Effects of directional hearing aid settings on different laboratory measures of spatial awareness perception

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Abstract

Hearing loss can negatively influence the spatial hearing abilities of hearing-impaired listeners, not only in static but also in dynamic auditory environments. Therefore, ways of addressing these deficits with advanced hearing aid algorithms need to be investigated. In a previous study based on virtual acoustics and a computer simulation of different bilateral hearing aid fittings, we investigated auditory source movement detectability in older hearing-impaired (OHI) listeners. We found that two directional processing algorithms could substantially improve the detectability of left-right and near-far source movements in the presence of reverberation and multiple interfering sounds. In the current study, we carried out similar measurements with a loudspeaker-based setup and wearable hearing aids. We fitted a group of 15 OHI listeners with bilateral behind-the-ear devices that were programmed to have three different directional processing settings. Apart from source movement detectability, we assessed two other aspects of spatial awareness perception. Using a street scene with up to five environmental sound sources, the participants had to count the number of presented sources or to indicate the movement direction of a single target signal. The data analyses showed a clear influence of the number of concurrent sound sources and the starting position of the moving target signal on the participants' performance, but no influence of the different hearing aid settings. Complementary artificial head recordings showed that the acoustic differences between the three hearing aid settings were rather small. Another explanation for the lack of effects of the tested hearing aid settings could be that the simulated street scenario was not sufficiently sensitive. Possible ways of improving the sensitivity of the laboratory measures while maintaining high ecological validity and complexity are discussed.

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Introduction

In daily-life environments, listeners and sound sources are in constant motion. The human auditory system is capable of making sense of the acoustic information that arises from such spatial dynamics. The resultant percept – auditory spatial awareness – is the awareness of the auditory objects in the surrounding space in relation to one's own position. Research into the field of spatial awareness perception has its basis in the investigation of mechanisms related to (static) localization and distance perception. These have been extensively researched during the last decades.[1-5] Normal-hearing listeners are adept at determining the direction and distances of sound sources, even in rooms with reverberation.[6] However, listeners with sensorineural hearing loss exhibit considerable difficulties with this, especially in complex environments. Their localization performance generally decreases,[7] and motion perception is likely also adversely affected.

With the recent advances of spatial audio technology, it has become possible to simulate realistic environments virtually and in this way to study auditory movement perception. Such simulations can incorporate the acoustic information underlying movement perception, for example changes in interaural difference or monaural spectral cues as a function of space and time.[1] However, investigations into the spatial hearing abilities of hearing-impaired listeners and the effects of hearing aid processing thereupon have so far been largely restricted to localization and discrimination performance in relatively simple acoustic scenarios.

To address this lack of research, we recently investigated the influence of different signal enhancement algorithms on the detectability of left-right (angular) and near-far (radial) source movements with a group of older hearing-impaired (OHI) listeners.[2] That is, we used virtual acoustics to simulate complex sound scenarios with a moving target source and multiple static interferers and simulated different hearing aid (HA) algorithms using a Master Hearing Aid research platform.[8] The algorithms were designed to suppress distracting sounds coming from the sides and the back and to attenuate diffuse sound and reverberation. For a group of listeners tested in the presence of reverberation and four lateral interfering sounds, we found substantial improvements in the detectability of a frontal target source moving along the left-right and near-far dimensions.

The results from our previous study raise the question of how directional processing settings available in head-worn HAs affect spatial awareness perception in comparable scenarios where head movements are possible. In the present study, we therefore performed experiments to evaluate this. To that end, we used a higher-order Ambisonics-based system for simulating complex sound scenes together with bilateral receiver-in-the-ear (RITE) devices. The HAs were programmed to process the stimuli in different ways. More specifically, the chosen settings were designed to attenuate non-frontal sounds either only slightly or strongly. The aims of our study were: i) To investigate the extent to which our earlier movement detection results obtained with a headphone-based setup and simulated HA settings can be transferred to a loudspeaker-based setup and head-worn devices; ii) To extend our earlier results towards other aspects of spatial awareness perception.

Materials and Methods

Physical test setup

The experimental setup was based on the one from our previous study.[9] The virtual environment was simulated using a toolbox for creating dynamic virtual acoustic environments (TASCARpro version 0.128).[10] A two-dimensional (horizontal-plane) 7th-order Ambisonics receiver with max-r_E decoding was used.[11] The Ambisonics decoder was a dual-band type with a crossover frequency of 500 Hz. It was configured to map the output signals onto a horizontal-plane layout with 16 physical loudspeakers spaced 22.5° apart. The order of the Ambisonics receiver was chosen to match this loudspeaker array (for a given order m, the minimum number of loudspeakers is $N_{\min} = 2m+1$).[12] The loudspeaker setup is shown in Figure 1. The speakers were mounted at a height of 1.65 m and a distance of 1.5 m from the center position of the array. The participants were seated on a chair (not shown) that was adjusted in height to ensure a consistent positioning during the measurements.

Stimulus presentation was via a 24-bit RME (Haimhausen, Germany) Hammerfall HDSPe RayDAT soundcard connected to a Digidesign (Avid Technology, Daly City, CA, USA) 192 Digital Interface together with a Rosendahl (Rosendahl Studiotechnik Inc., Utting am Ammersee, Germany) Nanosyncs HD, multistandard sync engine. All outputs were controlled via a ProTools HD10 Version 10.3.9 (Avid Technology) system. The signals were fed through Furman (Petaluma, CA, USA) M-10LX E pre-amplifiers to Genelec (Iisalmi, Finland) 8050B loudspeakers in the sound studio. For implementing the different psychoacoustic measurements, we used the *psylab* toolbox.[13]

Acoustic analyses

To characterize the changes of the dynamic stimuli within the simulated environment, we performed accompanying acoustic analyses. In order to do so, we recorded the stimuli with a head-and-torso simulator (HATS, B&K Type 4128-C) equipped with two RITE HAs that were fitted according to the average hearing loss of the participants (see Participants paragraph). We created a set of single- and multi-source stimuli that included source movements with velocities corresponding to the median detection thresholds of our OHI listeners (see Results paragraph). In this manner, we captured the changes in the acoustic properties of the target and interferer signals that the two groups of participants could just about detect. To be able to reveal short-time changes in the measures of interest (*e.g.* overall level of the interferers), we used a 100-ms analysis window with 50% overlap.

Stimuli and simulated sound scenarios

Left-right and near-far movement detectability

The simulated acoustic scenario was an entrance hall of approximately 10.5 m × 6 m × 2.8 m with solid walls (including various large glass surfaces) and a wooden floor and a reverberation time of $T_{60} = \sim 0.8$ s.[9] The listener was seated 1 m away from the middle of the shorter wall facing along the longer side at a height of 1.5 m. In the reference condition, the target source was located 1 m away from, and directly in front of, the listener. A change in complexity of the scenario was achieved by adding two or four static interfering sound sources at a distance of 1 m each with azimuthal angles of ±45° and ±90° relative to the frontal direction. The stimuli were the same to those from our previous study.[9] That is, we made use of five different environmental sounds. A broadband noise-like fountain signal served as the target sound. As interferer sounds, we used recordings of ringing bells, bleating goats, pouring water and humming bees. The target sound (S1) was presented at a nominal level of 65 dB sound pressure level (SPL) and the other sounds (S2-S5) at 62 dB SPL (nominal) each, as measured under reverberant conditions at the position of the virtual listener. The duration of each sound was 2.3 s without reverberation and 3.1 s with reverberation.

Figure 1. Physical test setup used for the measurements. Only the 16 loudspeakers in the horizontal plane were used in the current study.

Movement direction and number of concurrent sources

To assess other aspects related to spatial awareness perception, we created another scenario in which the participants had to fulfill two different tasks. Using TASCAR, we created a street scene (Figure 2) with remote traffic noise and a duration of 15 sec. A change in complexity of the scenario was achieved by presenting different environmental sounds that could either move around the listener or were static. The chosen stimuli were made up of up to five different sounds from a street scenario (car, van, garbage truck, bike, and pram). Each of these sounds could be the target signal and was presented at a nominal level of 65 dB SPL.

Participants

The participants were 15 OHI listeners (6 male, 9 female) aged 41-79 yrs (mean: 66.5 yrs, standard deviation = 9.5 yrs). All of them had bilateral HA experience of at least 2 yrs. Initially, we measured the participants' hearing thresholds at the standard audiometric frequencies from 0.125 to 8 kHz. All participants had symmetric, sloping mild-to-moderate sensorineural hearing losses. The participants were divided into two groups based on the results of an initial target detectability task (see Procedure paragraph). The average audiograms of the two resultant groups are depicted in Figure 3. The mean pure-tone average hearing loss calculated across 0.5, 1, 2 and 4 kHz and both ears (PTA4) for the two groups was 37.0 dB hearing level (HL) (group 1 (target) +2 (interferers)) and 34.1 dB HL (group 1(target) +4 (interferers)), respectively. The mean age was 66.9 yrs (group 1+2) and 64.0 yr (group 1+4), respectively. All participants provided written informed consent and received financial compensation for their travel expenses.

Hearing aid settings

The HAs used for the measurements were Oticon Opn devices. They were connected via a Flexconnect to an Expresslink[3] (Sonic Innovations Inc., Somerset, USA) USB device and a laptop with the fitting software (Genie2 version 17.1) installed on it. We used RITE devices with power domes of various sizes according to the ear canal diameters of our participants. In this manner, we ensured that mainly the processed sound from the HAs reached the eardrums. To fit the HAs to the individual hearing loss of each participant, we used the Voice Aligned Compression rationale, which aims at creating improved speech understanding and sound quality.[14]

Three HA conditions with different degrees of directionality and noise reduction were tested:

Omnidirectional

The Omnidirectional (OMNI) condition corresponded to a HA setting in which most of the advanced algorithms (*e.g.* noise reduction) were turned off. The focus was on providing a natural perception of the auditory scene by providing amplification for stimuli coming from all directions.

Automatic

In the Automatic (AUTO) condition, the noise reduction algorithm available in the test devices was set to -7 dB attenuation for complex conditions and 0 dB for simple conditions. The purpose of this setting was to achieve some noise reduction in complex environments while maintaining sufficient information for spatial hearing purposes.

Directional

The Directional (DIR) condition was designed to reach the maximally possible noise reduction for stimuli coming from non-frontal directions. The settings were the same as for the AUTO condition, but the microphone directionality was set to a fixed forward-facing beamformer.

Procedure

Target detectability and left-right and near-far movement detectability

At the first appointment, we assessed target detectability in the presence of four interferers. For this purpose, we used a single-interval 2-alternative-forced-choice paradigm with 50 trials. In half of the trials, a static target sound was present, while in the other trials only the four interferers were presented. Each interval had a duration of 3.1 s. On each trial, the task of the participants was to indicate whether they heard the target sound by pressing a button on the screen ("Yes" or "No"). Using a threshold criterion, $p_{correct}$, of 90% detection accuracy, we divided the participants into groups that could (*good performers*, group 1+4 (*N* = 2, which is far

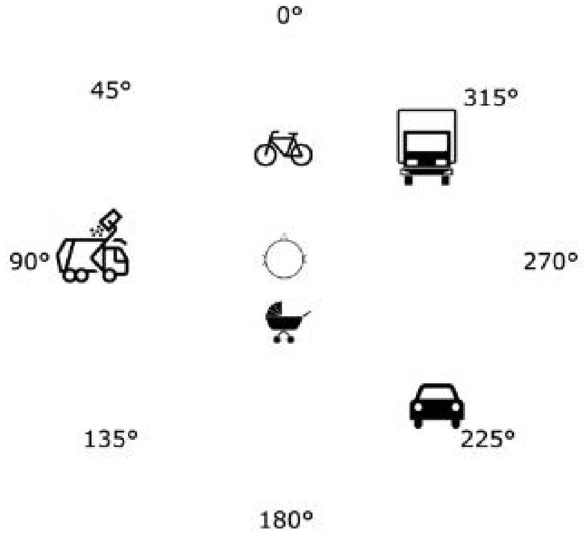

Figure 2. Top-down schematic of the simulated street scenario. The possible sounds and starting positions are depicted. During a trial (15 s), one of the presented sounds (out of up to five) moved 45° around the listener in the middle.

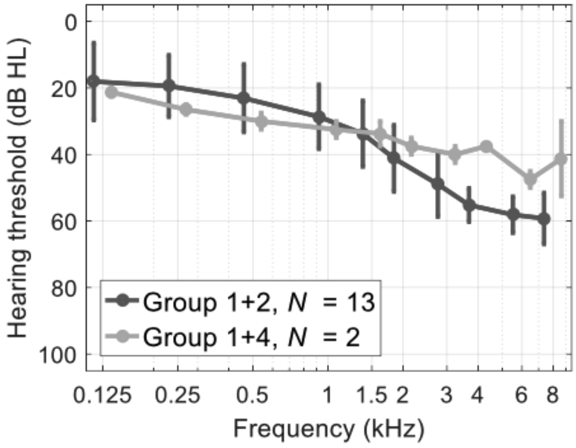

Figure 3. Mean hearing thresholds averaged across left and right ears for the two participant groups. Error bars denote ±1 standard deviation.

from ideal regarding statistical analysis): mean p_{correct} = 98%, standard deviation = 2.8%) or could not (*poor performers*, group 1+2 (N = 13): mean p_{correct} = 64.8%, standard deviation = 15.1%) easily hear out the target sound.

Depending on the target detectability outcome, the movement detection thresholds were measured without (group 1+0, poor performers) or with (group 1+4, good performers) the four interferers. The procedure for measuring the detection thresholds was very similar to that in our previous study.[9] On half of the trials, we simulated a moving target sound, whereas in the other trials the target sound remained static at the reference position (0°, 1 m). For the angular measurements, we randomized the direction of movement (towards the left or right), whereas for the radial measurements we always simulated a withdrawing (N-F) movement. In this manner, we ensured the same reference position (0°, 1 m) for both movement dimensions. To control the extent of the movement, we varied the velocity (in °/s or m/s) in the adaptive procedure. For the angular source movement measurements, the velocity ranged from 2 to 30°/s (starting value: 17.4°/s) across all tracks. For the radial source movement measurements, it ranged from 0.25 to 3.7 m/s (starting value: 1.74 m/s). The smallest step size was 2° or 0.25 m. The stimulus duration was constant (2.3 s), thus the amount of movement was proportional to the velocity. On each trial, the task of the participants was to indicate whether they heard a movement (independent of the direction) of the target sound or not by pressing a button on the screen ('Yes' or 'No'). For the adaptive procedure, we used the single-interval adjustment-matrix method of Kaernbach.[15] This procedure takes hits, misses, false alarms and correct rejections into account and in this way enables unbiased adaptive testing. A so-called payoff matrix determines the magnitude of the changes made to the adaptive parameter (in our case, the velocity) for each combination of stimulus and response. The adjustment factors that we used were -1 (hits), 1 (misses), 2 (false alarms) and 0 (correct rejections). For our measurements, we chose a desired target performance of t = 0.5. A run was terminated after 12 reversals, and the first four reversals were discarded from the analyses. A single run took 3-5 min to complete. Before the actual measurements, each participant completed two training runs with six reversals each, one with the OMNI condition and the other with the AUTO condition. The actual measurements were performed with the OMNI, AUTO and DIR conditions.

We estimated the detection thresholds by taking the arithmetic mean of the last eight reversal points of each measurement run. In this manner, we quantified the smallest displacement (in ° or m) of the target source that the participants were able to detect within the 2.3 s over which the movements occurred. In the following, we will refer to these thresholds as the minimum audible movement angle (MAMA) and minimum audible movement distance (MAMD) thresholds.

We carried out the L-R and N-F source movement measurements in separate blocks. Within these blocks, we tested the various conditions in randomized order. In total, we measured three L-R thresholds and three N-F thresholds per listener (and thus 90 thresholds in total). We had to exclude the data from one participant because of problems with understanding the tasks.

Prior to the statistical analyses, we examined the distributions of the various datasets. According to Kolmogorov-Smirnov's test, all datasets fulfilled the requirements for normality (all P > 0.05). We therefore used parametric statistical tests to analyze our data. Whenever appropriate, we corrected for violations of sphericity using the Greenhouse-Geisser correction.

Movement direction and number of concurrent sources

At the second appointment, all participants (the division of groups was removed) were asked to perform the two tasks in the virtual street environment, that is, indicating the movement direction of the target source and counting the number of concurrent sound sources. On each trial, we presented a random number of sounds (1-5) from random positions (0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°). To keep the scene realistic, the vehicle sounds were placed a greater distance away from the listener (10-15 m) whereas the bike and pram sounds were closer (5 m). One of the sounds moved within the 15 s of stimulus presentation (±45°), while the others remained static. After the presentation, the participants had to press a button on a touch screen. The two tasks were administered using a graphical user interface that was visible during the whole stimulus presentation. The first task was to indicate the number of sound sources in the last trial. Here, buttons with numbers from 1-6 were provided (Figure 4A). The second task was to indicate in which direction the target source moved. For that purpose, eight buttons were provided containing arrows depicting different movement directions (Figure 4B).

Each of the blocks consisted of 24 trials, where task 1 (count the sound sources) and task 2 (indicate the movement direction) were equally distributed. The three HA conditions were tested in randomized order. This resulted in a total of 144 trials and a measurement time of about 1 hr. Data from one of the participants could not be used for the same reason as stated before (*i.e.* inability to understand the tasks).

Results

Left-right movement detectability

Figure 5A shows means and 95% confidence intervals of the MAMA thresholds for the different groups and HA conditions. For group 1+2, the mean thresholds were between 30° and 40° for the different HA conditions. The variance of the data was high in this group; some participants achieved good performance, while others performed rather poorly. For group 1+4, there were only thresholds from two participants available, which is why no statistics were performed on these data. Qualitatively speaking, the thresholds for the OMNI and DIR conditions were similar, while the ones for the AUTO condition were higher. To test for statistical differences among the data of group 1+2, we conducted a repeated-measures analysis of variance (ANOVA) with HA condition (OMNI, AUTO, DIR) as within-subject factor, which was not significant ($F_{2,16}$ = 2.5, P = 0.14).

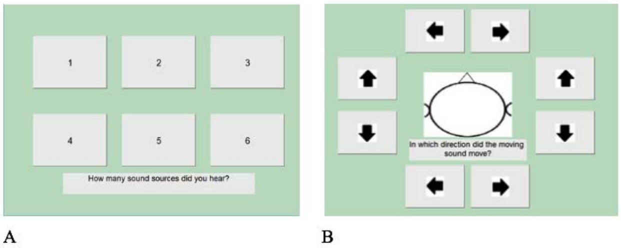

Figure 4. Graphical user interface for counting the number of sound sources (A) and indicating the direction of the moving sound source (B).

Near-far movement detectability

Figure 5B shows means and 95% confidence intervals of the MAMD thresholds for the different groups and HA conditions. As can be seen, group 1+2 obtained mean thresholds between 3 and 4 m throughout. In other words, the HA conditions did not affect the performance of these participants. Again, the variance across participants was generally large. In contrast, for group 1+4 (*N* = 2 only) there was a trend towards lower thresholds in the DIR condition. To test for statistical differences among the data of group 1+2, we conducted a repeated-measures ANOVA with HA condition (OMNI, AUTO, DIR) as within-subject factor, which was not significant ($F_{2,14}$ = 1.8, P = 0.2).

Movement direction and number of concurrent sources

The results for counting the number of sound sources are depicted in Figure 6A. A decrease in performance with an increase in the number of concurrent sound sources is clearly visible.

To test for statistical differences, we conducted a repeated-measures ANOVA with HA condition (OMNI, AUTO, DIR) and number of sound sources (1-5) as within-subject factors. We found no effect of HA condition ($F_{2,18}$ = 2.9, P = 0.83), whereas the effect of the number of sound sources was highly significant ($F_{4,36}$ = 54.5, P < 0.0001). Given that all participants, regardless of their performance on the target detectability task, carried out the same task for these measurements, we did not perform these analyses separately for the 1+4 and 1+2 groups. However, given the small sample size of group 1+4, the results would only differ marginally from the ones shown above. The results for the second task, indicating the movement direction of the target source, are depicted in Figure 6B. The highest scores were achieved for the two lateral starting positions (90° and 180°). Consistent with the collected data, many participants informally reported that they perceived many signals from coming from the back, resulting in rather poor performance in the frontal hemisphere. To test for statistical differences, we conducted a repeated-measures ANOVA with HA condition (OMNI, AUTO, DIR) and starting position (0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°) as within-subject factors. We found no effect of HA condition ($F_{2,26}$ = 0.38, P = 0.69), whereas the effect of starting position was highly significant ($F_{7,91}$ = 7.2, P < 0.0001).

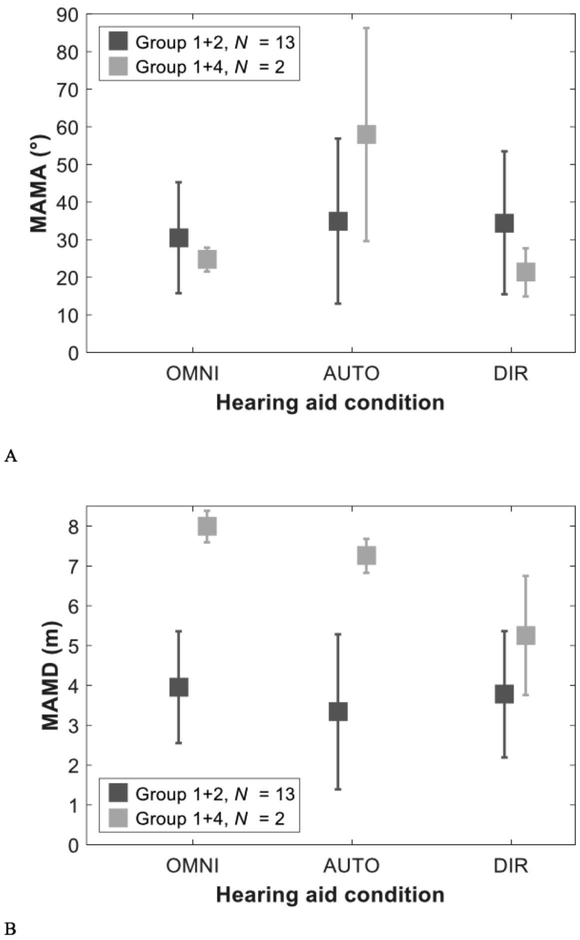

Figure 5. (A) Means and 95% confidence intervals of the minimum audible movement angle (MAMA) thresholds for the different groups and hearing aid conditions. OMNI, Omnidirectional; AUTO, Automatic; DIR, Directional; (B) means and 95% confidence intervals of the minimum audible movement distance (MAMD) thresholds for the different groups and hearing aid conditions.

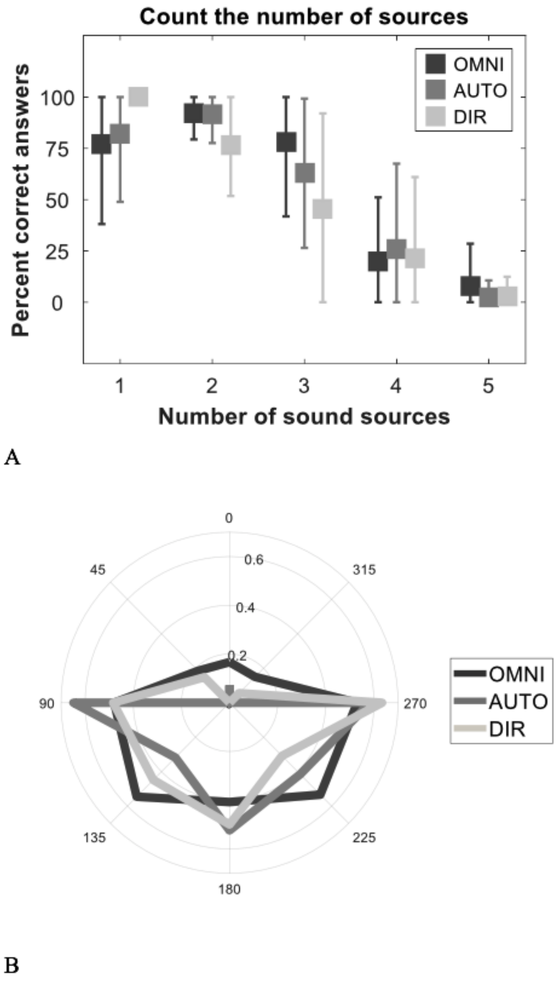

Figure 6. (A) Mean percent-correct scores and 95% confidence intervals for the *count the number of sound sources* task. The legend shows the different hearing aid conditions; (B) mean percent-correct scores for indicating the movement direction. The legend shows the different hearing aid conditions. The angular parameter is the starting position of the source movement.

Acoustic analyses

The results of the acoustic analyses regarding the short-term changes of the measures of interest revealed no substantial differences. That is, the differences of the overall level of the interferer sounds were negligible between the three HA conditions (data not shown).

Discussion

In the current study, we investigated the extent to which source movement detectability results obtained previously with a headphone-based setup and simulated HA settings could be transferred to a loudspeaker-based setup and head-worn behind-the-ear (BTE) devices. Another aim was to extend the results towards other aspects of spatial awareness perception. For that purpose, we used an established method from virtual acoustics to render complex sound fields over a loudspeaker array. We evaluated three directional processing settings available in a BTE device with the help of 15 OHI listeners. The data analyses showed the expected decrease in performance with increased scene complexity for the *count the number of sources* task, but no differences between the three HA settings – neither for source movement detectability, nor for the other spatial awareness tasks. Below, we discuss these results in more detail.

Left-right and near-far movement detectability

At a practical level, we were able to transfer the headphone-based test setup from our previous study to a loudspeaker-based test setup for the current study. At the perceptual level, we could not replicate our previous (movement detectability) results, however. In general, we found no effects of HA condition for group 1+2 ($N = 13$). For group 1+4 ($N = 2$), there were too few listeners, thereby ruling out any detailed statistical analyses. Nevertheless, there was a trend towards lower (better) thresholds with DIR compared to OMNI in the N-F dimension for this group. Broadly speaking, this is in line with our previous study where we found lower thresholds with a bilateral beamformer (see figure 9 in Lundbeck *et al*., 2018).[2] With a larger sample size, it is possible that we would have observed a similar effect of the DIR setting.

The non-significant results for group 1+2 could have been due to small acoustic differences between the tested HA settings (see Acoustic analyses), a decrease in spatial reproduction quality with the loudspeaker-based setup, or insufficient training of the listeners. Recall that the OMNI setting aimed to preserve a natural spatial impression, while AUTO was designed to achieve some speech enhancement while also allowing for non-frontal sounds to be perceived. The DIR condition, on the other hand, aimed for a more extreme attenuation of non-frontal sources. While the bilateral beamformer in our previous study[2] could improve the signal-to-noise ratio, it also introduced some clear spectral distortions into the output signal. In contrast, the commercially available RITE device tested here achieved less noise attenuation but also maintained a better sound quality for non-frontal sources. In general, the results of group 1+2 were in-between the results from the previous study, where we had tested participants with (1+4) or without (1+0) interferers. In that study, we had not found an effect of the HA algorithms for group 1+0 either. Qualitatively speaking, group 1+2 tested in the current study behaved similarly, at least for the left-right dimension. Together, this provides an indication that only in more complex scenarios (*e.g.* with four lateral interferers) HA users may profit from more advanced directional processing algorithms that introduce acoustic changes in support of source movement detection, for example changes in monaural spectral cues.

For the near-far dimension, again in comparison with group 1+0 from our previous study, the thresholds of group 1+2 were shifted to higher values. Even though the target signal did not overlap spatially with the interferers, no effect of directional processing could be found. A few of our participants performed as well as young normal-hearing listeners,[9] and as the OHI listeners tested only with the target sound in our previous study (group 1+0). For them, neither reverberation nor the concurrent interferers seemed to increase their thresholds. These differences are consistent with the large variability among hearing-impaired listeners that is typically observed in relation to spatial hearing (and other) tasks.[16] To better understand the factors that are responsible for the differences across our studies described above, in-depth acoustic analyses of the HA settings in the different scenarios could provide useful insights into the available physical cues and differences among the tested conditions (or the lack thereof).

Movement direction and number of concurrent sound sources tasks

The current study relied on two new ways of evaluating the influence of HA algorithms on spatial awareness perception. Together with the psychoacoustically driven movement detectability task, this was meant as a step into the direction of a procedure covering different aspects of spatial awareness perception. Other researchers have also addressed this issue with the help of multiple test scenarios. This included the ability to count the number of sound sources under static spatial conditions, which can be a challenging task even in non-reverberant situations. Best and colleagues found that older hearing-impaired listeners made already errors with just two simultaneous talkers.[17] In the current study, we already observed errors for one sound source, at least for the OMNI and AUTO conditions. Only in the DIR condition were the listeners able to achieve 100% correct performance (Figure 6A). For three sound sources performance started dropping drastically, and higher numbers led to scores close to 0% for all HA conditions. These results give some indication of how OHI listeners can or cannot cope with acoustically complex scenarios. For the further development of spatial awareness measurements, the performance range from easy to hard should ideally be covered to produce test conditions that are sufficiently sensitive to the effects of directional HA algorithms.

The new tasks also included the identification of the movement direction. In real life, not only the accurate perception of a static scenario is necessary; it needs to be also possible to detect dynamic changes in the environment. Another level of complexity is thus introduced, which ideally should be possible to reproduce in the laboratory. In our study, many participants reported informally that they found this to be a very difficult task, and the obtained results represent this impression quite well. Therefore, our approach serves as a first step into the direction of new assessments of the ability of HA wearers to perceive a spatially dynamic scene.

Conclusions

In contrast to our previous headphone-based study,[2] we rendered the scenarios over loudspeakers in the current study. Our participants were therefore able to listen with their own heads (rather than with non-individualized head-related transfer functions) and to take advantage of head movements. Small head rotations have been found beneficial for localization accuracy and for reducing front-back errors in particular.[18] Natural head movements can also substantially differ among individuals[10] and are considered an important factor for spatial perception under dynamic conditions.[19]

Head movements (*e.g*. the tendency of participants to turn their *better* ear towards the target source) could also be observed in the current study. Future work should ideally disentangle the influence of head movements on source movement detectability and spatial awareness perception. Our study was also limited to one particular acoustic environment. It would be useful to investigate other types of environments and scenarios that reflect other complex tasks such as a group discussion.[20] Challenges with multiple sources occur in various real-life scenarios that differ in spatial complexity and the task of the listener. Although we considered non-frontal starting positions for the moving target signal in the street scene, future studies ideally assess the influence of non-frontal source movements in multi-source environments. Although we could reveal an influence of the number of sound sources in the second part of the study, no differences in HA condition was found. Additional training for the participants to better accustom themselves to the different conditions and changes of the test setup into the direction of scenarios that already show differences among the HA settings on the acoustic level are possible starting points for improvement. Especially for the AUTO and DIR condition, scenarios need to be designed that support the different advantages in features like noise-reduction or maintaining spatial information.

Using a loudspeaker-based setup for simulating complex listening environments combined with different directional processing settings available in a behind-the-ear HA, the current study found no effects of these settings on a number of spatial awareness percepts as assessed with a group of OHI listeners. The lack of effects could have been due to the settings themselves, insufficient sensitivity of the adopted test methods, or insufficient training of the study participants. In future studies, it will be of interest to improve the available methods for spatial awareness assessments to better understand how spatial perception is influenced by hearing loss and different types of hearing aid processing.

References

1. Carlile S, Leung J. The perception of auditory motion. Trends Hear 2016;20:1-19.
2. Lundbeck M, Hartog L, Grimm G, et al. Influence of multi-microphone signal enhancement algorithms on the acoustics and detectability of angular and radial source movements. Trends Hear 2018;22:1-13.
3. Blauert J, Allen J. Spatial hearing: the psychophysics of human sound localization. Review edition. Cambridge, USA: MIT Press; 1997.
4. Hawley ML, Litovsky RY, Colburn HS. Speech intelligibility and localization in a multi-source environment. J Acoust Soc Am 1999;105:3436-8.
5. Langendijk EH, Kistler DJ, Wightman FL. Sound localization in the presence of one or two distracters. J Acoust Soc Am 2001;109:2123-34.
6. Shinn-Cunningham B. Learning reverberation: Considerations for spatial auditory displays. Georgia Institute of Technology; 2000. Available from: http://hdl.handle.net/1853/50675
7. Akeroyd MA. An overview of the major phenomena of the localization of sound sources by normal-hearing, hearing-impaired, and aided listeners. Trends Hear 2014;18:1-7.
8. Grimm G, Herzke T, Berg D, Hohmann V. The master hearing aid: a PC-based platform for algorithm development and evaluation. Acta Acust United Ac 2006;618-28.
9. Lundbeck M, Grimm G, Hohmann V, et al. Sensitivity to angular and radial source movements as a function of acoustic complexity in normal and impaired hearing. Trends Hear 2017;21:1-14.
10. Grimm G, Luberadzka J, Herzke T, Hohmann V. Toolbox for acoustic scene creation and rendering (TASCAR)-Render methods and research applications. Proceedings of the Linux Audio Conference, 2015 Apr 9-12, Mainz, Germany.
11. Daniel J. Représentation de champs acoustiques, application à la transmission et à la reproduction de scènes sonores complexes dans un contexte multimédia. Paris, France: Université Pierre et Marie Curie; 2000.
12. Ward DB, Abhayapala TD. Reproduction of a plane-wave sound field using an array of loudspeakers. IEEE T Speech Audi P 2001;9:697-707.
13. Hansen M. Lehre und Ausbildung in Psychoakustik mit psylab: Freie Software für psychoakustische Experimente. Fortschritte der Akustik 2006;32:591.
14. Le Goff N. Amplifying soft sounds - A personal matter [White paper]. Available from: Oticon A/S 2015. http://www.oticon.global/professionals/evidence
15. Kaernbach C. A single-interval adjustment matrix (SIAM) procedure for unbiased adaptive testing. J Acoust Soc Am 1990;88:2645-55.
16. Noble W, Byrne D, Ter-Horst K. Auditory localization, detection of spatial separateness, and speech hearing in noise by hearing impaired listeners. J Acoust Soc Am 1997;102: 2343-52.
17. Best V, Buchholz JM, Weller T. Measuring auditory spatial perception in realistic environments. J Acoust Soc Am 2017;141:3692.
18. Wightman FL, Kistler DJ. Resolution of front-back ambiguity in spatial hearing by listener and source movement. J Acoust Soc Am 1999;105:2841-53.
19. Brimijoin WO, Akeroyd MA. The role of head movements and signal spectrum in an auditory front/back illusion. I-PERCEPTION 2012;3:179-82.
20. Grimm G, Kollmeier B, Hohmann V. Spatial acoustic scenarios in multichannel loudspeaker systems for hearing aid evaluation. J Am Acad Audiol 2016;27:557-66.