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RESEARCH ARTICLE

Free-field study on auditory localization and discrimination performance in older adults

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Abstract Localization accuracy and acuity for low- (0.375–0.75 kHz; LN) and high-frequency (2.25–4.5 kHz; HN) noise bands were examined in young (20–29 years) and older adults (65–83 years) in the acoustic free-field. A pointing task was applied to quantify accuracy, while acuity was inferred from minimum audible angle (MAA) thresholds measured with an adaptive 3-alternative forced-choice procedure. Accuracy decreased with laterality and age. From young to older adults, the accuracy declined by up to 23 % for the low-frequency noise band across all lateralities. The mean age effect was even more pronounced on MAA thresholds. Thus, age was a strong predictor for MAA thresholds for both LN and HN bands. There was no significant correlation between hearing status and localization performance. These results suggest that central auditory processing of space declines with age and is mainly driven by age-related changes in the processing of binaural cues (interaural time difference and interaural intensity difference) and not directly induced by peripheral hearing loss. We conclude that the representation of the location of sound sources becomes blurred with age as a consequence of declined temporal processing, the effect of which becomes particularly evident for MAA thresholds, where two closely adjoining sound sources have to be separated. While localization accuracy and MAA were not correlated in older adults, only a weak correlation was found in young adults. These results point to an employment of different processing strategies for localization accuracy and acuity.

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Abbreviations

3AFC	Three-interval, three-alternative forced-choice
ASW	Auditory source width
IC	Interaural coherence
ITD	Interaural time difference
ILD	Interaural intensity difference
MAA	Minimum audible angle
MEG	Magnetoencephalography
rm-ANOVA	Repeated measures analysis of variance
RMSE	Root-mean-square error
SE	Signed error

Introduction

In everyday life, we are surrounded by a multitude of sensory stimuli. Still, we are capable of perceiving and responding to distinct stimuli appropriately (e.g., to organize behavior and to make decisions), we can predict actions, and we can also store events and actions in memory. One important feature of sensory stimuli is "spaciousness," i.e., spatial coordinates, which are assigned to a specific sensory object. In the auditory system, localization of acoustic objects is achieved by processing interaural level and time differences (ILD and ITD), and by monaural processing of spectral information (review: Middlebrooks and Green 1991; Blauert 1997). There is a large literature on the specificities of acoustic space representation at the auditory brainstem level (review: Grothe et al. 2010) and the auditory cortex both in animals and humans (review: Recanzone et al. 2011). Auditory localization performance is psychophysically assessed through localization accuracy (Hartmann 1983; Moore et al. 2008) or localization acuity tasks (minimum audible angle [MAA]; Mills 1958). Localization accuracy is best for sound sources presented centrally and degrades toward the sides (Schmidt et al. 1953; Mills 1958; Blauert 1997). Systematic measurements of MAA as an indicator for localization acuity at different lateralities revealed localization acuity of 1° for sounds presented centrally and of 8° at the sides at 0.5 or 1.0 kHz (Mills 1958; Litovsky and Macmillan 1994; Grantham 1995). Many authors suggested a direct relationship between the two psychophysical measures, i.e., thresholds in MAA are limited by the accuracy to locate sound sources (e.g., Hartmann and Rakerd 1989; Recanzone et al. 1998).

Localization performance also depends on the interaural coherence (IC). IC reflects the similarity between the acoustic signals across both ears and is measured as the peak in the crosscorrelation function of the input signals from both ears (Faller and Merimaa 2004). For a perfect IC (IC = 1), localization performance is most accurate while it decreases for lower IC values, which, for instance, emerge in reverberant environments (Rakerd and Hartmann 2010). IC has been shown to correlate with the perception of auditory source width (ASW, i.e., the spatial extents of an auditory spatial image) (Blauert and Lindemann 1986; Wiggins and Seeber 2012; Whitmer et al. 2012), i.e., ASW decreases with increasing IC. Hence, the ability to detect changes in IC contributes to the localization of sound position and probably even more so to the discrimination of adjoining sound sources. To date, the central nervous processing of acoustic space information is a matter of ongoing research. Based on data from experimental animals and humans, a close relation between spatial acoustic encoding and precise temporal coding for ITD and ILD has been proposed (see Grothe et al. 2010). On the cortical level, the hypothesis was put forward that the encoding of sound source position is based on a hemifield code (also termed opponent-channel code; e.g., Harper and McAlpine 2004; Stecker et al. 2005; Chadderton et al. 2009; Magezi and Krumbholz 2010; Salminen et al. 2009, 2012), i.e., both cortical hemispheres comprise neuronal populations that are broadly tuned to either of both hemifields, and the location of the incoming sound is then inferred from the overall level between the leftward and rightward tuned channels (Magezi and Krumbholz 2010). Supporting evidence for this theory was provided by MEG and EEG studies (MEG: Salminen et al. 2009, 2012; EEG: Magezi and Krumbholz 2010).

About 40–45 % of people aged >65 years in industrialized countries, such as Germany (Zahnert 2011) and the USA (ASHA 2008; Nash et al. 2011), are affected by age-related hearing loss (presbycusis, Schuknecht 1955). In addition to the impact of peripheral hearing loss on auditory performance (Corso 1971; Gates et al. 1990; Cruickshanks et al. 1998), age-related modifications in the central auditory processing have also been reported to cause auditory impairments (CHABA 1988; Humes 1996). In particular, general temporal processing declines with age for monaural and binaural processing as reflected by increased thresholds for gap detection as well as in frequency, duration, and discrimination tasks on interaural time, phase, and level differences (Herman et al. 1977; Pichora-Fuller and Schneider 1991; Fitzgibbons and Gordon-Salant 1996; Frisina and Frisina 1997; He et al. 1998; Schneider and Hamstra 1999; Babkoff et al. 2002; Lister and Roberts 2005; Ross et al. 2007; Freigang et al. 2011) and declined neural processing of timing information (Alain et al. 2004; Ross et al. 2007; Tremblay et al. 2007; Ruggles et al. 2011, 2012; Shinn-Cunningham et al. 2013).

The effects of age and hearing loss on localization performance were addressed in a number of studies, which showed that the accuracy to localize sound sources declines with age, especially for spectrally restricted sounds (Häusler et al. 1983; Chandler and Grantham 1991; Cranford et al. 1993; Noble et al. 1994; Abel and Hay 1996; Rakerd et al. 1998; Abel et al. 2000; Eddins and Hall 2010; Dobreva et al. 2011; Neher et al. 2011). Abel et al. (2000) conducted a study with a large number of subjects ranging from 10 to 81 years and found an increased occurrence of front–back confusions with age, as well as a reduction in localization accuracy by 15 % in older adults, but the effect of hearing loss on localization performance did not yield clear results. Earlier, Abel and Hay (1996) had reported a negative effect of hearing loss on localization performance, while other studies claim that hearing loss alone is not a good predictor of localization performance (Noble et al. 1994; Neher et al. 2011). The MAA has been examined under a multitude of different experimental conditions (e.g., Mills 1958; Perrott 1984; Perrott et al. 1989; Hartmann and Rakerd 1989; Moore et al. 2008), but so far, only a limited number of studies focused on the MAA comparing young and older adults. These studies reported that MAA is affected negatively by hearing status and age, indicating a decline in binaural processing in older adults (Häusler et al. 1983; Chandler and Grantham 1991). In addition, Whitmer et al. (2012) found that older, hearing-impaired listeners exhibit broader perception of ASW, which correlates with the reduced sensitivity to detect changes in IC. They related this finding to the age-related increase in the neural temporal jitter in the central auditory system that affects the accurate processing of timing information, which is crucial to maintain acuity to represent sound source position. Still, there have been no studies in older adults showing a relationship between localization accuracy and spatial acuity.

The present study critically examines both measures by assessing localization accuracy and acuity in the acoustic free-field in young and older adults employing low- (0.375–0.75 kHz) and high-frequency (2.25–4.5 kHz) white noise bands. Our objective was to examine to what extent localization accuracy and MAA are affected by age. We hypothesized that age differentially affects the respective performances: on the one hand, older adults should still be able to precisely localize single isolated sound sources, because the positional information might find its central nervous representation in an adequate, though somewhat blurred neuronal code. The MAA, on the other hand, will more strongly be affected by age. Due to the blurred neuronal representation, larger spatial separations are required to identify spatially separated sound positions. If this holds true, then there should only be a weak correlation between localization accuracy and MAA, because in the two measures the performance is most likely based on processing mechanisms, which share only minor features (Moore et al. 2008). Further, a particular effect of noise band (LN or HN) will point to a specific change in the processing of ITD cue and/or ILD cue.

Materials and methods

Subjects

Sixty-four older adults (30 women; 68.1 years ±5.5; age range 65–83 years) and twenty-two young adults (12 women, 24.1 years ±2.3; age range 20–29 years) participated in this study. They signed an informed consent and received a compensation for expenses. The study was approved by the ethics committee of the University of Leipzig in agreement with the guidelines of the revised Declaration of Helsinki. All subjects were right-handed (Edinburgh Handedness Inventory, Oldfield 1971). Older subjects were screened for cognitive deficits with the Mini-Mental State Examination (MMSE; Folstein et al. 1975). All subjects scored 27–30 points in the MMSE identifying them as non-conspicuous, i.e., the older participants had normal cognitive abilities. Some older adults showed age-related increased hearing thresholds, which were corrected for during testing by adjusting stimulus levels. Eleven older subjects had to be excluded from the study, because their hearing thresholds exceeded 50 dB HL for the acoustic stimuli used in the experiments (low frequency: 0.375–0.750 kHz and high frequency: 2.25–4.50 kHz). The performance of the remaining 53 older adults was included in the analysis.

Experimental setup

Audiometric testing was conducted in an anechoic, sound-attenuated test booth (Industrial Acoustics Company, IAC Type 403 A, Niederkrüchten, Germany). Pure-tone thresholds were examined via headphones (Beyerdynamics, DT 770 Pro). Sounds were generated by the real-time processor RP2.1 (Tucker Davis Technologies (TDT), System III) and transmitted to headphones by means of a headphone power amplifier (TDT, HB7). Stimulus generation and hearing threshold acquisition were controlled by custom-written MATLAB (version 6.3, The MathWorks Inc, Natick, USA) scripts (Biedermann et al. 2008). Stimuli were generated with a sampling rate of 25 kHz.

The localization accuracy and acuity experiments were conducted in an anechoic, sound-attenuated free-field laboratory (45 m^2, IAC, Fig. 1). Forty-seven broadband speakers (Visaton, FRS8 4Ohm, Haan, Germany) were mounted in an azimuthal, semicircular array at ear level. A comfortable, fixed chair was positioned in the middle of the semicircle at a constant distance of 2.35 m from the speakers, such that subjects were aligned straight ahead to the central speaker at 0°. The loudspeaker array covered an azimuthal plane from −98° to the left to +98° to the right. The dimensions of the speaker casings were 150 × 130 × 400 mm, and the angular distance between two speaker membranes was 4.3° as measured between the centers of the speaker membranes. In the experiments, a minimal distance between two sound sources of 2.1° was achieved by crossfading the signals of two neighboring speakers. That is, two speakers were simultaneously active, and the in-between speaker position was generated by varying the relative sound levels of each speaker. Speakers were calibrated individually (for details on the calibration procedure see Schmiedchen et al. 2012).

The speaker array was combined with an array of 188 white light emitting diodes (LED; 2.52 lux, 0.6° visual angle) mounted in azimuthal steps of 1° at eye level. The LEDs were controlled by 51 printed circuit boards (PCB), which were arranged on top of the loudspeakers. Each PCB was assembled with four infrared (IR) sensitive phototransistors for the registration of pointing directions. The phototransistors were arranged with the same angular distances as the LEDs, but extended beyond the speaker and LED array by 8° to both sides. In combination with the IR-sensitive phototransistors, the LED array was used to provide visual feedback of the angular position pointed to by the subjects. A customized infrared torch served as pointing device (IR-torch, Solarforce L2 with 3W NVG LED, Fulidat Electronics Limited, Kowloon, Hong Kong). The IR torch emits light with a wavelength of 850 nm and exceeds human sensitivity range. The subtended angle of the IR light beam covered a maximum of 8° at the level of the LEDs. The mean position of all activated IR-sensitive phototransistors was computed online, and the corresponding LED flashed up as a visual feedback for the participant.

The speakers and the LEDs were hidden behind acoustically transparent gauze, which did not affect visibility of the LEDs. Thus, subjects were unable to make use of landmarks during the localization and the discrimination task. An infrared camera was installed in the test chamber to monitor subjects' performance during the experimental sessions. Custom-written MATLAB (version R2007b) scripts were used to control stimulus presentation and data acquisition. Visual and acoustic signals were digitally generated at a sampling rate of 25 kHz using RPvdsEx (Real-Time processor visual design studio and TDT) and delivered to two multichannel signal processors (Multi I/O RX8 and TDT System3).

Acoustic Stimuli

Audiometric testing Pure tones at 0.125, 0.25, 0.5, 1.0, 2.0, 4.0, and 8.0 kHz were presented with durations of 250 ms, including 10 ms $\cos^2$ ramps.

Free-field testing Stimuli were narrow band Gaussian noise bursts centered at 0.5 Hz (0.375–0.75 kHz, low noise [LN]) and 3.0 kHz (2.25–4.5 kHz, high noise [HN]) with a duration of 500 ms, including 10 ms $\cos^2$ on and off ramps. Noise bursts were generated afresh for every trial. The two noise signals were chosen because sound localization is based on two distinct neuronal processing mechanisms for ITDs and ILDs. The binaural integration of low-frequency noise bands is mainly based on the processing of ITDs, whereas the binaural integration of acoustic signals >2 kHz is mostly based on the processing of ILDs (Middlebrooks and Green 1991). Because the age-related sensorineural hearing loss more strongly affects high frequencies (Schmiedt 2010), the HN noise band was restricted to 4.5 kHz to have comparable experimental conditions in young and older subjects in terms of sound level perception.

Procedure

Audiometric testing

To quantify the subjects' frequency-specific air conduction thresholds, pure-tone hearing thresholds were obtained for each ear separately by using a *heard/not-heard* detection paradigm. Subjects were instructed to press the left button on a response box, when a sound was heard and the right button, when they did not hear the sound. For each detected sound, the intensity was initially decreased by 10 dB, while sound intensity was increased with the same step size for each sound that was not detected. A change from a success to a false response and vice versa was marked a turn point. After four turn points were obtained, the step size was decreased to 5 dB steps. A run was completed after eight turn points were measured, and the hearing threshold was calculated as the mean of the last four turn points. Hearing thresholds were obtained for seven different frequencies (see "Acoustic stimuli" section).

Free-field testing

Prior to measuring localization accuracy and acuity in free-field, hearing thresholds for the low- and high-frequency noise bands were determined to adjust the presentation intensity of the acoustic stimuli in the subsequent experiments to 40 dB SL (sensation level), i.e., at a constant intensity above the individual threshold level. For LN and HN stimuli, the signals were presented from the central loudspeaker and individual detection thresholds were determined by employing a *yes/no* [*heard/not heard*] paradigm. Initially, the noise stimuli were presented at 63 dB SPL. Subjects were instructed to press the left button on the response box for every sound that was heard and to press the right button when they did not hear the sound. Sound intensity was either decreased (heard-response) or increased (did not hear-response) by 2.5 dB. Subjects were prompted to iteratively adjust the sound intensity to a level at which the sound was just barely perceived and then to press the middle button on the response box, which ultimately terminated the run. To ensure that subjects actually reached the sound level which they only barely perceived, at least three turn points were collected per run and the last turn point from an inaudible to an audible sound level was taken as hearing threshold for the respective noise stimulus.

Absolute localization

Low-frequency noise and high-frequency noise were presented at eight different spatial positions when testing for accuracy of sound source localization: ±9° (central), ±30° (para-central), ±64° and ±90° (both lateral) in azimuth (− and + indicating left and right, respectively; Fig. 1a). Sound level was roved by ±3 dB (step size 1 dB) between successive trials to minimize possible effects of minute speaker-specific characteristics as an identification cue and to prevent adaptation due to repeated presentation of the respective sound source positions. Each position was tested three times, adding up to 24 stimulus presentations per noise band and 48 overall presentations. LN and HN stimuli were presented in separate blocks, and the order of spatial positions was randomized within a block. Subjects were instructed to align their posture by facing straight ahead and looking at a fixation point during stimulus presentation. A camera transmission system was used to control

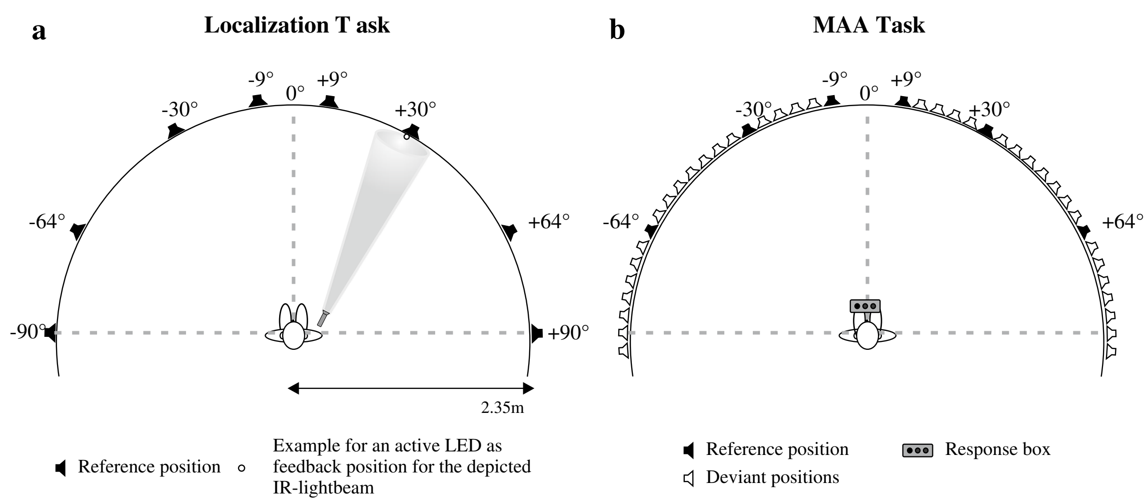


Fig. 1 Free-field setup with 47 loudspeakers arranged in a semicircular array, −98° left to +98° right. The distance between two loudspeakers was 4.3°. Acoustic targets of defined laterality were generated by activation of single speakers or interpolation of two adjacent speaker inputs; angular resolution was 2.1°. Subjects were seated in the center of the semicircle with the head oriented straight and looking at a fixation cross at 0° (*vertical dashed line*). The interaural axis extended to the speakers located at −90° and +90°, respectively (horizontal dashed line). a Localization accuracy: acoustic reference positions in the localization tests were ±9°; ±30°, ±64°, and ±90° (*black speaker symbols*). In the localization task, subjects indicated the direction of perceived sound source by pointing with an infrared torch. Exact pointing direction was calculated online with an accuracy of 1°. This was done by integrating the positions over the activated transistors. Subjects received feedback by a flashing LED that corresponded to the pointed position. **b** Localization acuity (minimal audible angle, MAA): Reference positions were ±9°; ±30°, and ±64° (*black speaker symbols*). Combining the 3AFC testing and an adaptive sampling procedure, MAA was quantified for the different reference positions. Subjects had to indicate by the means of button press on a response box which signal of a triplet originated from a different location with respect to two reference signals. Testing started with a maximum disparity of 30° (initial deviant position), and signal separation was stepwise reduced (2.1°) upon correct deviant identification (*open speaker symbols*)

for the position of the head. Subjects were asked to point immediately after the end of the acoustic stimulus with the IR torch to the perceived direction of the sound source. This procedure corresponds to the "remembered position of a sound source" condition in the study by Lewald et al. (2000, experiment *2A*), that is, subjects were allowed to move their head while pointing to the perceived position. An immediate visual feedback on the pointed position was given to the subject by lightening up the LED at the respective position (see above "Experimental setup" section). To confirm the designated position of the sound source, subjects had to release the button on the IR torch, whereby the corresponding LED flashed three times and signalized successful registration. The acquisition system for indicated directions (see "Experimental setup" section) quantified for each trial the difference between the sound source and the pointed direction. Subjects were allowed to practice before the data acquisition to become familiar with the experimental procedure.

Minimum audible angle

Minimum audible angle (MAA) thresholds were quantified for LN and HN signals. The MAA was examined by applying a *3-interval, 3-alternative forced-choice* paradigm (3AFC) and using the *1up/1down* staircase procedure aiming at 50 % correct response level (Green and Swets 1989). The interstimulus interval (ISI) was set to 750 ms. In the 3AFC testing, subjects were asked to differentiate between three signals, i.e., two reference signals coming from the same angular position and one target signal differing in the angular position, with the order of reference and target signals randomly altered within the stimulus triplets. Subjects were asked to identify the target signal; responses were given by pressing appropriate buttons on a response box. Reference positions were at ±9°, ±30°, and ±64° (Fig. 1b). At the start of each run, the deviant sound was presented with a spatial disparity of 30° toward more lateral positions. Spatial disparity between reference and target sound was decreased after each correct response and increased in case of a false response (step size = 2.1°). Any change from a correct to a false response or vice versa was marked as a turn point. A single test run was terminated after five turn points were obtained, and the thresholds were calculated as the mean of the last four turn points. As in the localization task, subjects were instructed to face straight ahead and to stay in that position during all stimulus presentations.

Data analysis

Hearing thresholds from the headphone audiogram and free-field measurement were calculated as mean values with standard deviation (±SD) and analyzed with a repeated-measures ANOVA (rm-ANOVA) including the factors age (young and old) and frequency (for headphone: 0.125, 0.25, 0.5, 1.0, 2.0, 4.0, 8.0, for free-field: LN, HN). In the rm-ANOVA for the headphone audiogram, we additionally included the factor ear (left, right).

Localization accuracy was statistically analyzed in terms of the absolute pointing error and the direction of error (undershoot: toward the midline; overshoot: toward the sides). To evaluate these two different aspects, root-mean-square errors (*RMSE*, Eq. 1) and signed errors (*SE,* Eq. 2) were calculated (Hartmann and Rakerd 1989).

$$\mathrm{RMSE} = \sqrt{\left(\sum_{i=1}^{n} (S_i - R_i)^2 \middle/ n\right)}. \tag{1}$$

$$\mathrm{SE} = \left(\sum_{i=1}^{n} |S_i| - |R_i| \middle/ n\right) \tag{2}$$

with S reference position, R response position, and n the number of trials. To validate whether localization accuracy SE at each position differed from zero, we used a one-tailed, one-sample t test against zero. For the comparisons within and between groups for RMSE values and MAA thresholds, we inferred statistical causality by computing rm-ANOVAs. We included the within-subject factors position (accuracy: ±9°; ±30°; ±64°; ±90°; MAA: ±9°; ±30°; ±64°) and noise band (LN and HN) as well as the between-subject factor age (young and old). Greenhouse-Geisser corrections were applied, where the GG Epsilon (ε) is indicated and multiple t tests were Bonferroni corrected. Correlation analysis was computed as Pearson correlation including Pearson's r and the two-tailed t test significance level p.

Kendall τ was used to calculate correlation of age and localization accuracy as well as age and MAA. The test computes a rank correlation, which can be used to test if two groups are statistically dependent.

Results

To investigate the effect of age on localization accuracy and spatial acuity (MAA), young and older adults were examined under free-field conditions. To differentiate between ITD and ILD processing, low- and high-frequency noise bands were used (0.375–0.75 kHz [LN] and 2.25–4.5 kHz [HN]). The statistical analysis (rm-ANOVA, within-subject factor hemifield) did not reveal a significant difference between the data from both acoustic hemifields. Therefore, data from both hemifields were collapsed for further analyses.

Hearing thresholds

We measured hearing thresholds to pure tones under headphone conditions and to noise bands in the acoustic free-field (see "Procedure" section; Fig. 2). The pure-tone audiogram (headphones) revealed a clear distinction between young and older adults with hearing thresholds being elevated in the older cohort. Hearing sensitivity was best for frequencies in the range from 0.5 to 4.0 kHz and declined toward higher and lower frequencies at both ears in each age group. Young adults had mean hearing thresholds (collapsed across ears) of 6 (SD: ±7), 2 (±6), 5 (±8), and 8 (±7) dB SPL for frequencies at 0.5, 1.0, 2.0, and 4.0 kHz, respectively. At the lowest test frequencies (0.125 and 0.25 kHz), 29 (±4) and 17 (±6) dB SPL were required, while at 8 kHz mean hearing thresholds reached 22 (±6) dB SPL. In older adults, mean hearing thresholds at 0.5, 1.0, 2.0, and 4 kHz were measured at 20 (±13), 16 (±14), 23 (±16), and 35 (±18) dB SPL. At 0.125 and 0.25 kHz, intensities of 43 (±12) and 30 (±13) dB SPL were required

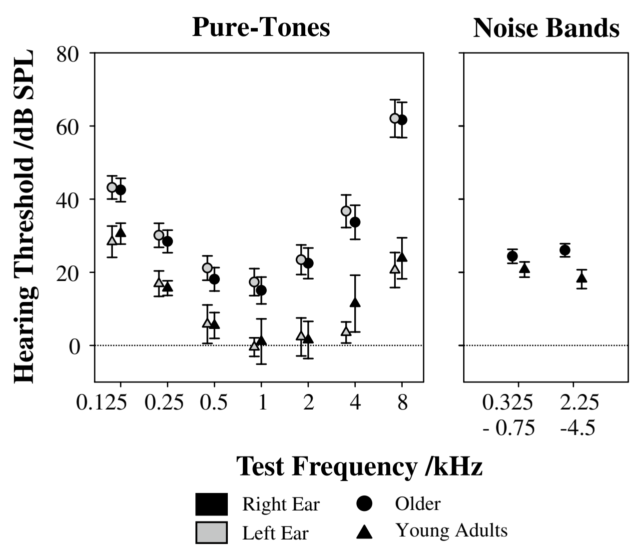


Fig. 2 Mean hearing thresholds (95 % confidence intervals [CI]) in young (*triangles*) and older adults (*circles*). The *left panel* shows hearing thresholds measured for pure tones by the means of headphones in the *left* (*gray*) and *right* (*black*) ear. Hearing sensitivity was relatively better for frequencies between 0.5 and 4.0 kHz. Older adults had significantly elevated hearing thresholds. The right panel shows mean hearing thresholds (95 % CI) for low-frequency (LN, 0.375–0.75 kHz) and high-frequency (HN, 2.25–4.5 kHz) noise bands measured in free-field. Hearing thresholds did not differ between both noise bands, though older adults had significantly elevated hearing thresholds

in elderly listeners. The highest hearing thresholds in older subjects were measured at the highest test frequency (8 kHz) with 62 (±19) dB SPL. Young and older adults did not reveal systematic differences between the ears. The statistical testing (rm-ANOVA) revealed significant main effects of frequency ($F(6,68) = 62.043$, $p < 0.001$, $\eta^2 = 0.884$) and age ($F(2,72) = 72$, $p < 0.001$, $\eta^2 = 0.421$). Also, an interaction between frequency and age was found ($F(6,68) = 8.455$, $p < 0.001$, $\eta^2 = 0.117$), i.e., hearing thresholds increased more strongly toward higher frequencies in the older group.

Under free-field conditions, mean hearing thresholds for the LN stimuli were 21 (±2) dB SPL in young adults and 24 (±7) dB SPL in older adults. For HN, young adults yielded hearing thresholds at 18 (±3) dB SPL, while older adults required 26 (±6) dB SPL. Hearing thresholds were elevated in the older age group ($F(2,72) = 6.849$, $p = 0.012$, $\eta^2 = 0.114$). However, no main effect of noise band was found ($F(2,72) = 0.314$, $p = 0.578$, $\eta^2 = 0.006$), indicating that older and young subjects had no preference for any of the two noise bands.

Localization accuracy

Localization accuracy was calculated as the root-mean-square error (RMSE) to quantify the error magnitude regardless of a potential under- or overshoot of the target position (the quantity of directional bias). Figure 3a shows RMSE values in young and older adults for LN (left panel) and HN signals (right panel). Most prominently, accuracy decreased in both age groups with laterality of the reference position, and this decrease was more pronounced in older adults. Mean RMSE values and standard errors are compared in Table 1 for all reference positions and both noise bands in young and older adults. The statistical analysis (rm-ANOVA including the factors frequency, position, and age) revealed a weakly significant effect of the between-subject factor age ($F(1,73) = 4.09$, $p = 0.048$, $\eta^2 = 0.066$) and a strong effect of the factor position ($F(3,71) = 102.278$, $p < 0.001$, $\eta^2 = 0.638$). The noise signals had a weak statistical effect on the RMSE values ($F(1,73) = 4.341$, $p = 0.042$, $\eta^2 = 0.070$) due to the fact that performance tended to be more accurate for LN. Also, an interaction of age and position was found ($F(2,72) = 3.93$, $p = 0.021$, $\eta^2 = 0.705$, $\varepsilon = 0.683$), which is explained by the fact that localization is less accurate for lateral reference positions in older adults.

Abel et al. (2000) showed that localization accuracy declined by 15 % with age. To assess our data with a similar measure, we calculated the mean for each age group by collapsing data across reference positions and both noise signals (Fig. 3b). We found a statistical significant decline of 21 % for localization accuracy in the older adults (two-tailed t test; $t = 2.4241$, $df = 71$, $p = 0.0179$). A pairwise comparison revealed that this drop in performance was driven by the decline in performance for LN, where performance declines by 23 % in older adults (two-tailed t test; $t = 2.1462$, $df = 71$, $p = 0.0353$).

Directional biases in localization accuracy were analyzed by calculating signed errors (SE) (Fig. 3c). In this analysis, positive values correspond to an undershoot, whereas negative values indicate an overshoot of the targets. That is, in relation to the target, the pointed directions were shifted to either more central or more lateral positions. SEs were found to be either at around zero, or values were positive indicating mostly underestimation on the reference positions. In general, signed errors increased as a function of stimulus laterality, and both young and older adults showed larger overall signed errors at 64° and 90° for both LN and HN stimuli (Fig. 3c). The statistical analysis (rm-ANOVA) including the factors frequency, position, and age showed a main effect of the within-subject factor position ($F(3,71) = 92.214$, $p < 0.001$, $\eta^2 = 0.622$) and the between-subject factor age ($F(1,73) = 4.101$, $p = 0.048$, $\eta^2 = 0.068$), though the effect of age barely reached significance levels. The factor frequency did not contribute to the observations ($F(1,73) = 0.781$, $p = 0.381$, $\eta^2 = 0.014$).

Additionally, a one-tailed, one-sample t test against zero was used to infer if the undershoot was significant (Table 2). For LN, undershoot in young and older adults was significant at 90° and 64° (Table 2; also indicated by asterisks in Fig. 3c). For HN, undershoot in young adults was significant at 90° and 64° and in older adults at 90°, 64°, and 30° (Table 2; also indicated by asterisks in Fig. 3c).

Taken together, a significant undershoot was observed in both age groups, albeit dependent on the noise signal and sound source position. The undershoot increased with the laterality of the sound source, and this effect was strongest for LN signals.

Minimum audible angle

Minimum audible angle thresholds were measured at six different horizontal positions with the same subjects in both age groups (Fig. 4). The rm-ANOVA did not reveal a significant effect of the within-subject factor hemifield. Thus, the data from both hemifields were collapsed for further data analyses. MAA thresholds systematically varied with the reference position, with the smallest values found at the central position (9°). Young adults performed significantly better than older adults. The repeated-measures ANOVA revealed a main effect of the within-subject factor position ($F(2,72) = 40.752$, $p < 0.001$, $\eta^2 = 0.375$) and the between-subject factor age ($F(1,73) = 70.877$, $p < 0.001$, $\eta^2 = 0.510$). Also, the factors position and age interacted

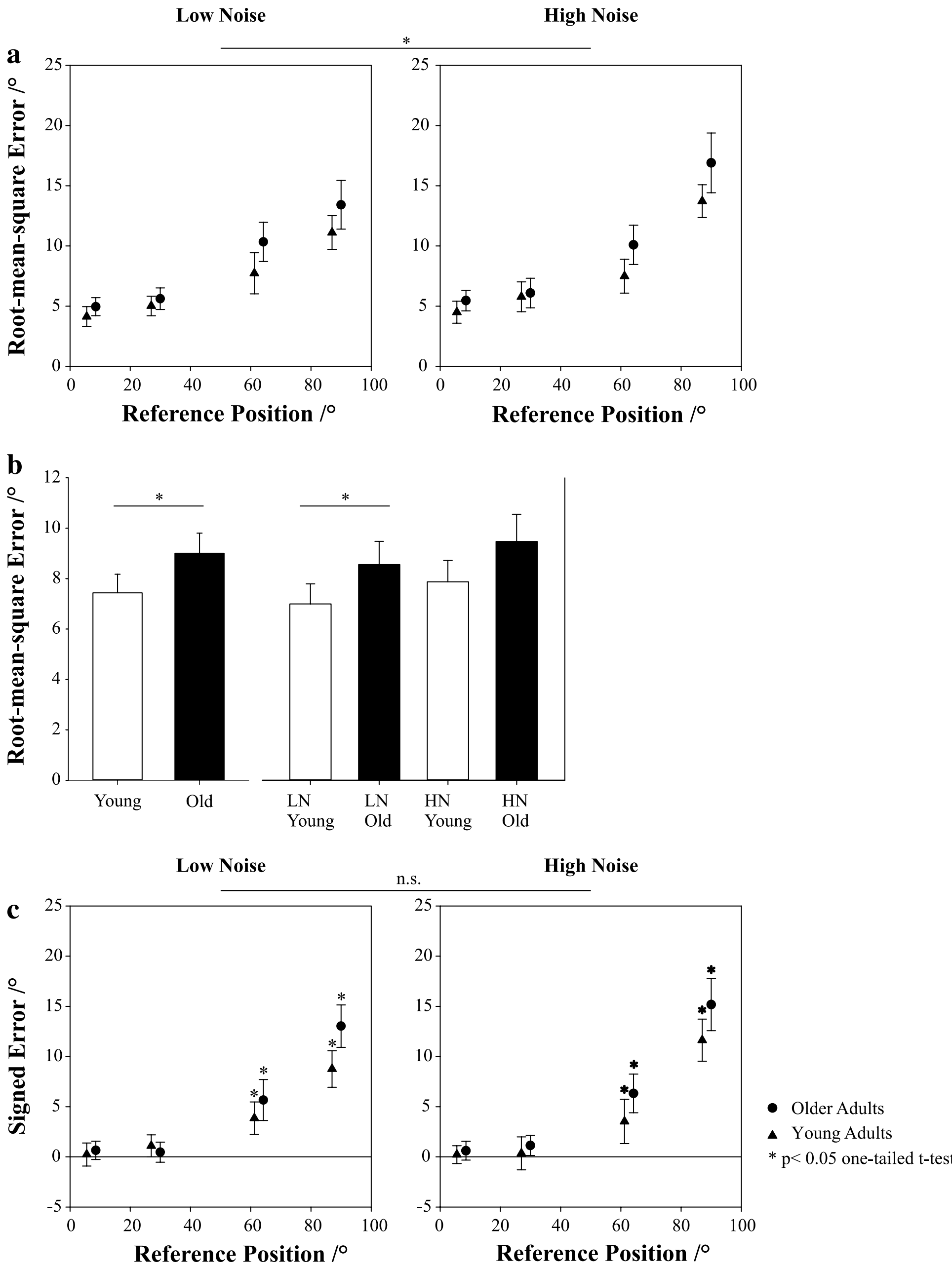


Fig. 3 Localization accuracy in young and older adults. **a** Root-mean-square errors (RMSE) for LN (*left*) and HN (*right*) at four reference positions with 95 % CI (*vertical bars*). Young adults—*triangles*, older adults—*circles*. Note that RMSE increased as a function of stimulus laterality, and accuracy was improved for LN. Overall, older adults performed significantly worse than young adults. *Asterisks* indicate significant effects, with significance levels: $*p = 0.05$ (rm-ANOVA) and *n.s.* not significant. **b** RMSE (95 % CI) collapsed across reference positions and noise bands in young (*white bars*) and older adults (*black bars*) [*left*], as well as data collapsed across reference position separately for the different noise bands (LN, HN) and each age group (Young, Old) [*right*]. Accuracy decreased significantly with age by 21 %, mainly due to a strong decline for LN signals (decrease by 23 %). *Asterisks* indicate significant effects, with significance levels: $*p = 0.05$ (two-tailed t test). **c** Mean signed error (SE) of localization performance with 95 % CI. Positive values correspond to a directional bias toward midline (*undershoot*), and negative values to a directional bias toward lateral positions (*overshoot*). *Asterisks* indicate values significantly different from zero with significance level $*p = 0.05$ (one-tailed one-sample t test); *n.s.* not significant (rm-ANOVA). Subjects tended to point toward midline at lateral positions (64° and 90°), and SEs were increased with laterality of the stimulus

with each other ($F(2,72) = 3.502$, $p = 0.036$, $\eta^2 = 0.049$, $\varepsilon = 0.928$), suggesting that the increase in MAA threshold with laterality was more pronounced in older adults. There was no main effect or interaction of the factor noise indicating that performance was similar for LN and HN noise bands.

Table 1 Mean and standard deviations of root-mean-square errors in young and older adults for each noise signal (LN and HN) and reference position (9°; 30°; 64°, and 90°)

Noise	Position	Young adults	Old adults
Low noise	**9°**	4.1 (±1.9)	4.3 (±2.1) (†)
	30°	5.0 (±1.8)	5.1 (±3.1) (†)
	64°	7.7 (±3.8)	10.0 (±5.7)
	90°	11.1 (±3.2)	13.7 (±6.8)
High noise	**9°**	4.5 (±2.1)	5.1 (±2.7) (†)
	30°	5.8 (±2.8)	4.9 (±4.4) (†)
	64°	7.5 (±3.2)	9.9 (±5.5)
	90°	13.7 (±3.1)	17.8 (±8.5)

The results for all positions differed significantly from each other (post hoc *t* test with $p < 0.05$, Bonferroni corrected) except for corresponding value pairs marked with (†)

Table 2 One-tailed one-sample *t* test statistics ($df = 74$) for signed errors in young and older adults at the respective reference positions

Condition	Age group	9°	30°	64°	90°
Low noise	Young				
	t	0.4257	2.337	4.981	10.023
	p	0.6747	0.0294	<0.05	<0.05
	Old				
	t	1.7472	0.8974	5.501	12.359
	p	0.0866	0.3737	<0.05	<0.05
High noise	Young				
	t	−0.4456	−0.2757	3.6273	11.521
	p	0.6604	0.7855	<0.01	<0.05
	Old				
	t	0.7490	0.7648	6.9088	11.8948
	p	0.4572	0.4479	<0.05	<0.05

Significant *p* values indicate SEs that are significantly different from zero

Interaction of localization performance and hearing status

Previous studies showed that hearing status in older adults may predict a decrease in localization performance, which is more strongly pronounced in hearing-impaired individuals compared to normal-hearing subjects (Noble et al. 1994; Abel and Hay 1996). In the present study, the pure tone audiograms of older adults showed different degrees of age-related sensorineural hearing loss, especially at higher frequencies (see "Hearing thresholds" section, Fig. 2). Also, hearing thresholds for noise stimuli measured in the free-field differed significantly between young and older adults, but the differences in magnitude were small (5–8 dB; see "Hearing thresholds" section, Fig. 2). To evaluate the influence of hearing status on the performance in the localization tasks, we separately analyzed correlations (Pearson's *r*) between localization accuracy (RMSE) and MAA thresholds with the hearing thresholds for both noise bands. For this, we collapsed data across the different reference positions for each noise signal in the older adults and transformed the hearing thresholds from the log dB scale into a linear scale. Pearson's *r* correlation yielded neither a significant correlation of hearing status with localization accuracy (RMSE LN: $r = 0.1650$, $p = 0.2733$, HN: $r = -0.0291$, $p = 0.8476$) nor with MAA thresholds (MAA LN: $r = 0.2832$, $p = 0.0565$; HN: $r = 0.1918$, $p = 0.2017$). Further, we analyzed whether localization performance might be predicted by pure-tone hearing thresholds. Pearson's r correlation analysis was performed with the hearing thresholds for 500 Hz and 4,000 Hz and the performance in the corresponding noise band. Also, this analysis did not reveal significant results (RMSE LN: $r = -0.0377$, $p = 0.7949$; MAA LN: $r = -0.0635$, $p = 0.6613$; RMSE HN: $r = -0.2274$,

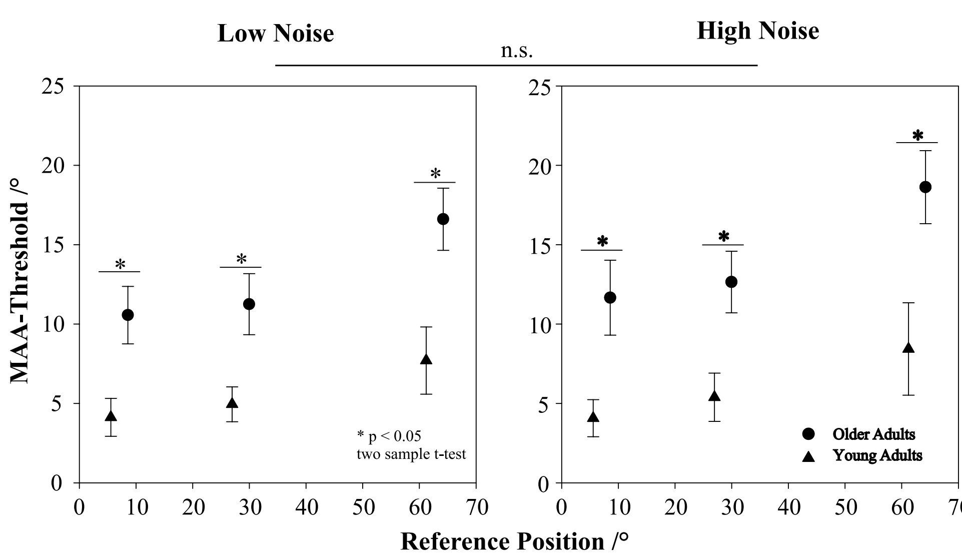
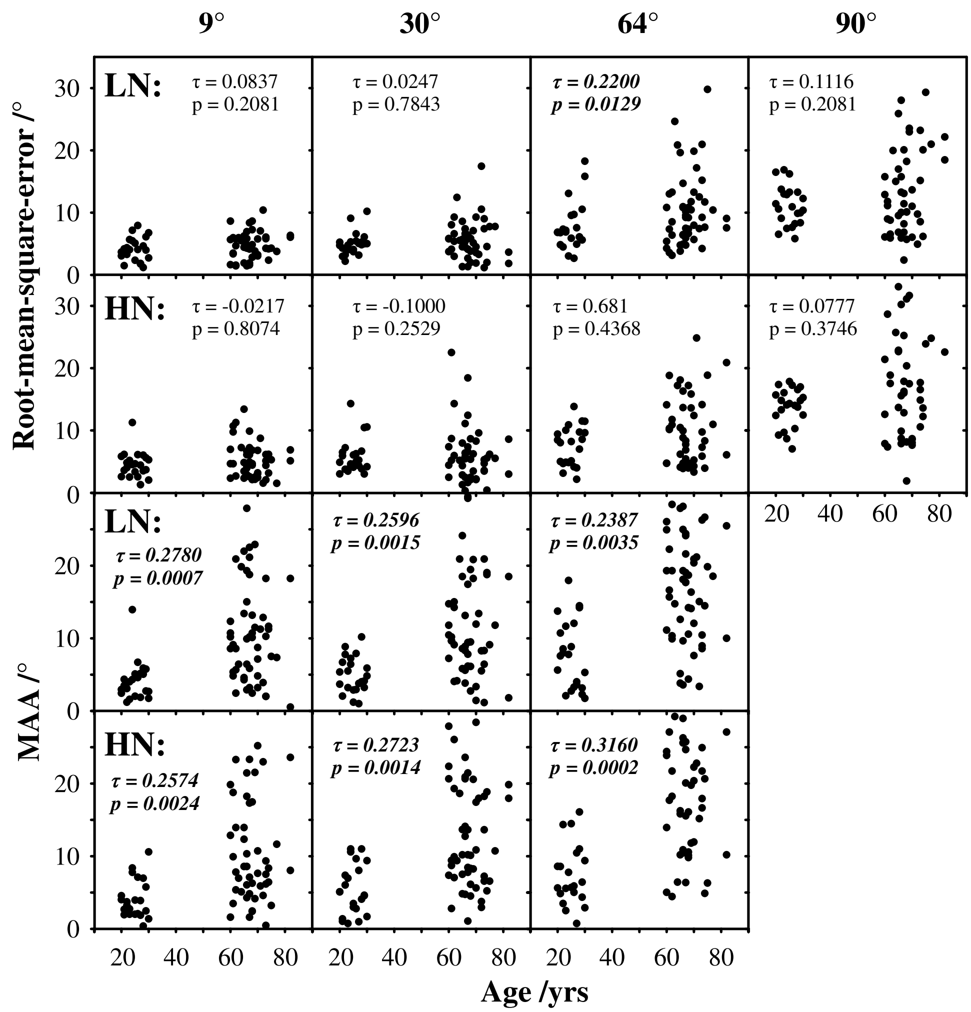


Fig. 4 Mean MAA thresholds in young and older adults for LN (*left*) and HN (*right*) signals. Triangles denote data of young adults and circles data of older adults. *Bars* correspond to 95 % CI. MAA thresholds increased with laterality of the reference stimulus. Older adults performed significantly worse than young adults. *Asterisks* indicate significant effects with $p < 0.001$ (two-sample *t* test, Bonferroni correction for multiple comparisons). Noise band did not have an effect on MAA thresholds (rm-ANOVA; *n.s.* not significant)

Fig. 5 Correlation (Kendall τ) between age and RMSE (LN: first row, HN: second row) and MAA (LN: third row, HN: fourth row) across both age groups. RMSE was only predicted by age for LN at 64°. However, MAA was strongly predicted by age for every reference position, i.e., MAA thresholds were highly increased with age. Significant results are *highlighted in bold and italic letters*



$p = 0.1122$, MAA HN: $r = 0.2417$, $p = 0.0908$; Bonferroni-corrected p value 0.00625).

Interaction of localization accuracy, acuity and age

In separate studies, it was reported that age influences the performance in localization accuracy (Abel et al. 2000) and acuity tasks (MAA, Häusler et al. 1983; Chandler and Grantham 1991). In the present study, we applied correlation analysis of localization accuracy and age, as well as of MAA thresholds and age for the two noise bands (Kendall τ; Fig. 5). Localization accuracy was (with one exception) not predicted by age for either of the two noise bands [exception LN signals at 64° ($\tau = 0.2200$, $p = 0.0129$)]. MAA thresholds, on the other hand, were highly dependent on age for both noise bands and all reference position (LN: 9°: $\tau = 0.2780$ $p = 0.0007$; 30°: $\tau = 0.2596$, $p = 0.0015$; 64°: $\tau = 0.2387$, $p = 0.0035$, HN: 9°: $\tau = 0.2574$, $p = 0.0024$; 30°: $\tau = 0.2723$, $p = 0.0014$; 64°: $\tau = 0.3160$, $p = 0.0002$; Fig. 5; Bonferroni-corrected p value 0.0036). Although the study was not designed to provide data on age-related changes in auditory performance on a continuous age-scale, the present data indicate more differentiated relationships: Age seems not to have a major effect on locating single sound sources but strongly affects spatial auditory discrimination performance as indicated by the MAA.

Interaction of localization accuracy and acuity

Finally, the relationship between localization accuracy (RMSE) and acuity (MAA thresholds) was analyzed to infer whether performance in one task predicts the outcome in the other task. In a study by Recanzone et al. (1998), a weak but significant interaction of acuity and accuracy was reported for younger adults. Here, we performed the respective analyses for both the young and older age group by calculating Pearson's r correlation coefficient separately for each reference position for both the LN and HN signals (Fig. 6). For the two signals, significant positive correlations between localization accuracy and acuity were

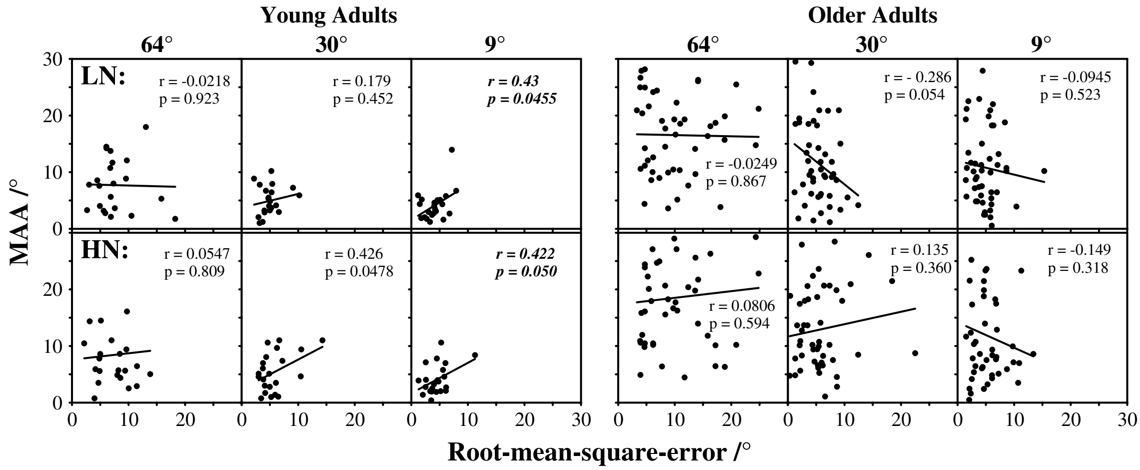


Fig. 6 MAA thresholds and RMSE in young (*left panels*) and older adults (*right panels*) at LN and HN noise (*top* and *bottom row*, respectively) and each reference position. For both noise bands and in young adults, errors in localization accuracy were significantly correlated with MAA thresholds at the central reference position (9°). Significant results are *highlighted in bold and italic letters*

only found for the central position in young adults (LN: $r = 0.43$, $p = 0.0455$; HN: $r = 0.422$, $p = 0.05$).

Discussion

The present study investigated how auditory localization accuracy and acuity are affected by age. Localization accuracy was measured in young and older adults using a pointing task. Acuity was assessed from MAA thresholds. All experiments were conducted in the acoustic free-field. Low- and high-frequency noise bands (LN and HN) were used as stimuli to address localization performance based on ITD and ILD cues. Additionally, to assess the impact of hearing loss, hearing thresholds were measured for pure-tones under headphone conditions and for noise bursts in the acoustic free-field.

The four main findings of the current study were that (1) localization accuracy and acuity declined as a function of age, but this decline was mostly independent of hearing sensitivity. (2) The age effect was most pronounced for the MAA task. (3) The decline in performance in older adults points toward a less efficient processing of binaural cues (ITD and ILD), which is presumably linked to declined temporal processing. (4) Localization accuracy and acuity were weakly correlated for the central condition in young adults. In older adults, no such correlations were observed, indicating that different processing strategies were utilized for localization acuity and accuracy. The results indicate a general deficit in central auditory processing and more specifically in auditory space perception. The results will be interpreted in light of altered processing of auditory space in connection to the age-related decline in temporal processing.

Localization accuracy

Young and older adults

In general, the data for both age groups showed less accurate localization for reference positions at the sides and for HN signals. The result that accuracy declines with laterality of the sound source has been confirmed by previous studies (for overview see Blauert 1997; Schmidt et al. 1953). The fact that the localization error was smaller for LN than for HN might be due to the dominant weighting of ITD-based sound source localization in anechoic rooms (Strut 1907; McFadden and Pasanen 1976; Wightman and Kistler 1992; Macpherson and Middlebrooks 2002). In agreement with this notion, both age groups showed significantly lower RMSE for LN than for HN stimuli. One has also to take into account that the perception of the ASW contributes to larger localization errors for ILD cues. It has been reported that the ASW increases drastically as ILDs exceed 8–10 dB (cf. Blauert 1997), which means that the spatial location is perceived as broad image. In our experiments, the most lateral reference position at 90° corresponds to a completely lateralized sound source with an ILD of 10–20 dB under headphones (Blauert 1997). Because the ASW is perceived as a broad image at these ILDs, localization accuracy in the free-field will also be less precise at these positions.

Further, we found a consistent underestimation of the laterality of the target position (measured as *Signed Error*) that increased with target laterality. Lewald et al. (2000) systematically assessed factors driving under- and overshoot of auditory targets in the free-field by varying pointing procedures and postures of the subjects. Those data provided evidence that biased localization errors are consequences of neural mechanisms for coordinate transformations, which enable the mapping of the head-centered auditory coordinates onto a trunk-centered reference frame. That is, depending on where the head is oriented in relation to the body, the occurring biases in localization performance indicate mechanisms that compensate for the disparity in orientation. Our results are in line with the described undershoot of the target position for "remembered" auditory objects in the study by Lewald and coworkers. Presently, subjects were instructed to remain in a fixed straight head position during stimulus presentation, but they were allowed to look in the direction of the perceived sound source position while pointing to it.

Older adults

Older adults performed less accurately in the localization task than young listeners. Furthermore, measurements of pure tone hearing thresholds under headphones revealed elevated hearing thresholds in elderly listeners. The evaluation of the impact of hearing loss on performance revealed that localization accuracy for both the low- and the high-frequency noise stimuli did not correlate with hearing thresholds. While it cannot be excluded that the physiological changes underlying age-related hearing loss are a confounding factor, the effects found for the localization performance are unlikely to be a mere consequence of hearing loss. This finding is in good agreement with the notion of previous studies (Noble et al. 1994; Abel et al. 2000; Dobreva et al. 2011; Neher et al. 2011). Noble et al. (1994) showed on the one hand that impaired localization performance in older adults was dependent on the specific type of hearing loss, but on the other hand hearing loss alone did not entirely explain the decline in localization performance. This led the authors to conclude that also altered central auditory processing affects the ability to localize sounds in space. Since hearing status did not predict localization performance in the present study, we conclude that the age-related decrease in localization performance is associated with a decline in the processing of binaural cues rather than with impaired peripheral processing of sound quality. We found an overall decrease in performance across the age groups of 21 % when noise bands were collapsed. Detailed analyses showed that the decline in performance was mainly driven by LN data. Abel et al. (2000) examined sound localization across young and older subjects aged from 20 to 80 years. Localization accuracy dropped by 15 % from the young to the older age group. The differences in the results between the present study and the one by Abel et al. (2000) might be related to differences in the experimental procedure. Abel and colleagues used an absolute identification task, in which subjects had to indicate the sound source position by choosing one of several discrete sound sources positions. In the present study, subjects were not informed about sound source positions and had to point to the position of each single sound source. Dobreva et al. (2011) systematically assessed the upper frequency limit of ITD utilization across age by presenting critical band-wide narrowband noise from 0.25 to 2.0 kHz in free-field. Interestingly, they found that elderly listeners showed pronounced localization errors for noise within 1.25–1.575 kHz. Summing up recent and previous findings of age-related effects on localization in free-field, it can be hypothesized that the degraded performance for ITD cues in older adults indicates an impairment in auditory temporal processing.

The effect of age on HN stimuli was not as pronounced as for LN stimuli, but the results still indicate that also the processing of ILD cues is influenced by age. Neural processing of ILD cues takes place in the auditory brainstem. Specifically, the lateral superior olive of the superior olivary complex receives excitatory inputs from the ipsilateral ear and inhibitory contralateral inputs from the contralateral anteroventral cochlear nucleus via the medial nucleus of the trapezoid body. For an efficient processing of ILDs, neural information from each CN must arrive in one temporal register in the respective LSO (review Tollin 2003). It has been shown that aging is accompanied by reduced temporal processing (Eckert 2011) and inhibition (Frisina and Walton 2006; Caspary et al. 2005, 2008), which might lead to impaired ILD processing.

More direct evidence for the specific impact of age on auditory temporal processing was provided by headphone studies in which binaurally presented click trains were lateralized with varying ITDs or ILDs (Herman et al. 1977; Babkoff et al. 2002) and by studies on ITD thresholds (Kirikae 1969; Strouse et al. 1998). In the study by Babkoff et al. (2002), ITD- or ILD-lateralized click trains were mapped to discrete locations by young and older adults. Their results showed that older adults were not able to accurately lateralize click trains based on ITD cues, whereas the age effect was absent for ILD-lateralized click trains. Findings by Strouse et al. (1998) showed that ITD thresholds for click trains were elevated by the factor 2 in older adults. The results of previous studies and the present experiments indicate that the processing of ITDs and ILD in older adults is declined as a consequence of impaired central auditory temporal processing, but that ITD processing declines more strongly with age. This might be due to the fact that ITD processing mechanisms are affected by two factors: (1) the general slowing of neural transmission and (2) the reduced fidelity of encoding temporal fine structure (TFS). However, effective ILD processing does depend on the speed of neural transmission, but not on the neural encoding of TFS at high frequencies. This might explain the more pronounced decline in processing of ITD cues in older listeners compared to when ILD cues are being used.

The effect of age on localization acuity: MAA

Localization acuity was measured as MAA using a 3AFC procedure to meet the criticism by Hartmann and Rakerd (1989) on the interpretation of the MAA results reported earlier by Mills (1958). They argued that the 2AFC task in Mills' study reflects absolute identification performance rather than localization acuity. In young adults, the present measurements yielded MAA thresholds as small as 2°, which is close to thresholds obtained by 2AFC testing by Mills and similar to results (~2°) obtained by Litovsky and Macmillan (1994) and Grantham (1995). Mean MAA thresholds in the present study ranged from 2° to 5° for central positions and from 4° to 11° for lateral positions. Here, we used narrow band low- and high-frequency filtered noise which provided rich spectral cues to allow optimal performance in both noise bands, so the measurements provide a reliable quantification of spatial resolution for adjacent sound sources.

Age strongly affected MAA thresholds for LN and HN signals, while individual hearing thresholds did not predict MAA performance. Häusler et al. (1983) measured MAA thresholds and speech perception in a large group of normal-hearing young and older subjects and in subjects suffering from different kinds of hearing losses or other clinical pathologies. They reported a negative impact on MAA thresholds only in subjects with declined speech perception performance and sensorineural hearing loss. Subjects with hearing loss, but with normal results in speech perception tests, did not show any decline in MAA, hence suggesting that central auditory processing is the key determining factor of the performance. In the present study, we did not find a significant effect of hearing status on MAA performance, though the impact of hearing loss cannot be excluded completely. In a study by Chandler and Grantham (1991) on auditory spatial resolution, a significant decline in MAA performance was reported for older adults, which was related to an age-related deficit in processing binaural cues (ITD and ILD). These findings fit with the results by Whitmer et al. (2012) who reported broader ASW percepts in older, hearing-impaired subjects under headphone conditions as a function of the declined sensitivity to changes in IC. Recent results suggest that sensitivity to IC declines with aging, because the loss of neural synchrony in the auditory system increases (i.e., temporal jitter increases) (Wang et al. 2011). This specific impairment in temporal processing might be linked to a reduced fidelity in processing timing information at the level of the auditory brainstem (Ruggles et al. 2011, 2012; Shinn-Cunningham et al. 2013) and was also observed in the auditory cortex (Ross et al. 2007). Ruggles et al. (2011) conducted experiments in young and middle-old listeners and measured frequency-following responses (FFR) to the syllable/ dah/which they related to measures of spatial selective attention in reverberant conditions. Their results indicate that the impairment of temporal processing is evident at very early processing stages in the auditory system and affects already middle-old subjects. The influence of aging on temporal processing was also observed by Ross et al. (2007) at the auditory cortex level who measured MEG in young, middle-aged, and older subjects. They also found that the decline in the neural encoding of interaural phase information starts in middle-aged subjects. Moreover, they argued that this decline at the cortical level reflects the impaired temporal processing at brainstem level. Given the results of previous studies and our present study, we hypothesize that the decrease in fidelity will result in less accurate processing information about a sound source position. Because the MAA depends on the acuity with which sound sources are being represented and perceived, we further suggest that the increase in MAA thresholds in older adults is due a more blurred representation of sound source position. This broader representation of sound source position might already be present at brainstem level and possibly lead to an inaccurate representation at cortical levels. It could be possible that the evoked hemifield code for single sound sources broadens with age, and therefore, larger spatial separations between adjoining sound sources are necessary to evoke non-overlapping spatial representations and distinct percepts of sound sources. However, further research on the underlying physiological activity is required to explain how the neural representation of sound sources at auditory brainstem level is linked to the representation in the auditory cortices.

Localization accuracy and acuity

Previous studies reported a correlation between localization accuracy and acuity and inferred a functional relationship between both measures (Heffner and Heffner 1988; Makous and Middlebrooks 1990; Recanzone et al. 1998). That is, the ability to detect a change in sound source position would be directly dependent on (and limited by) the precision of sound source localization. Recanzone et al. (1998) stated that the actual localization acuity thresholds are only a weak predictor for localization accuracy. We found a weak correlation between localization accuracy (RMSE) and acuity (MAA) only in young listeners for the central reference position (9°). The correlations between accuracy and acuity were not significant for any reference position or noise signal in older subjects, which reflects the most important point in the comparison between localization accuracy and MAA: Aging influences spatial discrimination (MAA) more strongly than localization accuracy. Localization accuracy depends on the perception of *mean position* of a sound source, irrespective of its ASW. That is, the perceived mean position of a sound source would be similar for sound sources, which are perceived with a small or large spatial width, given that the ASW is symmetrical. This would explain why the age affect was not strong for the accuracy data. However, the MAA depends on the perceived *width of a sound source*, and thus, MAA thresholds will be increased for larger ASWs. The reduced temporal fidelity at the subcortical level may lead to a reduction in IC, which in turn will cause an increase in the perceived ASW of a sound source (Whitmer et al. 2012). Therefore, larger spatial separations between neighboring sounds are required for a correct discrimination. Taken together, our results suggest that localization performance in older adults is impaired as a consequence of declined coding of timing information at a subcortical level, which in turn may cause a blurred representation and perception of sound sources. This effect will be most pronounced when multiple sound sources must be compared.

General conclusion

Localization accuracy and acuity of acoustic stimuli were examined in young and older adults, revealing an age-related decrease in performance, which was more pronounced for localization acuity. Most importantly, hearing sensitivity did not predict performance in either experiment. Based on previous studies indicating a decline in temporal processing in the central auditory system, we conclude that (1) the use of binaural cues (ITD and ILD) as well as the (2) early sensory processing of the auditory space at brainstem level is strongly declined in older adults. This impairment might result in a blurred representation of sound sources.

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Conflict of interest No conflicts of interest, financial or otherwise, are declared by the author(s).

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