Sensitivity to angular and radial source movements in anechoic and echoic single- and multi-source scenarios for listeners with normal and impaired hearing

MICHA LUNDBECK[1,2,*], GISO GRIMM[1,2], VOLKER HOHMANN[1,2], SØREN LAUGESEN[3], AND TOBIAS NEHER[1]

[1] *Medizinische Physik and Cluster of Excellence Hearing4all, Oldenburg University, Oldenburg, Germany*

[2] *HörTech gGmbH, Oldenburg, Germany*

[3] *Eriksholm Research Centre, Snekkersten, Denmark*

So far, very little is known about the perception of spatially dynamic sounds, especially under more complex acoustic conditions. Therefore, this study investigated the influence of reverberation and the number of concurrent sources on movement perception of listeners with normal and impaired hearing. Virtual listening environments were simulated with the help of a higher-order Ambisonics-based system that allows rendering complex scenarios with high physical accuracy. Natural environmental sounds were used as the stimuli. Both radial (near-far) and angular (left-right) movement perception were considered. The complexity of the scenarios was varied by adding stationary sound sources as well as reverberation. As expected, hearing-impaired listeners were less sensitive to source movements than normal-hearing listeners, but only for the more complex acoustic conditions. Furthermore, adding sound sources generally resulted in reduced sensitivity to both angular and radial source movements. Reverberation influenced only radial movement detection, for which elevated thresholds were observed. Altogether, these results illustrate the basic utility of the developed test setup for studying factors related to spatial awareness perception.

INTRODUCTION

Sensorineural hearing loss can lead to a multitude of hearing deficits, particularly under more complex listening conditions. For example, hearing-impaired (HI) listeners are known to experience great difficulty with listening in multi-source conditions and with judging distance and movement, and these problems appear to be related to their experience of handicap (Gatehouse and Noble, 2004).

Even though a number of studies have addressed distance and movement perception in normal-hearing (NH) listeners (e.g., Perrott and Saberi, 1990; Chandler and Grantham, 1992) the same is not true for HI listeners. Also, the studies that have

*Corresponding author: micha.lundbeck@uni-oldenburg.de

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been conducted so far have generally focused on simple situations: anechoic single-source scenarios. An exception to this is a recent study of Brungart *et al.* (2014) who presented multiple environmental sounds in various pseudo-dynamic arrangements to their listeners by adding to or removing sounds from the auditory scene. They found a decrease in performance with increased task complexity and the number of sound sources presented.

In the current study, we piloted a novel test setup that we developed for studying factors related to the perception of spatial dynamics. To that end, we used a toolbox that allowed us to simulate virtual acoustic environments with high physical accuracy. Our focus was on the perception of moving sounds, i.e., sounds that varied in terms of their angular (left-right) or radial (near-far) position. In particular, we investigated the influence of the number of concurrent sound sources as well as reverberation on the ability of young normal hearing (NH) and elderly hearing impaired (HI) listeners to detect changes in angular (left-right) or radial (near-far) source position. Our hypotheses were as follows:

1. Young NH listeners will generally outperform elderly HI listeners in terms of their thresholds for source movement detection
2. An increased number of sources will result in higher thresholds for source movement detection
3. Reverberation will generally also affect source movement detection

METHODS

Participants

The participants were eight young NH listeners (2 male, 6 female) aged 23-29 yrs (mean: 25.8 yrs) and 10 paid elderly HI listeners (6 male, 4 female) aged 64-79 yrs (mean: 74.5 yrs). Five of them were experienced hearing aid users with 2-6 yrs of experience. The NH listeners had normal audiometric thresholds (≤ 25 dB HL) from 0.125 to 8 kHz. The HI listeners had symmetric moderate-to-severe sensorineural hearing losses, as depicted in Fig. 1.

Setup

The “Toolbox for Acoustic Scene Creation and Rendering” (TASCAR; Grimm *et al.*, 2015) was used to simulate the virtual environments. TASCAR allows rendering complex scenarios with high physical accuracy, including moving sound sources. The acoustic environment was based on an entrance hall (approx. 10.5 m × 6 m × 2.8 m with solid walls, glass and wooden floor). The head of the virtual listener was placed 1 m away from the middle of the shorter wall facing along the longer side. The target source was located 1 m away from, and directly in front of, the listener (height of 1.5 m). A schematic top-down view of the room is shown in Fig. 2. A change in complexity of the scenario was achieved by adding two or four stationary sound sources at a distance of 1 m each and azimuths of ±30° and ±60° relative to the frontal direction. The room could be changed from an anechoic to an echoic (T_{60} = 0.8 s) environment.

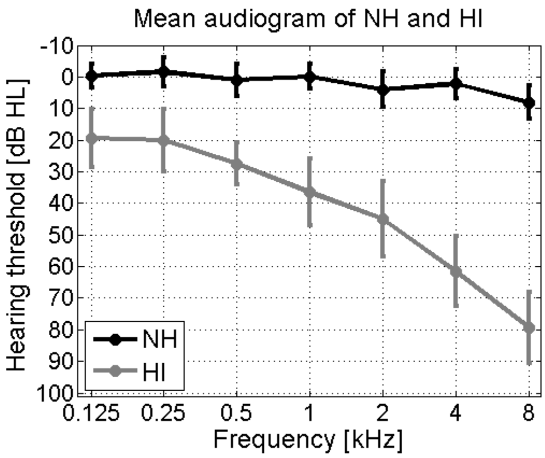

Fig. 1: Average hearing thresholds for the NH (black) and the HI (grey) group. Error bars denote standard deviations.

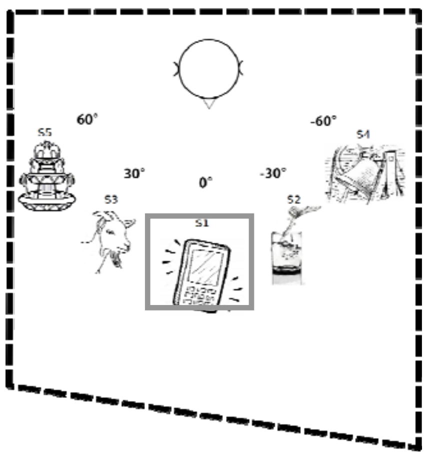

Fig. 2: Schematic top-down view of the simulated room, showing the virtual listener and the five sound sources at 0° (S1), ±30° (S2, S3), and ±60° (S4, S5). S1 (telephone sound) was moving either in the left-right or near-far direction (see text for details).

Stimuli

For reasons of comparability with the literature (Chandler and Grantham, 1992), we made reference measurements using a one-octave band of noise centered at 3 kHz as the stimulus. In this case, the velocity of the source movement was fixed at 20°/s for angular and 7 m/s for radial movements. The tracking variable in the adaptive procedure (see below) was the stimulus duration. The measured values of stimulus duration were then multiplied with the velocity to obtain the Minimum Audible Movement Angle (MAMA) or the Minimum Audible Movement Distance (MAMD) (e.g., 0.45 s × 20°/s = 9° of arc).

In addition, we made measurements with up to five different environmental sounds (similar to Brungart *et al.*, 2014). A ringing phone served as the target sound in all measurements (see Fig. 2). The other sound sources (soda pouring, goats, church bells, and a fountain) were fixed in location. Each sound was presented at an overall level of 65 dB SPL (nominal). For the measurements with the environmental sounds the stimulus duration was fixed at 3 s. To vary the extent of source movement the velocity was varied in the adaptive procedure.

Procedure

Initially, the hearing thresholds from 0.125 Hz to 8 kHz of all participants were determined. They were then seated in a soundproof booth in front of a screen where they could use a graphical user interface to provide their answers. Their task was to indicate whether or not they perceived the target sound source to move. For this, a single-interval 2-alternative-forced-choice (AFC) paradigm with an adaptive 1-up 2-down rule (Levitt, 1971) was implemented in the software framework "psylab" (Hansen, 2006). In half of the trials, the target sound source was simulated to move. In the angular movement conditions, the direction of movement (towards the left or right) was randomized, whereas in the radial movement conditions a withdrawing movement was always simulated. Playback was via a 24-bit Edirol UA-25 soundcard, a headphone preamplifier (Tucker-Davis HB-7), and a pair of Sennheiser HDA 200 headphones. For the HI listeners linear amplification was provided via the Master Hearing Aid research platform (MHA; Grimm *et al.*, 2006) according to the NAL-RP fitting rule to ensure adequate audibility.

Initially, a training run was completed for every new condition, i.e. before the reference measurements and whenever the movement direction (left-right to near-far or vice versa) was changed. Each participant completed two blocks of measurements divided into angular and radial movement measurements with a preceding reference condition. As apparent from Table 1, 12 environmental scenarios were tested (in randomized order). After two to three weeks a set of retest measurements was performed to assess test-retest reliability. The whole experiment took about four hours.

Spatial movement dimension	**Number of sound sources**	**Degree of reverberation**
Left-right (MAMA) vs. Near-far (MAMD)	1 source (moving or not) vs. 3 sources (1 moving or not) vs. 5 sources (1 moving or not)	Anechoic vs. Echoic

Table 1: Experimental variables chosen for the simulation of the different environmental scenarios. A total of 12 scenarios were tested.

Data analysis

In accordance with Chandler and Grantham (1992), a criterion was set to accept or exclude thresholds estimated by the adaptive procedure. In their study, thresholds were only accepted if the standard deviation of the tracking variable at the reversal points did not exceed one-third of the corresponding threshold value. Due to the fact that we observed large tracking excursions for some of our participants, we raised the criterion value to one-half of the threshold. As a result, a total number of 11 thresholds had to be excluded (out of 484 estimated thresholds).

Because of the relatively small sample size and the non-normal distribution of some datasets we performed non-parametric tests. To test for group differences we performed Mann-Whitney *U*-tests for independent samples. To test for the influence of the number of sound sources we performed Friedman's ANOVAs, while for testing the influence of reverberation within each group we performed Wilcoxon tests for dependent samples.

Two of the HI participants had great difficulties to hear out the target sound source in the multi-source scenarios. For these conditions, they therefore had to be excluded from the data analysis.

RESULTS

Reference measurements

In Fig. 3 the reference measurements for the two movement dimensions are depicted. The left panel shows the MAMA thresholds for both groups in comparison to a reference data point taken from Chandler and Grantham (1992). The right panel shows the MAMD thresholds for the two groups. The difference between the NH and HI thresholds was not significant for either reference condition (MAMA: $p = 0.54$; MAMD: $p = 0.17$).

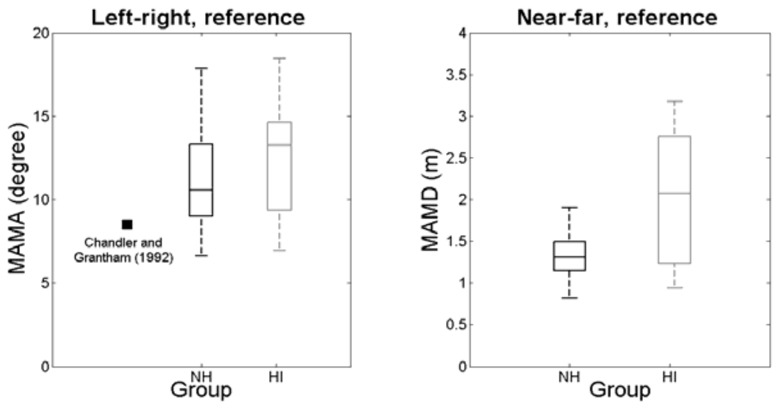

Fig. 3: Boxplots of reference measurements. Left: MAMA thresholds (fixed velocity of 20°/s) for NH and HI listeners. The black square shows a reference threshold value from Chandler and Grantham (1992). Right: MAMD thresholds for NH and HI listeners.

Compared to the literature value, the median MAMA threshold measured with our setup was slightly elevated. However, the reference value falls clearly within the range of our dataset. For the MAMD measurements, no corresponding literature data are available.

MAMA measurements with environmental sounds

Fig. 4 shows the thresholds for the angular movement detection task.

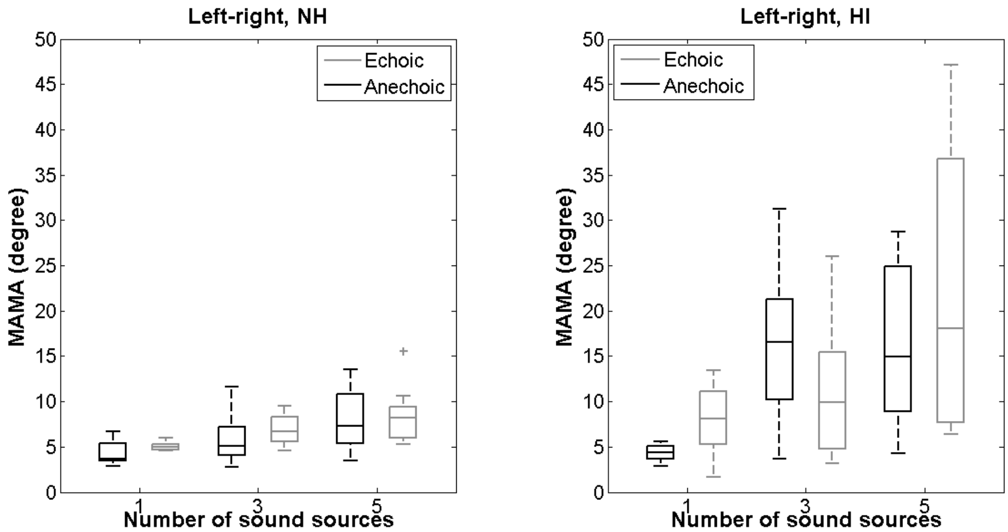

Fig. 4: MAMA thresholds for environmental sounds. NH data are depicted in the left and HI data in the right panel. Shown is the MAMA for different numbers of sound sources and degree of reverberation (black: without reverb; grey: with reverb).

A Mann-Whitney *U*-Test (2-tailed) performed on the data pooled across all conditions revealed a significant difference between the two groups ($U = -2.9$, $p = 0.004$). Furthermore, a significant change in threshold was found when the number of sound sources was increased (pooled across the two reverberant conditions). This was true for both groups and all conditions (all $p < 0.05$) except for the comparison of three and five sound sources within the HI group ($p = 0.3$). However, no influence of the degree of reverberation was found (NH: $p = 0.22$; HI: $p = 0.9$). A possible explanation for this could be that listeners may quickly 'learn' room reverberation patterns, enabling them to suppress spatial cues of signal components that have been corrupted by reflections (cf. Shinn-Cunningham, 2000).

MAMD measurements with environmental sounds

The results for the near-far movement detection task are depicted in Fig. 5. The data were analyzed in the same manner as the MAMA thresholds. Again, a significant difference between the two groups was found ($U = -2.6$, $p = 0.01$). Furthermore, unlike in the MAMA results, reverberation had a significant influence on both groups (both $p < 0.001$). Also, a general influence of the number of sound sources was found. Only the comparison of the 3- and 1-source scenario for the NH group and the 3- and 5-source scenario for the HI group was non-significant (all other $p < 0.05$). Interestingly, the thresholds for the 1-source scenarios were similar for the two groups. Sensitivity worsened for the multi-source scenarios, especially so for the HI group. Participants reported that they depended on level changes of the target stimulus and that it was difficult to imagine the withdrawing movement in the virtual environment. The combination of additional masker sounds and reverberation led to a more diffuse sound field that lowered the direct-to-reverberant sound ratio, an important cue for distance perception in rooms (Bronkhorst and Houtgast, 1999; Zahorik, 2002). Hence, the detection of level changes presumably became more difficult.

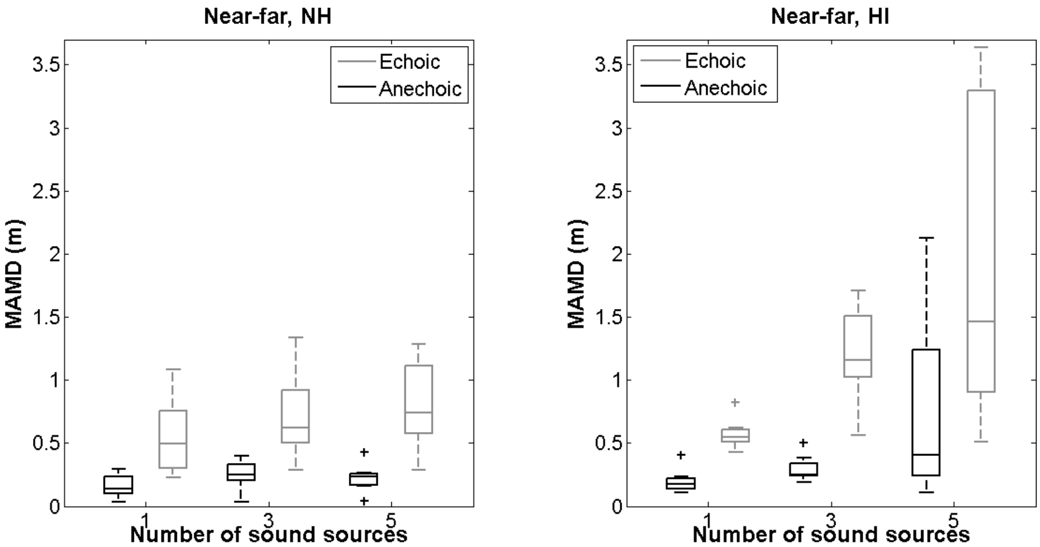

Fig. 5: MAMD thresholds for environmental sounds. NH data are depicted in the left and HI data in the right panel. Shown is the MAMD for different numbers of sound sources and degree of reverberation (black: without reverb; grey: with reverb).

SUMMARY

This study investigated the influence of the number of sound sources and reverberation on source movement perception in listeners with normal and impaired hearing. Comparison to some literature data showed that our (TASCAR-based) setup can be used for the assessment of spatial dynamics, as the thresholds we obtained were of comparable magnitude to those from the literature measured with a free-field setup. Results for the environmental sounds generally showed the expected differences between NH and HI listeners insomuch as the NH listeners

were more sensitive to angular and radial source movements in the multi-source conditions. Furthermore, an increase in the number of concurrent sound sources generally resulted in higher thresholds (except for the NH listeners in the near-far conditions). Finally, the expected change in thresholds under reverberant conditions was found for the near-far conditions, but not for the left-right conditions. Altogether, this study shows promise regarding the assessment of movement perception in complex listening scenarios with the developed test setup.

ACKNOWLEDGEMENTS

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