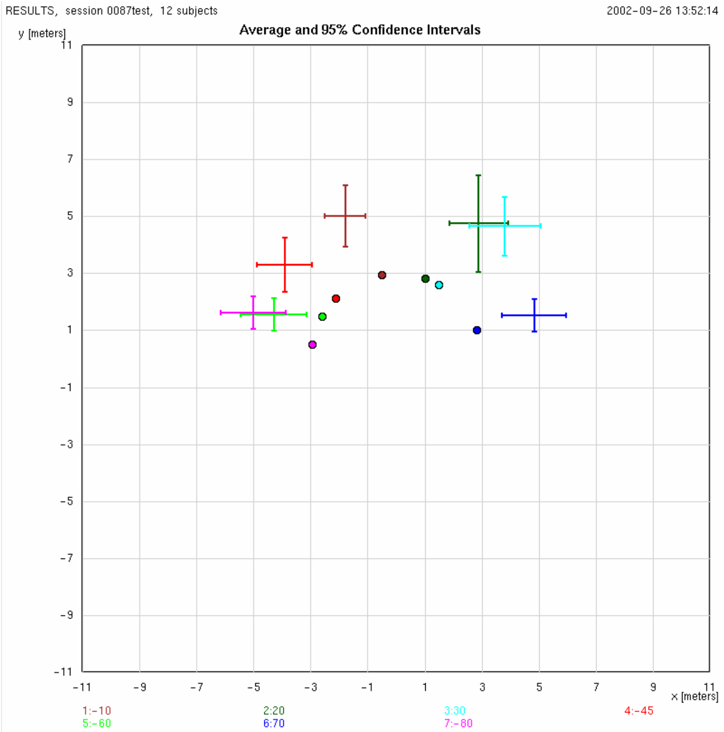

Figure 14: Experimet 3a – Localization – correct position indicated with circles (Item: Castanets)

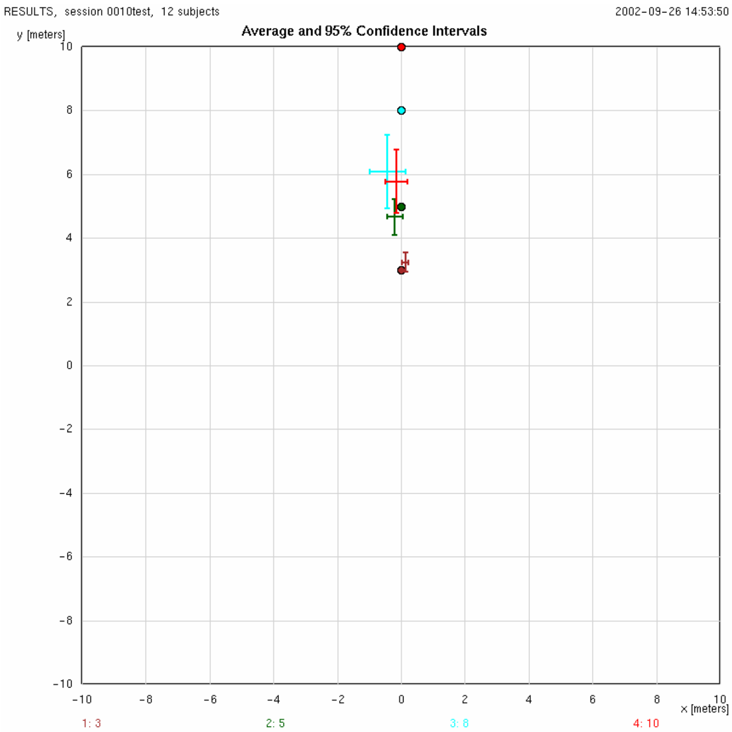

Figure 15: Experiment 3b – Localization –correct position indicated with circle (Item: Suzan Vega)

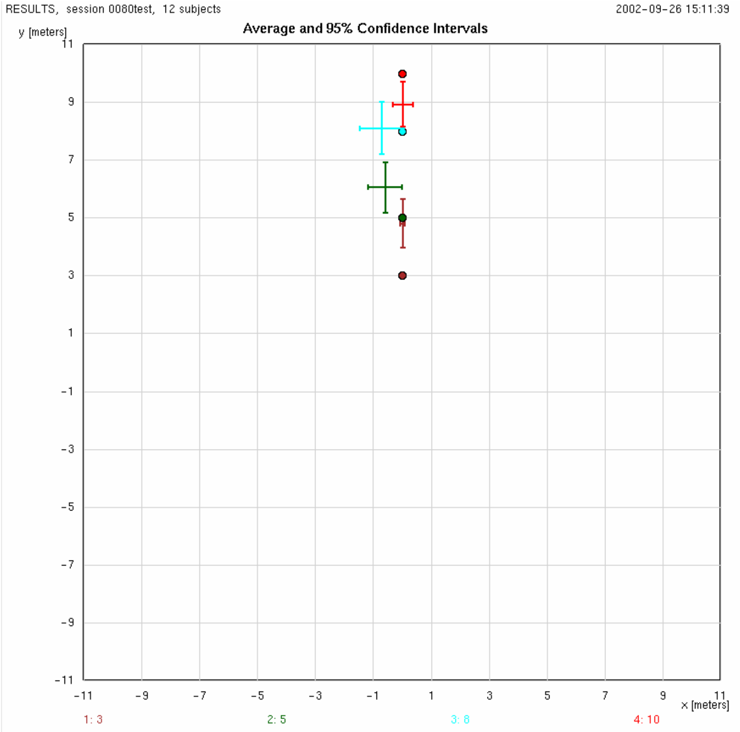

Figure 16: Experiment 3b– Localization –correct position indicated with circle (Item: Castanets)

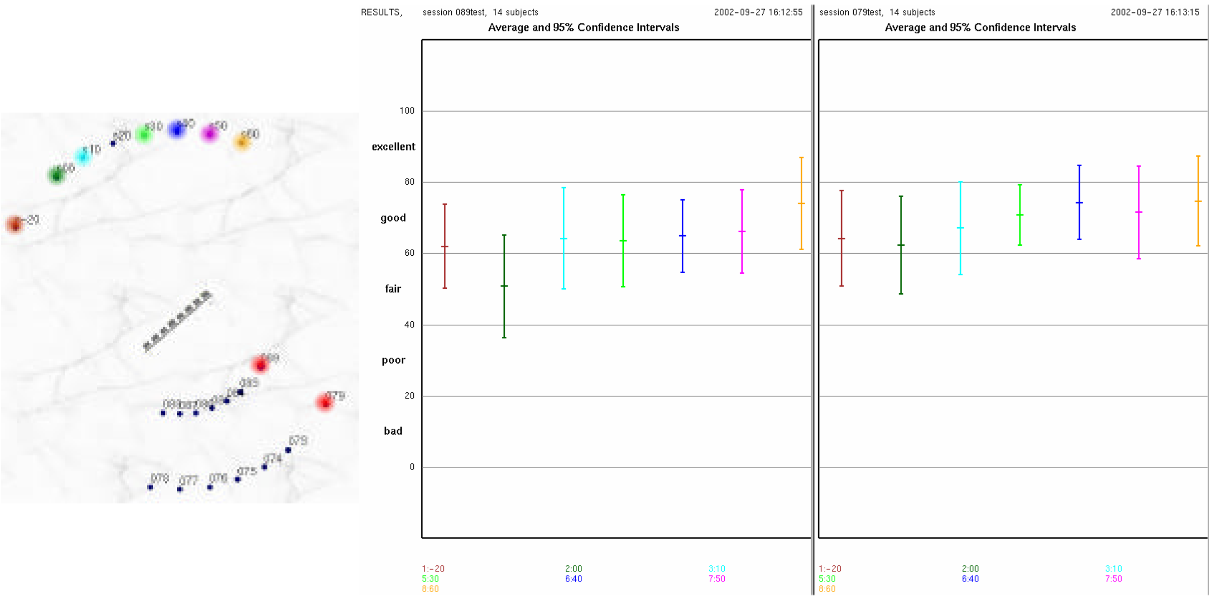

Figure 17: Experiment 4a - listener position -20°

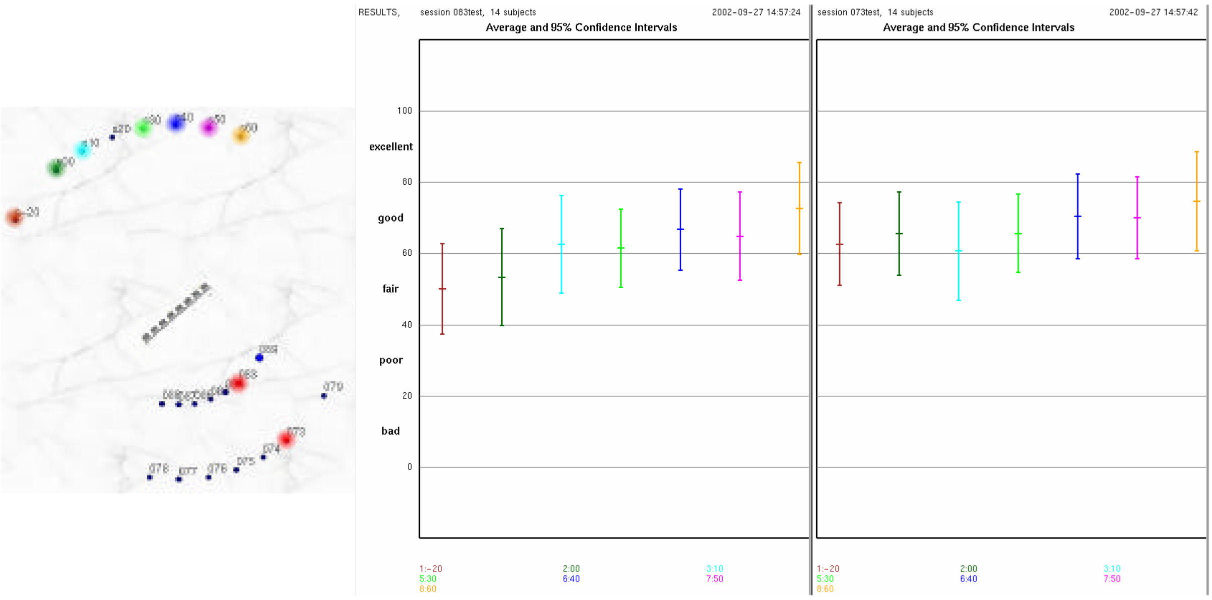

Figure 18: Experiment 4b- listener position 0°

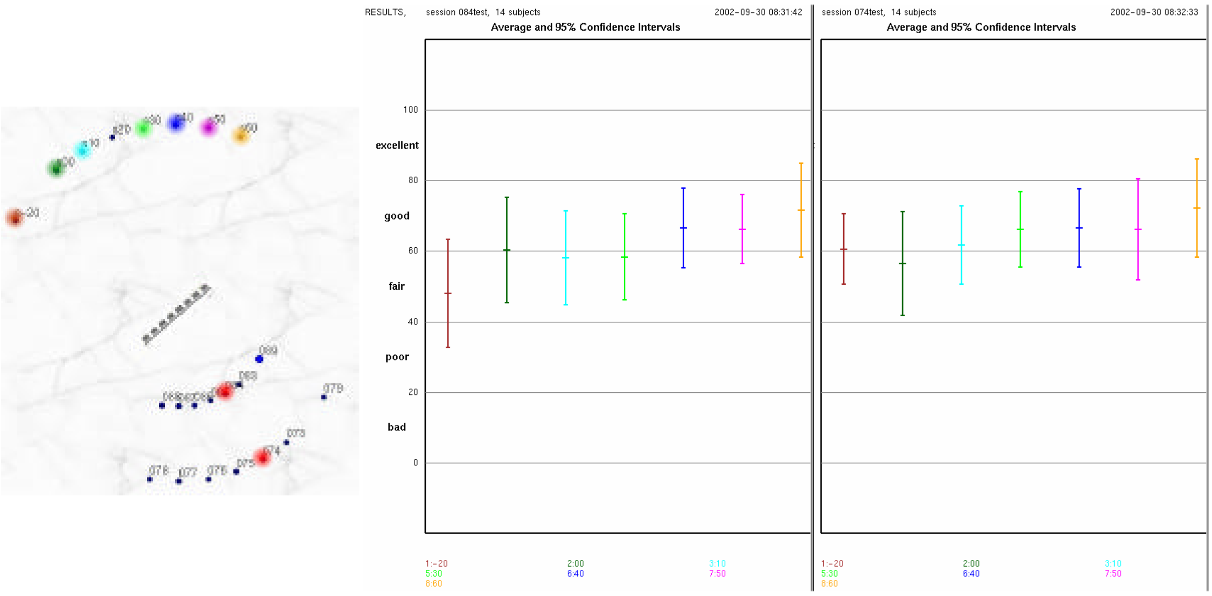

Figure 19: Experiment 4c - listener position 10°

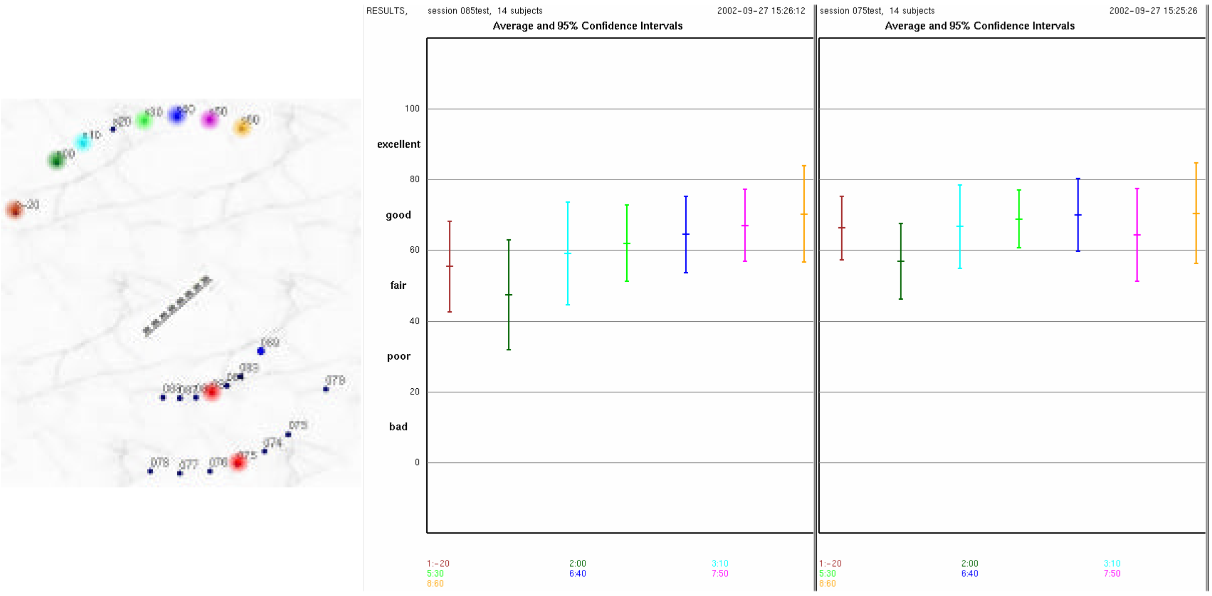

Figure 20: Experiment 4d- listener position 20°

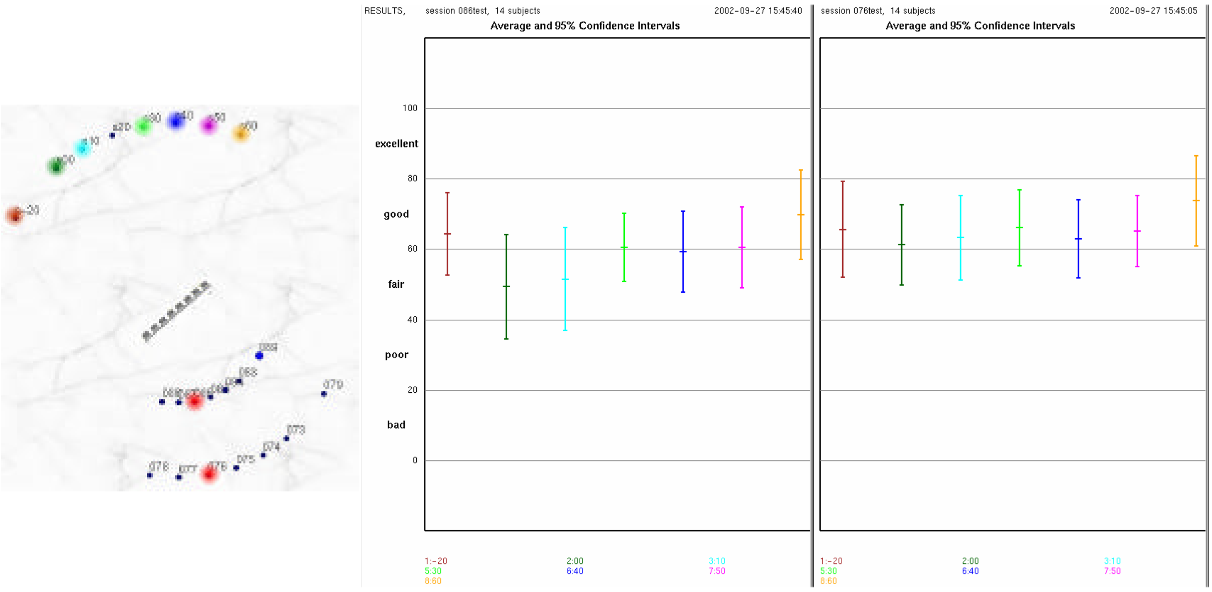

Figure 21: Experiment 4e - listener position 30°

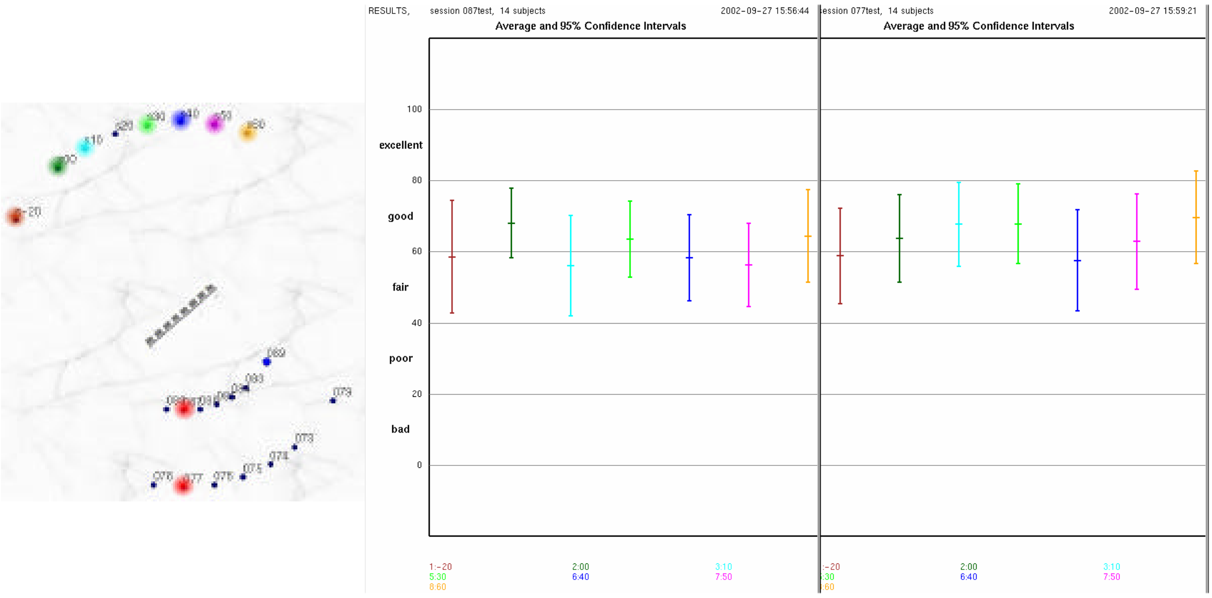

Figure 22: Experiment 4f - listener position 40°

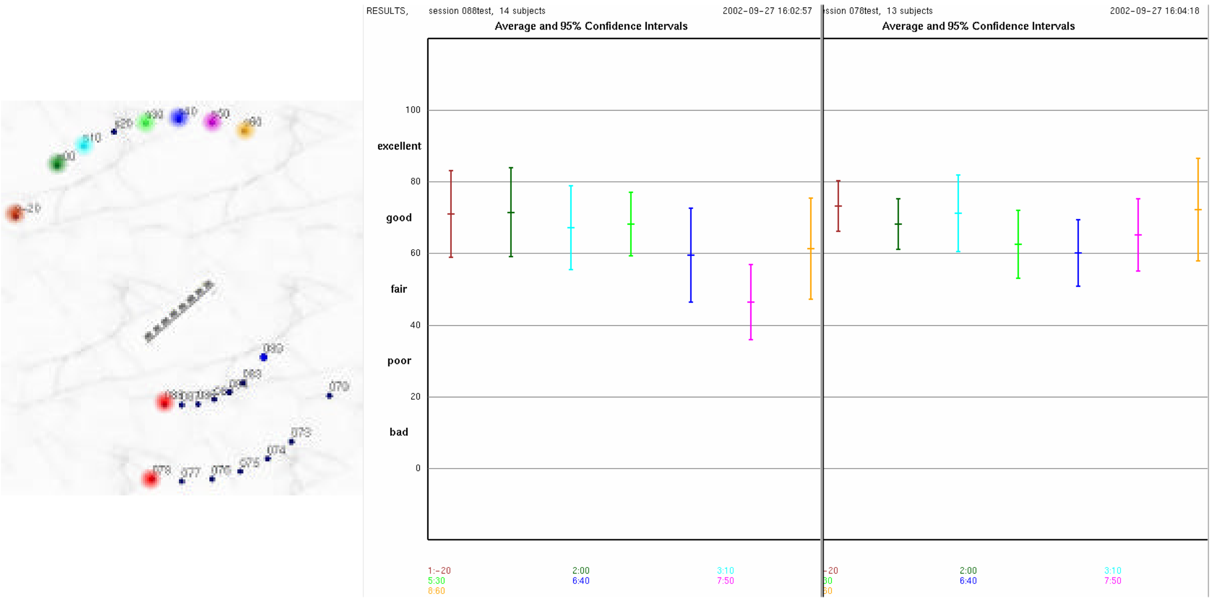

Figure 23: Experiment 4g - listener position 50°

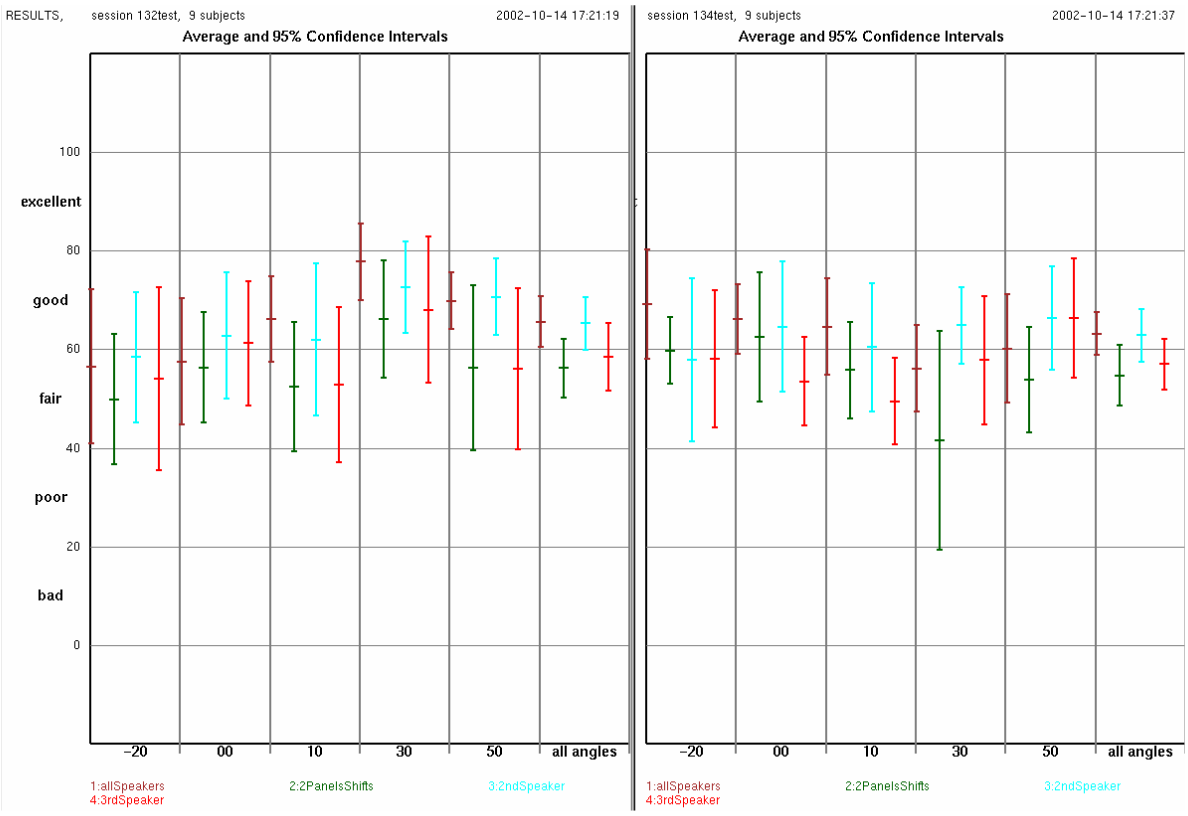

Figure 24: Experiment 5: audio quality at listener position 0° (left) and 30° (right)