Auditory spatial resolution studies in the Helsinki Music Centre

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One factor in the appreciation of symphonic music is the listener's ability to spatially segregate the various orchestral sections and even individual instruments. This ability depends on the acoustic conditions in the concert hall, and is investigated here with measurements from the recently opened main concert hall of the Helsinki Music Centre. Binaural room impulse response measurements using loudspeakers distributed at close spacing across the stage were taken, and assessment of spatial resolution at various listening positions was conducted using psychoacoustic experiments with male and female speech signals. Furthermore, listening experiments were conducted with impulse responses windowed or truncated at various time steps. Auralizations made with partial impulse responses allowed insight in to the most perceptually relevant portions of the room response, and hence determination of the most critical properties of the room. Spatial resolution is gauged using an adaptive up-down threshold procedure in which the listener is asked to distinguish which of two sources is to the left of the other. These tests were conducted for three listening positions and compared to previous experiments in a theater and simulated concert hall. It is found that this hall allows for very accurate spatial judgments of only 1.5° even at some of the furthest seats.

1 INTRODUCTION

This paper investigates auditory spatial discrimination in the Helsinki Music Centre. The influence of the relative strength of the direct sound is investigated by measuring listeners' spatial discrimination at seats located various distances from the stage. Furthermore, the role of late reverberation in spatial discrimination is investigated by conducting tests with auralizations generated from truncated impulse responses. The relationship between the relative strength of the

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direct sound and auditory spatial discrimination informs understanding of which cues the auditory system is utilizing for localization in concert halls. For example, if spatial discrimination remains constant with increasing receiver distance, then it is apparent that the direct sound is sufficient, and the reverberation is not interfering with localization, possibly reflections are even aiding in localization. On the other hand, if spatial resolution reduces with distance, it can be concluded that the localization cues are primarily in the direct sound and reduced direct to reverberant ratio prevents utilization of the information in the direct sound. If localization is impaired by late reverberation, the truncated responses should produce better spatial discrimination results.

Some previous research has examined auditory discrimination of simultaneous sources, but not in the context of performance venues. For example, Perrott[1] found that listeners could distinguish the relative positions of two similar simultaneous tones within 5-10°. Best *et al.*[2] investigated simultaneous noise bursts and found that listeners perceived two sources when they were separated about the center by 10-20°. Kopčo *et al.*[3] found that listeners could localize one speaker in a mixture of four others with about ± 5-7° accuracy. The present study uses speech signals convolved with measurements from the reverberant concert hall to examine concurrent minimum audible angle.

Previous research[4] has shown that reflections from diffusive architectural surfaces produce poorer spatial discrimination as compared to specular or absorptive reflections. In the present experiment, the room surface conditions are held constant and the receiver position is varied to examine auditory spatial discrimination as a function of distance, rather than surface treatments. The present results will be compared to those previously attained using auralizations of a measured theater and a simulated concert hall.

2 EXPERIMENT

Impulse response measurements were conducted in the Helsinki Music Centre at three receiver positions with 16 sources spread across the stage. The sources were Genelec 1029A powered studio monitors set on stands 1.2 m above the stage, 62 cm from center to center. A Cortex Mk II binaural dummy head was placed at three distances in front of the stage representing front, middle, and back listening positions. A swept sine was played on each loudspeaker in sequence and the recordings were post processed to obtain a binaural impulse response from each loudspeaker to each listening position. The impulse responses were normalized to contain equal broadband energy for each distance, such that each condition would be presented at approximately the same loudness. The measurement setup is illustrated in Figure 1. The receivers were 11.6, 17, and 24.2 meters from the center source. Figure 2 illustrates the measured impulse responses for the three listening positions. Gating the late reverberation from the impulse response at the rear-most listening position generated three additional listening conditions. These conditions are pseudo-anechoic, in which only the direct sound is preserved, and two others, in which the first 50 and 200 milliseconds of the response are preserved.

Using an adaptive up-down threshold testing procedure, listeners were presented with two simultaneous talkers from the coordinate response measure speech corpus[5], a male and a female, from two positions on stage and asked whether the male or the female was on the left. The sentences spoken in the samples follow the format, "Ready *call sign* go to *color*, *number* now." For each trial the call sign, color, and number were randomly chosen for the male and female, and the relative position of the male and female were also randomly chosen. This procedure was repeated to obtain a threshold for each listening distance and gated reverberation case.

The talkers were simulated equidistant from the center of the stage, whereas in the previous experiment[4] one was in the center and the other was offset to the left. This keeps the azimuth of the center of separation constant, rather than having it move towards the center as the separation decreases. Another difference between this experiment and the previous one is that directional loudspeakers were used. This results in a higher direct to reverberant energy ratio than would be attained with omni-directional sources, since more of the energy is directed at the listener and less at the room's reflecting surfaces. The direct to reverberant energy ratios for all of the conditions are indicated in Table 1.

The talkers were initially presented at the widest separation. For different receiver distances the angular separation varied, since the width of the loudspeaker array remained constant. From the furthest position to the nearest, the maximum separations between sources were, 22°, 31°, and 44°, and the minimum separations were 1.5°, 2.1°, 3.1°. During the listening test, all three distance conditions were randomly interleaved, so the listener was not directly aware of which condition was being presented. Two correct answers resulted in the separation narrowing for the next trial, and a single incorrect answer resulted in the separation widening. This process was continued until eight reversals were recorded, and the threshold was calculated as the average of the last four separation widths. The final recorded width corresponds to the threshold at which the listener will answer correctly 70.1 percent of the time.[6]

Seven subjects participated in the listening tests. All were associated with the Department of Media Technology at Aalto University. All had extensive previous experience with listening experiments, and none reported any hearing abnormalities. The listeners were seated in a quiet office with a PC and operated a Matlab GUI to take the test. Sennheiser HD650 supra-aural headphones were connected to a PreSonus Firepod digital audio interface, which received signals from Matlab.

3 RESULTS AND DISCUSSION

Figure 3 illustrates the results of the listening test. Note that the minimum possible separation angle for the front position is 3.1°, for the middle, 2.1°, and for all other conditions 1.5°. The primary finding here is that listeners are very accurate in discriminating multiple sources. The overall mean for all conditions for all listeners was 4.4°. This compares to prior results for a small theater of 7.9°, and 9.5° for a simulated concert hall. The main identifiable difference between this hall and the previous ones is the absence of strong lateral reflections. In the theater, there were large proscenium splay surfaces, and similar surfaces in the hall simulation. However, in the vineyard style Helsinki Music Center, the early reflecting surfaces are primarily absorptive or diffusive and not oriented as to give pronounced reflections to the audience. This absence may account for the more accurate localization, even though many other parameters of the spaces were similar.

A second main finding is that, distance does not have an influence on the accuracy; listeners can distinguish two sources when they are sitting in the back row as when they are sitting in the front row. This is initially surprising, but upon further investigation, consistent with previous findings. Localization has been found to be accurate until signal-to-noise ratios fall below 0 to -6 dB.[7] If the direct sound is to be considered the signal and reverberation is to be considered as noise, the most distant seat in this test has a signal to noise ratio of -5.1 dB. This is still within the region that localization is accurate, particularly considering that the reverberation is not purely noise, but may offer some localization cues itself. This also explains why gating the late reverberation has no effect, since the total reverberation is not above the threshold at which it would interfere with localization.

4 CONCLUSIONS

Due to the absence of strong lateral reflections, and the high direct to reverberant ratios in even the furthest seats, source position discrimination is very accurate in the Helsinki Music Center's main concert hall. This was determined by conducting impulse response measurements at many closely spaced positions across the stage, and using these to generate simulations. The simulations were used for listening tests, in which, the listener was asked to distinguish which of two talkers was to the left of the other. Further research is necessary to determine the spatial discrimination characteristics for halls of similar and varying typologies, and to determine which features of the halls affect localization and discrimination accuracy.

5 ACKNOWLEDGEMENTS

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Table 1 – Acoustic parameters for the three receiver positions.

Receiver	R1	R2	R3	R3-DS	R3-0-50	R3-0-200	Hall	Theater
T_{30} [s](250-2000 Hz)	2.3	2.3	2.3	N/A	N/A	N/A	2.00	0.87
IACC (Broadband)	0.62	0.59	0.33	0.88	0.46	0.35	0.26	0.43
Direct/Reverberant[dB] (Broadband)	2.3	0.4	-5.1	Inf	-2.3	-4.46	-8.3	-0.5
Mean Discrim. Angle [deg.]	4.5	4.4	4.7	3.4	4.4	4.6	9.5	7.9

Fig. 1 – Source and reciever positions in the Helsinki Music Centre.

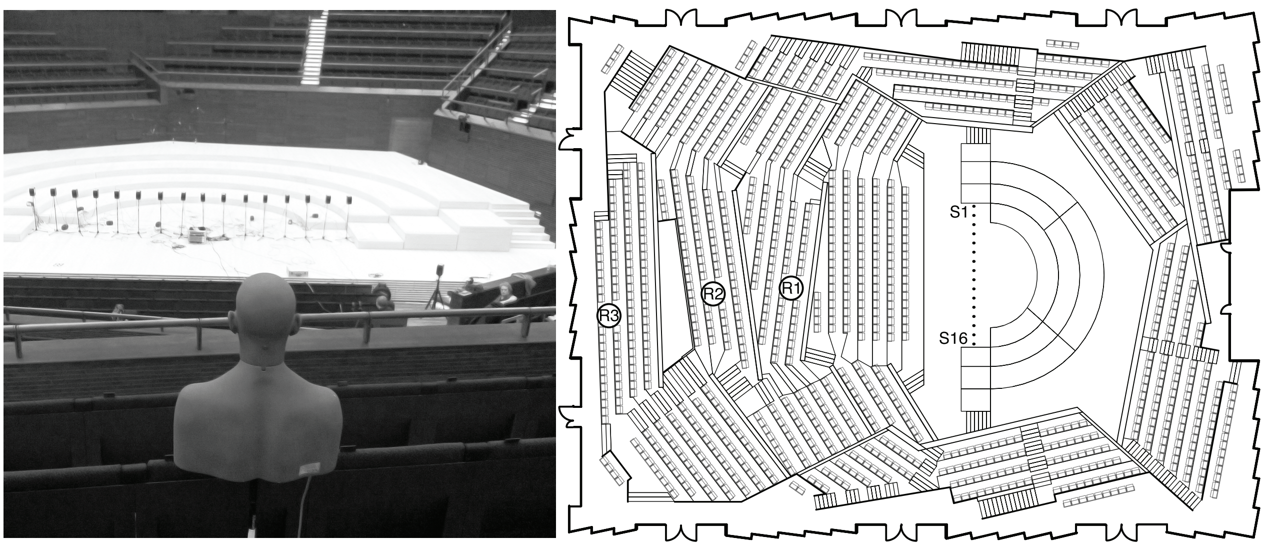

Fig. 2 – Measured impulse responses from three listening positions in the Helsinki Music Center.

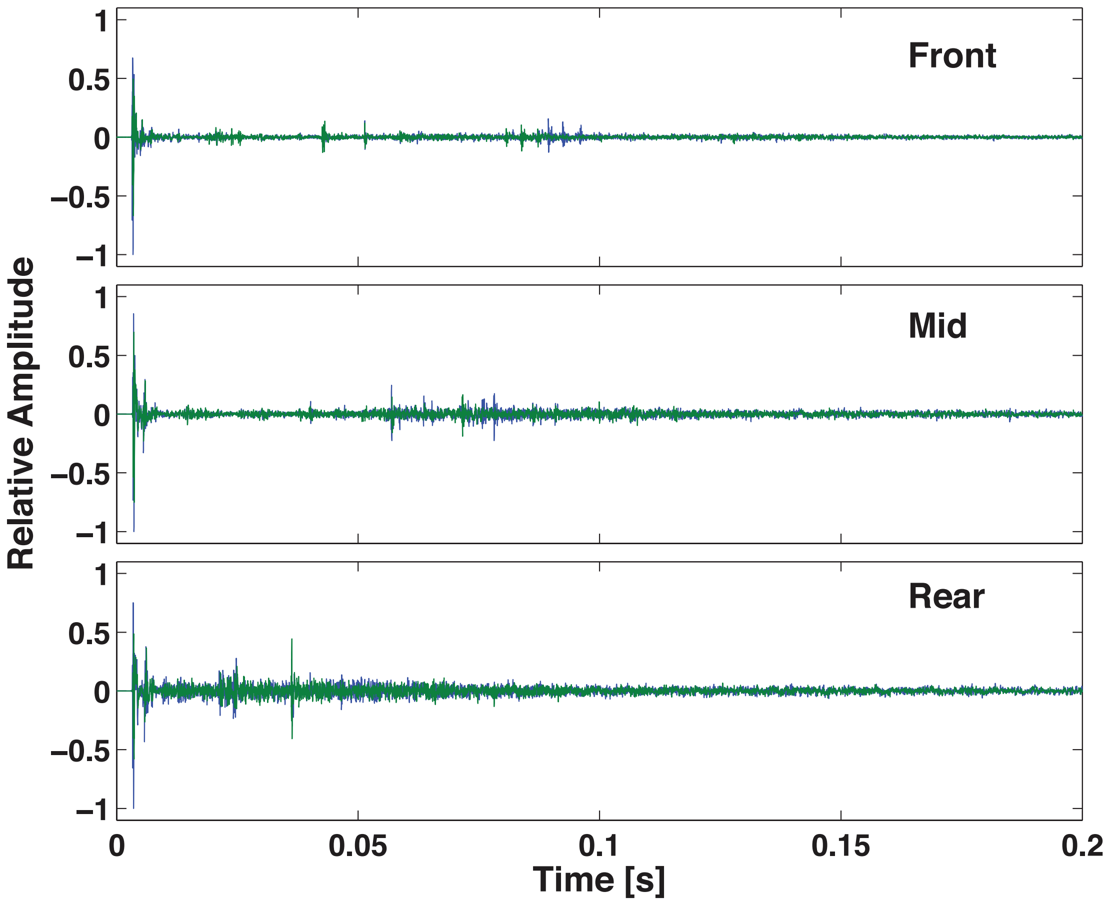

Fig. 3 – Listening test results for concurrent minimum audible angle in the Helsinki Music Center. Red crosses represent individual subjects' results, blue lines represent 95% confidence intervals, and blue dots represent the means, for each listening position. No significant differences can be found between the listening conditions.