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Does learning a room's reflections aid spatial hearing?

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Abstract

Sound reflections are abundantly present in everyday environments; yet, our spatial hearing abilities are usually not impaired by them. One contributor to this robustness is the adaptation to the reflections after being repeatedly exposed to the room's reverberation. The echo threshold, the delay at which a reflection starts being separately audible as an echo, increases with repeated exposure to the reflection pattern. Benefits from prior exposure to a room's acoustics have also been shown for speech understanding. Here we study if learning the characteristics of the room's reverberation pattern can improve sound localization.

Stimuli were presented in the free-field of the Simulated Open Field Environment (v3), a room acoustics simulation and auralization tool based on the extended mirror-image source method with auralization over 96 loudspeakers. Participants localized target noise bursts presented in the front of the listener in a virtual room either with no prior information about the room, after a short exposure phase consisting of two noise bursts presented in that room, or after a long exposure phase consisting of 14 noise bursts. The exposure stimuli were presented from random locations for each burst at the sides in order to transmit information about the room, but to prevent interference with the target stimulus locations. Localization ability as measured by RMS error and standard deviation was improved after prior exposure to the room acoustics. Results indicate that learning room acoustics can aid our ability to locate sound sources in rooms. Since exposure and target stimuli did not share the same positions and reflection patterns, results also demonstrate a generalization within the room in that the improvement from room learning can carry over from one to another position.

Keywords: Sound localization, Binaural hearing, Precedence effect, virtual acoustics, room acoustics

Does learning a room's reflections aid spatial hearing?

1 Introduction

Sound reflections are abundantly present in everyday environments, from the walls of houses when we walk down the street to rooms in which most of us spend the largest part of the day. Yet, sound localization appears robust. What is more, sound reflections might even help us, as evidenced in blind people who can navigate by echo-location [1]. The precedence effect has been associated with our ability to correctly locate sound sources in the presence of reflections [2]. The echo threshold, the delay at which a reflection starts being separately audible as an echo, is not fixed, but increases with repeated exposure to the reflection pattern. It seems that we adapt to the reflections such that they become less audible with repeated exposure.

Clifton [3] and Clifton et al. [4] have studied the effect of reflection adaptation on echo thresholds. Clifton [3] presented repeated click-pairs from two loudspeakers with a time delay of 5 ms, and the lead-lag click pair was perceived as only one click, indicating its delay being shorter than the echo threshold. When the leading and lagging speakers were switched, listeners would suddenly hear clicks from both speakers, denoting a breakdown of the precedence effect. Over a series of 8-10 clicks the echo again faded away as the precedence effect ("echo suppression") built up. A following study [4] examined a similar effect, playing listeners a "conditioning" train of clicks, and then changing the time interval, frequency content, or intensity. They found that changes that would correspond to a highly improbable room acoustic event (such as a suddenly moving wall) were most likely to cause a breakdown of the precedence effect. Djelani and Blauert [5] showed that adaptation can also occur to multiple reflections of a room. Moreover, adaptation was shown to depend on a particular direction. We will show here that benefits for localization can generalize to the whole room and will not depend on a particular, adapted direction.

Benefits from prior exposure to a room's acoustics have also been shown for speech understanding. Brandewie and Zahorik [6] measured speech identification (from a closed set) at varying signal-to-noise ratios in a room. The words were presented either in isolation, or as part of a sentence (with a preceding "adaptor"), with the additional length of the target signal providing listeners a greater opportunity to adapt to the room acoustics. An average decrease of 2.68 dB in speech reception threshold was seen when the longer signal was used, showing evidence that adaptation to room acoustics is beneficial for speech intelligibility in rooms.

While these studies showed reflection adaptation leading to increased echo thresholds and improved speech intelligibility, effects on sound localization have not been studied to our knowledge. We ask here if learning the reflection characteristics through repeated exposure to a room's reverberation can improve sound localization. This improvement could be seen in a reduced (mean) bias when localizing sounds, i.e. in a more accurate position estimate on average, or in a reduction of localization variance, i.e. a more stable positions estimate, irrespective of a bias, or in a combination of both as, e.g., expressed in reduced rms-error. The benefit for localization from prior exposure to a room's reflections was studied by comparing localization ability of a noise bursts in a virtual room in three conditions: 1) a baseline without prior exposure to the room acoustics, 2) a short exposure condition where two noise bursts were presented in the same room prior to the localization target stimulus, and 3) a long exposure condition in which 14 noise bursts were played prior to the target to transmit more information about the room. Room exposure and target stimuli came from different locations, thereby testing the brain's ability for general adaptation to the room's acoustics rather than to a specific reflection pattern. In other words, we tested not only if there is a benefit from exposure to room reflections, but also if the benefit could stem from stimuli played anywhere in the room and improve localization of a new stimulus at a different position. Tests were conducted in three different virtual rooms to test if results generalize.

2 Methods

2.1 General setup

Localization tests were conducted in the Simulated Open Field Environment (SOFE), version 3 at AIP TUM [7]. The SOFE consists of software for room acoustics simulation, and a horizontal ring of 96 loudspeakers (3.75º spacing) with individually equalized frequency response. The room simulation software, implemented in Matlab, is based on the image source method. Image sources are simulated up to a high order (here 100) to model high reflection density in late room reverberation. Each individual reflection is rendered as the impulse response of a filter carrying the accumulated absorption characteristics of all reflections surfaces on the reflection path. Reflections are attenuated according to distance and merged into room impulse responses for each loudspeaker according to their travel delay, thereby applying a temporal jitter to later image sources to simulate diffusion. Each individual room reflection is mapped to the nearest loudspeaker in the array, with elevated sources mapped to the horizontal loudspeaker at the same azimuth. Stimuli are convolved with the channel-wise impulse responses and played via the loudspeakers to produce auralizations in the simulated room.

Listeners' localization judgments were collected using the proprioception-decoupled pointer (the *ProDePo*-method) [8]. Participants positioned a laser pointer projecting onto a white paper ring sitting just above the loudspeakers to the localized sound position by turning on a trackball.

2.2 Test stimuli

Stimuli were frozen noise bursts presented in simulated room reverberation. 20 noise bursts of 2 ms duration (with 0.2 ms Gaussian ramps), band-pass filtered to 0.2-12 kHz, were generated at a direct-sound level of 60 dB SPL. Noise bursts were randomly chosen (without direct repetition) for the experiment and convolved with the loudspeaker's room impulse responses for auralization. The bursts were used as target and exposure stimuli.

In the *no-exposure condition*, no exposure stimuli were presented and only a single noise burst serving as the target was played from the target direction. Target directions were always in the front and randomly chosen from ±15°, ±7.5° and 0°.

In the *short-exposure condition*, two noise bursts serving as the exposure stimuli preceded the target noise burst by 500 ms (Figure 1). Exposure noise bursts were presented at an interval of 250 ms from randomly chosen directions from 20 possible directions on either side of the listener. Exposure directions were ±22.5°, ±30.0°, ±37.5°, ±52.50°, ±67.5°, ±82.5°, ±97.5°, ±112.5°, ±127.5° ±135.0°, leaving space to the target directions and all directions to the rear of the listeners with binaural cues similar to those of target directions (stimuli on the cone of confusion to the target locations) in order to avoid potential interactions (Figure 2).

The *long-exposure condition* was similar to the short-exposure condition except that 14 noise bursts were used as exposure stimuli and presented from randomly chosen exposure directions (Figure 2). While providing longer exposure to the reverberation of the test room, the long exposure stimuli should also allow a more in-depth sampling of room acoustics since stimuli are played from more directions. Exposure stimuli were played with equal probability from the left and the right side, i.e. 7 noise bursts were played from each side.

In order to test for generalization of possible adaptation effects across rooms, testing was done in 3 different rooms. All rooms were rectangular and simulated with heavy carpet on the floor, a wooden ceiling and gypsum board on the side walls. Room 1 was 4x3x6 m^3 =72 m^3 in size and had a reverberation time T30 of 0.43 s. Room 2's dimensions were 4.7x6.8x2.5 m^3 = 80 m^3 and T30 was 0.46 s. Room 3 was 3.7x12.8x2.5 m^3 = 119 m^3 in size with a T30 of 0.86 s. The receiver was placed at an asymmetric position to each wall in order to reduce the impact of room modes.

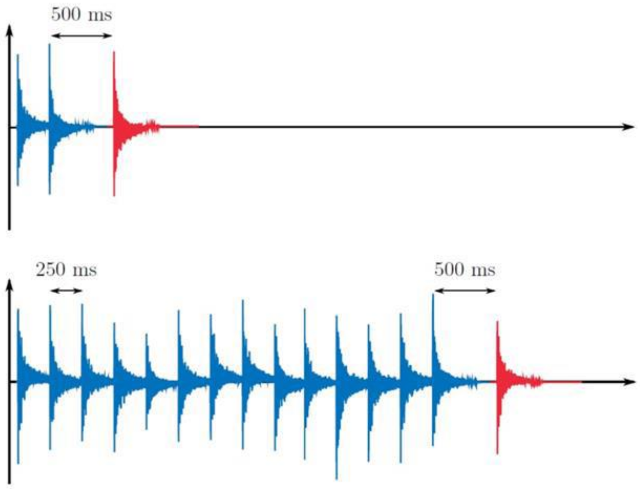

Figure 1. Example stimuli of the short exposure condition (top) and the long exposure condition (bottom).

2.3 Test Procedure and Participants

Localization in the three exposure conditions was tested in separate runs whose order differed across participants to reduce the effect of a potential learning bias on average results. In each of these runs, targets from 5 positions were tested in full combination with 20 different exposure stimuli which were combinations of bursts from random exposure directions. The stimuli were presented in 3 different rooms with room order being random, however, the same room was never chosen again in direct succession in order to keep adaptation local to the just-tested room. For each exposure condition 3 rooms x 5 target directions x 20 exposure stimuli = 300 trials were collected.

Participants were sat on a chair in the middle of the loudspeaker array, facing the frontal loudspeaker (0º). The room was completely dark. After presenting the (target) stimulus, the light spot of the laser pointer appeared at 0º and subjects were instructed to position it to the perceived position of the last, target noise burst and to confirm their response by pressing the left button on the trackball.

Eight subjects took part in the tests, 7 of them male (average age 27.1 years). Participants reported no impairment of hearing. There was no training phase for the experiment because the localization procedure is intuitive and prior room learning was to be avoided.

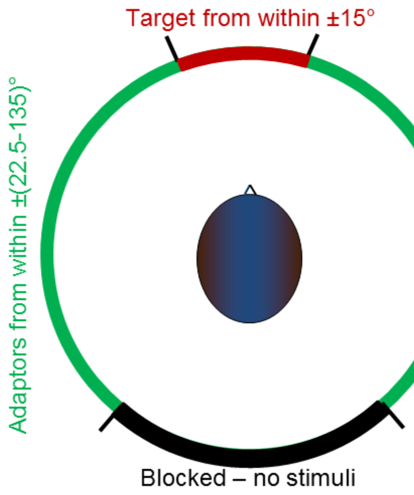

Figure 2. Directional range for stimulus presentation: Target stimuli were always presented from the front from randomly selected loudspeakers within ±15º. Exposure stimuli were presented from random positions on both sides. In order to prevent binaural cues on the cone of confusion to interfere with frontal stimuli, no stimuli were presented from a direction range at the rear.

3 Results

Localization results in room 1 of all participants are presented in Figure 3, where the left figure presents localization results as absolute localized azimuthal angle and the right figure replots those results relative to the target direction in order to highlight the differences between conditions. Medians and quartiles are presented for the three exposure conditions.

With no exposure stimulus participants tended to overestimate the lateral position of the stimuli. Targets at 15º laterality were localized to around 18º. With the short exposure this trend inverted: stimuli were localized closer to the midline and their laterality was somewhat underestimated. With the long exposure smaller (average) bias was seen in room 1. The trend to localize stimuli closer or further from the midline depending on the exposure condition were similar in the other rooms.

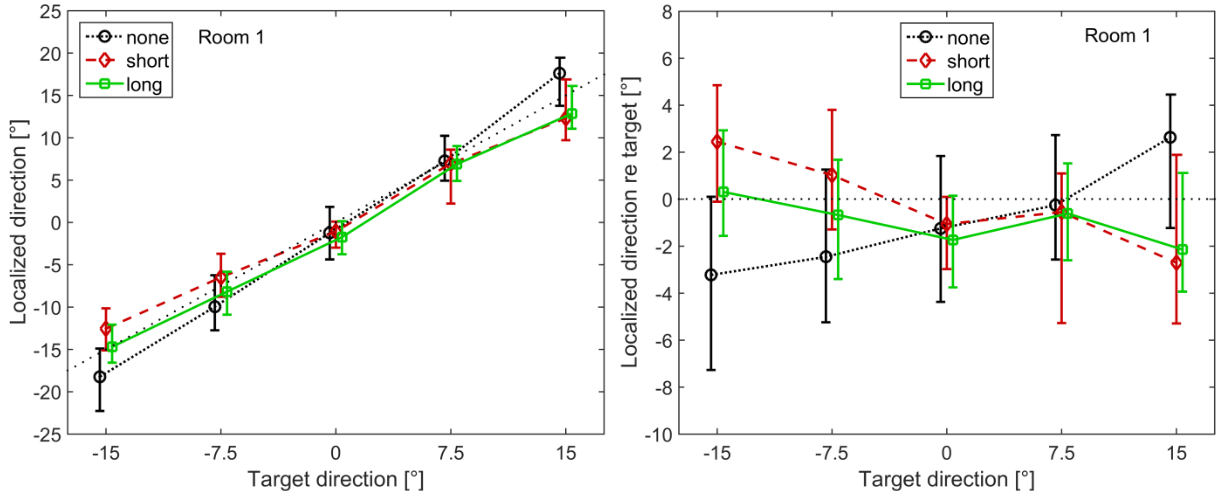

Figure 3: Localized sound position in room 1 presented as medians and quartiles for each target direction in the three adaptation conditions: without exposure to the room's reflections, with a short exposure stimulus, and with a long exposure stimulus. Localization results are given as azimuthal angle (left figure) and as deviation from the target direction (right figure).

Can we conclude that localization is improved after adaptation, i.e. that room information is learned and used for more accurate localization? Figure 4, left, plots rms-localization error across all participants for all rooms and conditions. RMS-error is strongly reduced in the conditions with exposure stimuli, indicating that room learning took place to improve localization ability.

A potential improvement due to room learning could also be seen as an improvement of localization acuity, i.e. a reduction of localization variance. When looking at the results in Figure 3, right, for a target at -15º, it is apparent that – in agreement with this hypothesis – interquartile ranges for both exposure conditions are smaller than for the no-exposure condition. This is highlighted in Figure 4, right, which shows the standard deviation of localization responses averaged across participants. Standard deviations are reduced by about 1 degree in the conditions with exposure in all three rooms, indicating that prior exposure to the room's reverberation can lead to improved sound localization. Similar improvements are seen in all three rooms which differ strongly in their acoustical properties, indicating that results are not restricted to a particular room acoustical condition but are generally present.

While these effects appear strong and clear cut, we want to caution that they are driven by two of the eight subjects which show stronger effects than the others. Over- and underestimations of the lateralized horizontal angle depend on the position and timing of early reflections, and in particular of the relative energy in floor and ceiling reflections which emphasize the target's binaural cues. While we have attempted to produce results that are generalizable by testing in three different rooms at different positions, more research will be needed to understand the effects of stimulus distribution, stimulus type, reflection location, and room parameters on the perceptual learning of room acoustics.

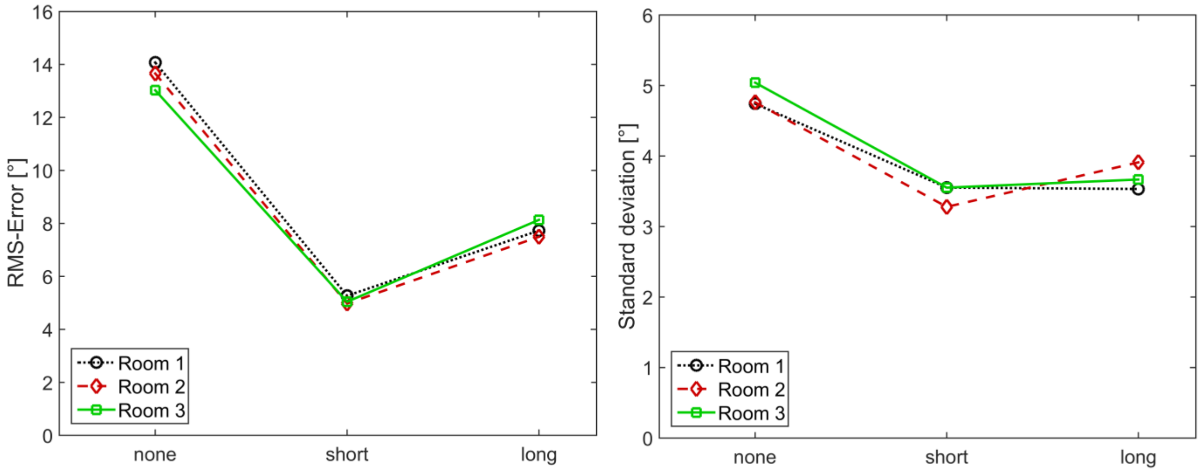

Figure 4. ***Left***: **Root-mean-square localization error across all subjects for the three rooms tested and for the three exposure conditions: without exposure, with a short exposure and with a long exposure stimulus.** ***Right***: **Standard-deviation of localization responses for all conditions as in the left sub-figure.**

4 Conclusions and future work

In this study we tested the hypothesis that repeated exposure to a room's reverberation can lead to perceptual learning of room acoustics which can aid the ability to locate sound sources. Sound localization ability was measured in different rooms and after prior exposure to stimuli played in the room. Both localization error and variance were reduced after prior exposure to stimuli played in that room. It appears that the auditory system can learn the room geometry or calibrate to the room's reflection patterns in order to improve sound localization ability. Importantly, exposure stimuli and target stimuli were from different directions and hence carried different reflection patterns, indicating that the improvement depended on the room acoustics per se and not on particular reflection patterns as in previous studies of the precedence effect. The improvement from room learning generalizes within the room in that learning benefits carry over from one to another position. Hence results indicate a general ability to learn room acoustical properties, statistical or geometrical, to improve spatial hearing in a room. Here we presented exposure stimuli in quick succession from different, pre-defined locations in order to transmit information about the room. In a companion paper at this conference [9] we investigate if the benefit from room learning can be larger when listeners actively control the exposure stimulus location and receive feedback about the stimulus location.

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