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Effects of Hearing Aids on Sound Localization in Noisy Environment for Individuals with Unilateral Hearing Loss

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Abstract

Objective: This research aimed to investigate the effects of hearing aids(HAs) on sound localization in noisy environment for individuals with unilateral hearing loss(UHL). **Method:** The study used an experimental approach with 43 participants (22 with UHL, 21 with normal hearing). Hearing thresholds were measured at 500 - 4000 Hz using pure-tone audiometry. Sound localization experiments were conducted in a 2 m × 2 m room with five loudspeakers arranged in a semicircle, both with and without hearing aids, in a simulated noisy environment. Tests were performed at different signal-to-noise ratios (SNR 5, SNR 0, SNR −5), and localization accuracy was assessed by participants pointing to the speaker playing the target signal, ignoring background white noise. Each participant completed at least 45 trials. Data were statistically analyzed to compare localization accuracy between groups and evaluate hearing aid effectiveness in complex listening conditions. **Results:** Pure tone tests showed substantial hearing loss in UHL individuals' impaired ear (40 - 80 dB HL), but aided conditions brought thresholds closer to normal hearing level. Unaided UHL individuals had lower mean correct identification rate (CIR) (26.36% at SNR 5, 23.03% at SNR 0, 22.12% at SNR −5) than aided (45.76% at SNR 5, 39.70% at SNR 0, 38.12% at SNR −5). Hearing aids reduced mean angle deviation from 74.18˚ (SNR 5), 76.09˚ (SNR 0), and 77.73˚ (SNR −5) unaided, to 45.82˚ (SNR 5), 48.41˚ (SNR 0), and 47.73˚ (SNR −5) aided. It is proven that the accuracy in sound localization is improved statistically (p-values < 0.05) at all SNRs. However, a big performance gap persisted between UHL individuals using HAs and those with NH, especially under challenging SNR conditions.

Conclusion: The study concludes that HAs enhance sound localization for UHL in noise although there remains a notable gap when compared to NH individuals, it proves the need for HAs technology improvement to optimize auditory outcomes for UHL individuals.

Subject Areas

Audiology

Keywords

Hearing Aids, Sound Localization, Unilateral Hearing Loss, Noisy Environments

1. Introduction

Hearing loss is one of the common global health issues that affect a large number of people in a variety of age groups. In 2015, an estimated 115 million people in China (8.4% of the population) had moderate-to-complete hearing loss, with 85.7% over 50 years old and 2.4% under 20 years old. This number is projected to rise by 110% in the future decades [1]. The importance of having a healthy hearing is crucial for effective communication, social interaction, and general quality of life [2]. The ability to hear clearly is pivotal for individuals to actively engage in educational pursuits, professional environments, and social interactions, underscoring the profound role of auditory function in daily life.

UHL affects 7.2% of the population, with 5.7% of adults having mild UHL and 1.5% experiencing moderate-to-severe UHL, with 1.4% using hearing aids [3]. UHL is linked to impaired speech recognition in noisy environments and difficulties in sound localization [4]. Adults with UHL often report a diminished quality of life and may use HAs [5]. Children with UHL favor their better-hearing ear, leading to issues with spatial orientation, balance, and language acquisition [6] [7]. Causes include congenital anomalies, acoustic trauma, infections, age-related deterioration, and noise exposure [8] [9]. In noisy settings, the impaired ear struggles to manage competing sounds, complicating sound localization and auditory cue interpretation [10] [11].

A significant challenge for individuals with UHL is sound localization, which relies on processing auditory cues from both ears, including variations in timing and intensity [12] [13]. In typical hearing, low-frequency noise masking Interaural Time Difference (ITD) cues can be compensated by high-frequency Interaural Level Difference (ILD) cues for sound localization [14]. However, in UHL, the impaired ear diminishes the efficacy of these binaural cues, leading to difficulties in pinpointing sound sources, especially in noisy environments due to reduced directional hearing capabilities [15]. Sound localization is particularly challenging for individuals with UHL due to the head/shadow effect and the loss of ITDs or squelch effect [16]. The head/shadow effect attenuates high-frequency sounds from the side opposite the impaired ear, making it difficult to localize sounds from that direction [17]. Additionally, UHL results in the loss of the binaural summation effect, where sounds heard by both ears are perceived as louder [18]. This reduces overall audibility and clarity, especially in quiet or noisy environments. The absence of the binaural squelch effect makes it harder to localize sounds amidst background noise [19]. Central processing typically subtracts background noise, but with UHL, this process is less effective, further complicating hearing in noisy situations.

In noisy environments, accurate sound localization is crucial, especially for individuals with UHL. UHL challenges spatial hearing due to overlapping sound sources and impaired auditory processing mechanisms like ITDs [20] [14]. This leads to difficulties in localizing essential sounds for safety and social interactions, causing anxiety and isolation [21]. UHL compromises spatial awareness, posing safety risks and hindering daily activities. Sound localization benefits speech communication by helping listeners focus on active talkers and separate sounds in noisy environments [22] [23]. However, UHL makes it harder to block out background noise, reducing speech comprehension and reliance on visual cues.

Modern HAs have advanced significantly, offering features like amplification, noise reduction, and directional microphones to enhance sound clarity [24] Previous research shows HAs improve auditory perception in noise and localization for children with UHL. Early intervention is crucial, but without bilateral benefits, UHL children often lag in localization, especially in focusing on specific sounds and reducing background noise [25]-[27]. The impact of HAs on UHL localization remains a research focus.

Recent academic research has confirmed the benefits of HAs for individuals with UHL, particularly in enhancing sound localization. Both cross-sectional and longitudinal studies have demonstrated that continuous use of these devices not only leads to immediate improvements in auditory localization but also fosters long-term adaptive changes in the auditory processing regions of the brain, potentially inducing positive plastic changes specifically in terms of temporal envelope sensitivity [28] [29]. These findings collectively underscore the compensatory potential of HAs in addressing the deficits associated with UHL, thereby enhancing the functional capabilities and overall quality of life for affected individuals. While HAs have been shown to help people with UHL locate sounds, there's limited research on their performance in noisy environments. Unlike most of the previous studies that tested sound localization in quiet or controlled environments [27] [29]-[32], this study aims to address this gap by examining how HAs work in real-world settings, in different noise levels like busy streets or crowded buses, by simulating the complex sounds of everyday life. This approach helps understand how HAs perform in the real world for people with UHL.

The aim of this study is to investigate the efficacy of HAs in enhancing sound localization for individuals with UHL in noisy environments. The research will evaluate the impact of various SNRs and HAs configurations on localization accuracy, with the aim of establishing whether HAs can elevate localization skills to a level comparable to those with normal bilateral hearing. The study hypothesizes that HAs can enhance localization abilities to levels similar to those with normal bilateral hearing. This study is significant as it seeks to inform the design of more effective HAs and rehabilitation strategies, ultimately improving the auditory experience and quality of life for individuals with UHL.2.

2. Methodology

2.1. Technical Road Map

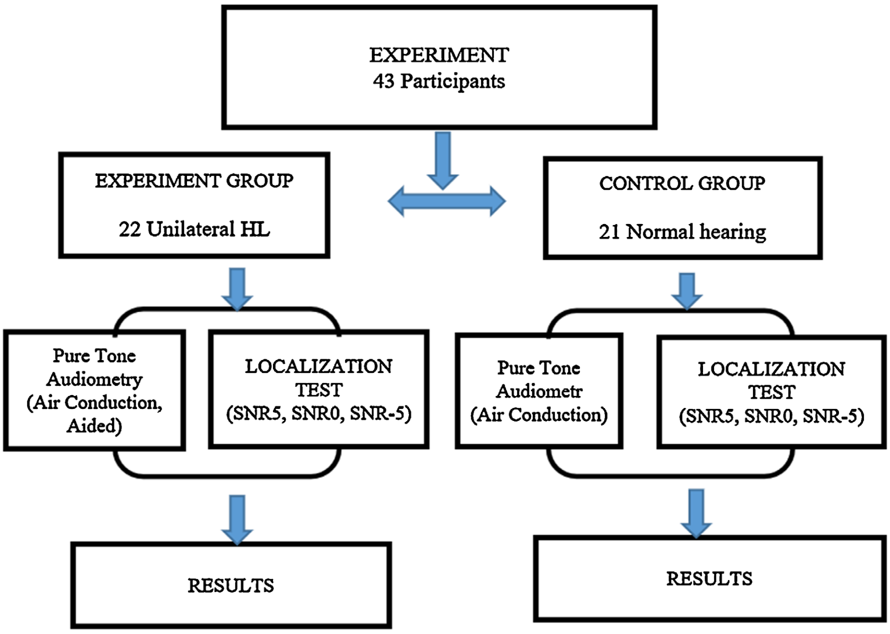

Figure 1. Illustrates the step-by-step methodological approach taken in the study, detailing the process from experiment setup to data analysis and the results.

2.2. Selection Methodology

2.2.1. Sampling and Enhanced Criteria

The methodology used in this study was experimental, focusing on sound localization experiments in a simulated noisy environment. The stages of the methodology involved setting up the experiment, conducting sound localization tests, and analyzing the results. The experimental design was chosen to provide empirical data and insights into the research questions. Participants were selected using a stratified random sampling technique to ensure representativeness and eliminate selection bias. This stratification was based on auditory health status to achieve comparative analytical robustness, focusing on unilateral sensorineural hearing loss only, excluding those with conductive or mixed hearing loss, neurological, otological, cognitive, or language disorders to control for confounding variables. Native Chinese speakers were selected for cultural and linguistic consistency, with ear health confirmed through Otoscopy, audiometry, and tympanometry to ensure validity in comparing normal hearing (NH) and UHL individuals. This methodical approach was designed to provide a balanced and unbiased representation of the study population, enhancing the reliability of the findings.

2.2.2. Study Population

The study included 43 participants from Hui'er Hearing Clinic in China. They were divided into a control group (21 individuals with normal hearing) and an experimental group (22 individuals with UHL). In the experimental group, 15 had UHL in the right ear and 7 in the left. The control group consisted of 21 participants, with 9 describing themselves as male and 12 as female, while the UHL group had 22 participants, 14 describing themselves as male and 8 as female. Ages ranged from 7 to 62 years, with a mean age of 39.5 years. Participants in the control group had normal hearing (≤20 dB HL at 500 to 4 kHz), while the experimental group comprised individuals with UHL of 40 - 80 dB (using WHO) [33] at the same frequencies, using hearing aids for amplification. 21 UHL participants had hearing loss for at least 5 years, and only 1 for less than 6 months. 16 wore RIC hearing aids, and 6 wore CIC hearing aids. Age selection was based on participants' ability to understand instructions, and all participants were native Chinese speakers.

2.3. Setup and Procedure

2.3.1. Pure Tone Audiometry (PTA)

Pure tone audiometry (PTA) was conducted at Hangzhou Hui'er Hearing Clinic in a soundproof booth using a pure tone audiometer to assess hearing thresholds at various frequencies and intensities. Participants underwent air conduction testing with TDH-39 headphones, bone conduction with the B-71 bone vibrator, and aided thresholds with loudspeakers for those using HAs [34]. Masking was applied to prevent cross-hearing, with testing frequencies ranging from 500 to 4000 Hz [35]. Calibration equipment ensured accurate audiometer output.

2.3.2. Sound Localization Experiment

Set up

The sound localization experiments were also conducted at Hangzhou Hui'er Hearing Clinic in a simulated noisy environment to replicate real-life scenarios where individuals with unilateral hearing loss may struggle with sound localization. Audiometer and Calibrated Sound Level Meters were used to ensure that the sound stimuli including warble Tone Bursts as targeted signal and white noise as background noise at various SNRs (SNR 5, SNR 0, SNR −5). To ensure that the SNRs used in the experiment accurately reflect real-world noisy environments, such as busy streets or crowded buses, The SNRs were chosen to simulate varying degrees of background noise commonly encountered in daily life. For example, on a busy street with lots of background or ambient noise. If a car horn suddenly sounds, that's like the target signal (warble tone) in this experiment. The different SNRs help us simulate how easy or hard it is to hear that car horn over the background noise. These were delivered at the correct levels and frequencies, maintaining the accuracy and reliability of the tests. The room used was a Custom-built soundproof booth to minimize echo and reverberation. The room size was 2 M by 2 M, with five loudspeakers set up in a semicircular configuration at different angles as shown in Figure 2. Participants were seated facing away from the speakers at a distance of 1.5 M. HAs used were digital, programmable devices set to optimal settings for each participant based on their audiometry profiles.

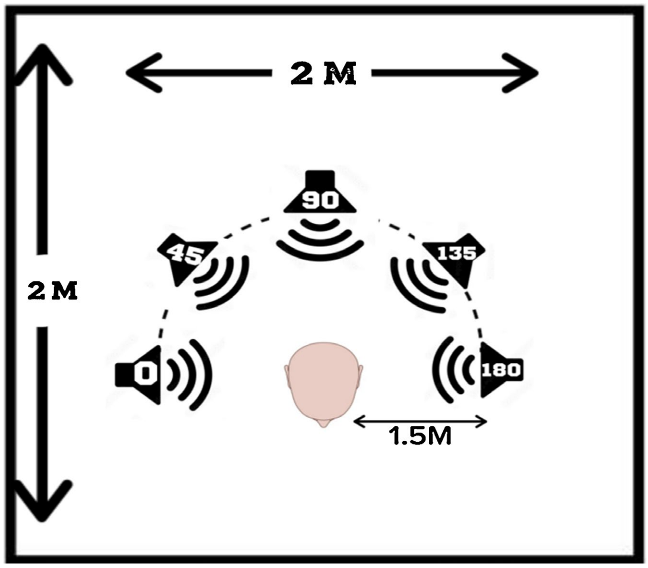

Figure 2. The five loudspeakers set up in a semicircular configuration, background noise always presented at 90˚ speaker, and the targeted signal presented from the 5 speakers in the random order.

Procedure

Participants with normal hearing completed only one unaided sound localization experiment, while those with unilateral hearing loss (UHL) completed both aided and unaided experiments. UHL participants first performed the unaided experiment, followed by a minimum 15-minute rest before the aided experiment. All participants were tested with both signal and diffuse white background noise presented simultaneously at SNR 5, SNR 0, SNR −5. Both signal and noise were presented at 1 kHz, with the white noise consistently behind the participant on a speaker labeled 90˚. Target signals were warble tone pulses randomly played from five speakers in a semi-circular configuration labeled 0˚, 45˚, 90˚, 135˚, 180˚. Normal-hearing participants had a signal level of 65 dB, while UHL participants had their signal level adjusted to 10dB below the impaired ear's threshold to prevent binaural hearing during the unaided experiment. Participants were instructed to ignore background noise and identify the speaker producing the target signal by pointing at it. Noise difficulty increased from SNR 5 to SNR −5. A minimum of 45 trials were conducted, with each SNR tested 15 times. Trials were presented in random order with a fixed speaker sequence to avoid bias. Localization results were measured and examined within a specific timeline for consistency and efficiency.

2.4. Data Analysis

The Mean Correct Identification Rate (MCIR) and Angle Difference (MAD) were used to evaluate participants' ability to locate sound sources under various conditions by measuring the deviation between the actual sound source angle and the participant's reported angle. CIR was calculated as a percentage of correct identifications, represented by the formula;

$$\text{MCIR} = \frac{\text{Number of correct identification}}{\text{Toal number of trials}} \times 100\%$$

While MAD measured the accuracy of sound localization, the Wilcoxon signed-rank test was applied to compare MCIR and MAD between aided and unaided conditions [36], and p-values less than 0.05 ($p < 0.05$) indicated statistically significant differences.

3. Results

3.1. PTA for Unaided Hearing in Unilateral Hearing Loss (UHL)

Individuals with unilateral hearing loss (UHL) have impaired ear thresholds of 40 - 80 dB HL, while their normal ear and normal hearing (NH) individuals have thresholds ≤ 20 dB HL across 500 - 4000 Hz. Unaided UHL shows elevated thresholds, but aided UHL shows variable reductions. This improvement helps restore some binaural cues, enhancing sound localization and speech comprehension in noisy environments. The extent of improvement depends on the HAs efficacy, technology, and the SNR of the environment [37]. Highlighting hearing aids' role in mitigating UHL effects Table 1.

Table 1. Mean pure tone audiometry results (dB) (Shows the mean pure tone audiometry for all participants (UHL and NH) across different frequencies).

N = 22	500	1000	2000	4000
Unaided	66.75 ± 10.80	69.25 ± 10.75	70.00 ± 13.3	76.40 ± 14.90
Aided	34.50 ± 9.87	34.25 ± 8.90	35.90 ± 8.82	40.00 ± 14.60
Normal Ear	12.50 ± 5.90	14.10 ± 7.01	12.25 ± 7.36	15.50 ± 12.90

3.2. Sound Localization

3.2.1. Mean Correct Identification Rate in UHL

Table 2 below presents a comparison between the performance of participants with UHL when using HAs (aided condition) and without using them (unaided condition) across different SNR. These results consistently highlight the substantial impact of HAs across varying auditory environments. For instance, at SNR 5, the aided rate is 45.76 vs. 26.36 unaided. HAs consistently enhance performance across varying noise conditions. The Wilcoxon test shows significant differences in MCIR between Unaided and Normal conditions at SNRs of −5 dB, 0 dB, and 5 dB, with p-values < 0.05. The same applies to Aided vs. Normal conditions. Unaided UHL participants have lower MCIR than NH, especially at challenging

SNRs, suggesting that while HAs improve sound localization, they don't fully match natural binaural hearing.

Table 2. Mean Correct Identification Rate (%) (Presents the mean correct identification rate for the aided versus unaided conditions at different SNR levels in mean figures).

N = 22	SNR 5	SNR 0	SNR −5
Unaided	26.36 ± 15.60	23.03 ± 20.76	22.12 ± 10.37
Aided	45.76 ± 17.97	39.70 ± 20.52	38.12 ± 14.13
P value	>0.05	>0.05	>0.05

3.2.2. Mean Angle Difference in UHL

Unaided UHL participants showed poor localization accuracy with mean angle deviations of 74.18˚ ± 26.0˚ at SNR 5, 76.09˚ ± 25.4˚ at SNR 0, and 77.73˚ ± 17.5˚ at SNR −5. In contrast, aided UHL participants significantly improved with mean deviations of 45.82˚ ± 26.8˚ at SNR 5, 48.41˚ ± 23.8˚ at SNR 0, and 47.73˚ ± 21.1˚ at SNR −5. Statistical analysis confirmed these improvements were significant ($p < 0.05$) across all noise conditions as illustrated in **Table 3**.

Table 3. Mean angle difference (Shows the mean angle deviation, which measures the average difference between the actual sound source location and the participant's response, provided further insights).

N = 22	SNR 5	SNR 0	SNR −5
Unaided	74.18 ± 26.0	76.09 ± 25.4	77.73 ± 17.5
Aided	45.82 ± 26.8	48.41 ± 23.8	47.73 ± 21.1
P value	>0.05	>0.05	>0.05

4. Discussion

Unilateral hearing loss (UHL) presents a distinct challenge in sound localization, a skill crucial for perceiving the spatial origin of auditory stimuli. This study sought to investigate the potential of HAs in mitigating the difficulties faced by UHL individuals, especially in noisy environments, where localization issues are often exacerbated. The primary hypothesis posited that HAs would significantly enhance sound localization abilities in UHL individuals, even in the presence of background noise. Additionally, this study explored secondary hypotheses concerning the variability in HA effectiveness based on factors such as SNR, HAs technology, noise type, and noise level, as well as the impact of these improvements on real-world situations and quality of life.

The results of this study demonstrate significant improvements in sound localization accuracy with the use of HAs, as indicated by the substantial increase in CIR and the reduction in MAD in aided conditions compared to unaided scenarios. Individuals with UHL showed poor localization accuracy without HAs, especially in noise (e.g., SNR −5 dB). The mean CIR was 22.12% ± 10.37% in the most challenging noise condition. With hearing aids, CIR improved to 38.12% ± 14.13%, highlighting the critical role of HAs in compensating for lost binaural cues. This improvement was statistically significant across all SNRs, indicating that HAs effectively mitigate UHL challenges in noisy environments. These findings align with prior research showing the positive impact of HAs on sound localization in UHL individuals [29] [30].

The influence of noise on HAs effectiveness in sound localization was pivotal. Noise levels significantly impact localization performance, with lower SNRs reducing accuracy for UHL participants, both with and without HAs [38]. In quieter conditions (e.g., SNR 5 dB), UHL participants localized sounds better, especially with aids (mean CIR 45.76% ± 17.97%). However, as noise increased (e.g., SNR 5 dB), HAs effectiveness decreased but remained better than unaided conditions. This highlights noise as a challenge for UHL individuals, even with HAs. These findings align with prior research on UHL's difficulty in noisy environments, such as Haragopal's work [39]. The study reinforces that while HAs provide significant benefits, they cannot entirely overcome noise challenges.

A key observation is the performance discrepancy between quiet and noisy environments. UHL participants showed more improvement in localization accuracy in quieter settings with hearing aids, but the gap with normal hearing widened in noise. This suggests hearing aids are more effective in less noisy environments but face challenges in noise [40]. The head-shadow effect and loss of binaural summation contribute to diminished effectiveness in noisy settings [41]. HAs struggle to provide effective localization in noise due to limited binaural cue transmission like ILDs and ITDs [42]. Noise affects these cues, making ILDs more reliable for localization [43].

The study aligns with prior research on HAs role in mitigating directional hearing challenges for UHL individual Improvements in CIR support theoretical benefits of HAs in restoring binaural cues essential for accurate localization, like ITD and ILD [44]. Localization accuracy declines as SNR lessen, with off-median plane sounds more detectable due to the head shadow effect [45].

Another observation wad UHL individuals tend to perceive sound as coming from their better-hearing ear, skewing spatial perception due to lack of binaural cues like ITD and ILD. Initial unfamiliarity with the task also affected performance at SNR 5, suggesting a familiarization phase could help.

Localization ability was more disrupted at higher signal levels, possibly due to dynamic range limitations in hearing aid processors [32] [33]. Compression in HAs reduces ILDs, shifting perceived sound location toward the median plane [46]. Lower sensitivity settings may enhance localization in noisy environments [47]. High signal levels with intense noise may diminish ILD effectiveness, highlighting dynamic range limitations [48]. Specific stimulation strategies may not prioritize target sound channels at negative SNRs, affecting ILD cue acquisition [49]. Optimizing HA settings to enhance localization in noise is crucial, considering the impact of noise on cue transmission [50]. This complex sensory processing is influenced by top-down factors like attention, expectation, and perceptual task [51].

The study provides critical insights into auditory processing for UHL individuals, showing that HAs significantly enhance sound localization by compensating for missing binaural cues like ITD and ILD [52]. It reinforces the theoretical framework of auditory spatial perception and highlights practical mechanisms such as signal enhancement, noise reduction algorithms, and directional microphones [53]. These findings align with existing literature and suggest ongoing technological advancements are crucial for improving quality of life for UHL individuals.

Improved sound localization through HAs can enhance daily functioning, reduce cognitive load, and improve social interactions and workplace performance [54]. Patient education on the benefits and limitations of HAs, and strategies for optimal use in various environments is essential. The study also emphasizes the need for a holistic approach to auditory rehabilitation, including counseling, auditory training, and assistive listening devices [55]. This comprehensive approach can significantly enhance the user experience, enabling UHL individuals to lead more fulfilling lives.

Individuals with unilateral hearing loss (UHL) face significant challenges in sound localization, particularly in noisy environments such as public spaces or vehicles. These challenges are exacerbated by the loss of binaural cues, which are essential for accurate spatial perception [55]. To address these difficulties, future hearing aids could incorporate advanced noise reduction algorithms and adaptive directional microphones to enhance signal-to-noise ratios (SNRs) and improve localization accuracy. Additionally, rehabilitation strategies could focus on auditory training programs designed to help UHL individuals better utilize the remaining auditory information. These programs could include exercises that simulate real-world noise environments, helping users to develop more effective listening strategies. Furthermore, interdisciplinary collaboration between audiologists, engineers, and cognitive scientists could lead to innovative solutions that combine technological advancements with personalized rehabilitation approaches, ultimately improving the quality of life for individuals with UHL.

The study's limitations encompass several key areas: a limited participant sample size (43), limited hearing loss of 40 to 80 dB on the impaired ear, the study focused on HAs only, and this study focused on individuals with unilateral sensorineural hearing loss (USNHL only. These limitations highlight the need for future research to address these gaps and explore the broader implications of hearing aid technology on sound localization.

Future studies should diversify participant pools and expand sample sizes to better assess hearing aid efficacy across various noise environments. It is crucial to include individuals with single-sided deafness, where the impaired ear has a hearing threshold exceeding 80 dB, as well as those with cochlear implants. Additionally, considering other types of hearing loss, such as conductive or mixed hearing loss, will provide a more comprehensive understanding of sound localization challenges.

5. Conclusion

There's a clear improvement in correct identification rates and accuracy with hearing aids, a gap remains compared to normal hearing, particularly in poor SNR conditions. This indicates that HAs, while beneficial, do not fully restore normal hearing, highlighting ongoing challenges for UHL individuals. The research recommends technological advancements to improve localization abilities and suggests strategies to enhance SNR, such as advanced noise reduction and adaptive direction. It also emphasizes the impact of SNR on localization performance, guiding future hearing aid designs for various acoustic environments. HAs play a crucial role in improving the quality of life for UHL individuals in challenging listening conditions, demonstrating consistent effectiveness in enhancing auditory performance across different SNRs.

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Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Wang, Y., Xie, Y., Wang, M., Zhao, M., Gong, R., Xin, Y., *et al.* (2024) Hearing Loss Prevalence and Burden of Disease in China: Findings from Provincial-Level Analysis. *Chinese Medical Journal*, **138**, 41-48. https://doi.org/10.1097/cm9.0000000000003096

[2] Podury, A., Jiam, N.T., Kim, M., Donnenfield, J.I. and Dhand, A. (2023) Hearing and Sociality: The Implications of Hearing Loss on Social Life. *Frontiers in Neuroscience*, **17**, Article ID: 1245434. https://doi.org/10.3389/fnins.2023.1245434

[3] Golub, J.S., Lin, F.R., Lustig, L.R. and Lalwani, A.K. (2017) Prevalence of Adult Unilateral Hearing Loss and Hearing Aid Use in the United States. *The Laryngoscope*, **128**, 1681-1686. https://doi.org/10.1002/lary.27017

[4] Snapp, H.A. and Ausili, S.A. (2020) Hearing with One Ear: Consequences and Treatments for Profound Unilateral Hearing Loss. *Journal of Clinical Medicine*, **9**, Article No. 1010. https://doi.org/10.3390/jcm9041010

[5] Galloway, J., Zhang, V., Marnane, V., Hou, S., Stewart, G. and Bardy, F. (2019, March 21) Individual Perspectives on How Unilateral Hearing Loss (UHL) Affects Their Daily Lives, Attitudes, and Relationships. Middle-Ear Implants, Research, Surveys & Statistics. https://hearingreview.com/inside-hearing/research/impact-unilateral-hearing-loss-adult-life

[6] Lieu, J.E.C. (2018) Permanent Unilateral Hearing Loss (UHL) and Childhood

Development. *Current Otorhinolaryngology Reports*, **6**, 74-81. https://doi.org/10.1007/s40136-018-0185-5

[7] Purcell, P.L., Cushing, S.L., Papsin, B.C. and Gordon, K.A. (2020) Unilateral Hearing Loss and Single-Sided Deafness in Children: An Update on Diagnosis and Management. *Current Otorhinolaryngology Reports*, **8**, 259-266. https://doi.org/10.1007/s40136-020-00293-8

[8] Tyagi, A.K., Gupta, K., Kumar, A., Varshney, S., Sood, R., Malhotra, M., *et al.* (2020) Rare Causes of Unilateral Sensorineural Hearing Loss in Adults: Our Experience. *Indian Journal of Otolaryngology and Head & Neck Surgery*, **72**, 428-436. https://doi.org/10.1007/s12070-020-01837-6

[9] Horrocks, L.M., Kitterick, P.T., Jayasinghe, D.S., Willis, K.R., Martin, K.R.M., Dixit, A., *et al.* (2023) Multiple Congenital Anomalies and Adverse Developmental Outcomes Are Associated with Neonatal Intensive Care Admission and Unilateral Hearing Loss. *Frontiers in Pediatrics*, **10**, Article ID: 1068884. https://doi.org/10.3389/fped.2022.1068884

[10] Corbin, N.E., Buss, E. and Leibold, L.J. (2021) Spatial Hearing and Functional Auditory Skills in Children with Unilateral Hearing Loss. *Journal of Speech, Language, and Hearing Research*, **64**, 4495-4512. https://doi.org/10.1044/2021_jslhr-20-00081

[11] Brown, K.D., Dillon, M.T. and Park, L.R. (2021) Benefits of Cochlear Implantation in Childhood Unilateral Hearing Loss (CUHL Trial). *The Laryngoscope*, **132**, S1-S18. https://doi.org/10.1002/lary.29853

[12] Sheffield, S.W., Wheeler, H.J., Brungart, D.S. and Bernstein, J.G.W. (2023) The Effect of Sound Localization on Auditory-Only and Audiovisual Speech Recognition in a Simulated Multitalker Environment. *Trends in Hearing*, **27**. https://doi.org/10.1177/23312165231186040

[13] Carlini, A., Bordeau, C. and Ambard, M. (2024) Auditory Localization: A Comprehensive Practical Review. *Frontiers in Psychology*, **15**, Article ID: 1408073. https://doi.org/10.3389/fpsyg.2024.1408073

[14] Zheng, Y., Swanson, J., Koehnke, J. and Guan, J. (2022) Sound Localization of Listeners with Normal Hearing, Impaired Hearing, Hearing Aids, Bone-Anchored Hearing Instruments, and Cochlear Implants: A Review. *American Journal of Audiology*, **31**, 819-834. https://doi.org/10.1044/2022_aja-22-00006

[15] Derleth, P., Georganti, E., Latzel, M., Courtois, G., Hofbauer, M., Raether, J., *et al.* (2021) Binaural Signal Processing in Hearing Aids. *Seminars in Hearing*, **42**, 206-223. https://doi.org/10.1055/s-0041-1735176

[16] Kumpik, D.P. and King, A.J. (2019) A Review of the Effects of Unilateral Hearing Loss on Spatial Hearing. *Hearing Research*, **372**, 17-28. https://doi.org/10.1016/j.heares.2018.08.003

[17] Brown, K.D. and Balkany, T.J. (2007) Benefits of Bilateral Cochlear Implantation: A Review. *Current Opinion in Otolaryngology & Head & Neck Surgery*, **15**, 315-318. https://doi.org/10.1097/moo.0b013e3282ef3d3e

[18] Epstein, M. and Florentine, M. (2012) Binaural Loudness Summation for Speech Presented via Earphones and Loudspeaker with and without Visual Cues. *The Journal of the Acoustical Society of America*, **131**, 3981-3988. https://doi.org/10.1121/1.3701984

[19] Wick, C.C., Durakovic, N., Herzog, J.A. and Buchman, C.A. (2022) Hearing Rehabilitation Following Acoustic Neuroma Surgery. In: Bambakidis, N.C., Megerian, C.A. and Spetzler, R.F., Eds., *Surgery of the Cerebellopontine Angle*, Springer International Publishing, 157-167. https://doi.org/10.1007/978-3-031-12507-2_12

[20] Firszt, J.B., Reeder, R.M. and Holden, L.K. (2017) Unilateral Hearing Loss:

Understanding Speech Recognition and Localization Variability—Implications for Cochlear Implant Candidacy. *Ear & Hearing*, **38**, 159-173. https://doi.org/10.1097/aud.0000000000000380

[21] Fernandes, Z. (2023) Sound Localization—The Biggest Challenge for People with Unilateral Hearing OSS.

[22] Akeroyd, M.A. (2014) An Overview of the Major Phenomena of the Localization of Sound Sources by Normal-Hearing, Hearing-Impaired, and Aided Listeners. *Trends in Hearing*, **18**, 1-7. https://doi.org/10.1177/2331216514560442

[23] Valzolgher, C., Capra, S., Gessa, E., Rosi, T., Giovanelli, E. and Pavani, F. (2024) Sound Localization in Noisy Contexts: Performance, Metacognitive Evaluations and Head Movements. *Cognitive Research*: *Principles and Implications*, **9**, Article No. 4. https://doi.org/10.1186/s41235-023-00530-w

[24] Jespersen, C.T., Kirkwood, B.C. and Groth, J. (2021) Increasing the Effectiveness of Hearing Aid Directional Microphones. *Seminars in Hearing*, **42**, 224-236. https://doi.org/10.1055/s-0041-1735131

[25] Aldè, M., Zanetti, D., Ambrosetti, U., Monaco, E., Gasbarre, A.M., Pignataro, L., *et al*. (2024) Unilateral Sensorineural Hearing Loss in Children: Etiology, Audiological Characteristics, and Treatment. *Children*, **11**, Article No. 324. https://doi.org/10.3390/children11030324

[26] Shiraishi, K. (2021) Sound Localization and Lateralization by Bilateral Bone Conduction Devices, Middle Ear Implants, and Cartilage Conduction Hearing Aids. *Audiology Research*, **11**, 508-523. https://doi.org/10.3390/audiolres11040046

[27] Johnstone, P.M., Náblek, A.K. and Robertson, V.S. (2010) Sound Localization Acuity in Children with Unilateral Hearing Loss Who Wear a Hearing Aid in the Impaired Ear. *Journal of the American Academy of Audiology*, **21**, 522-534. https://doi.org/10.3766/jaaa.21.8.4

[28] An, Y., Lee, E.S., Kim, D.H., Oh, H.S., Won, J.H. and Shim, H.J. (2022) Long-Term Effects of Hearing Aid Use on Auditory Spectral Discrimination and Temporal Envelope Sensitivity and Speech Perception in Noise. *The Journal of International Advanced Otology*, **18**, 43-50. https://doi.org/10.5152/iao.2022.21228

[29] Mondelli, M.F.C.G., Santos, M.D.M.d. and Feniman, M.R. (2020) Unilateral Hearing Loss: Benefit of Amplification in Sound Localization, Temporal Ordering and Resolution. *CoDAS*, **32**, e20180202. https://doi.org/10.1590/2317-1782/20192018202

[30] Zavdy, O., Fostick, L., Fink, N., Danin, S., Levin, A., Lipschitz, N., *et al*. (2022) The Effect of Hearing Aids on Sound Localization in Mild Unilateral Conductive Hearing Loss. *Journal of the American Academy of Audiology*, **33**, 357-363. https://doi.org/10.1055/a-1889-6578

[31] Teschner, M.J., Seybold, B.A., Malone, B.J., Hüning, J. and Schreiner, C.E. (2016) Effects of Signal-to-Noise Ratio on Auditory Cortical Frequency Processing. *The Journal of Neuroscience*, **36**, 2743-2756. https://doi.org/10.1523/jneurosci.2079-15.2016

[32] Gilbert, C.D. and Sigman, M. (2007) Brain States: Top-Down Influences in Sensory Processing. *Neuron*, **54**, 677-696. https://doi.org/10.1016/j.neuron.2007.05.019

[33] Olusanya, B.O., Davis, A.C. and Hoffman, H.J. (2019) Hearing Loss Grades and the International Classification of Functioning, Disability and Health. *Bulletin of the World Health Organization*, **97**, 725-728. https://doi.org/10.2471/blt.19.230367

[34] Interacoustics 2024, BSA (2018). https://www.interacoustics.com/academy/audiometry-training/pure-tone-audiometry/pure-tone-audiometry-introduction

[35] Perkins, C.J. and Mitchell, S. (2022) Audiology Clinical Masking. StatPearls Publishing. https://www.ncbi.nlm.nih.gov/books/NBK580541/

[36] Wilcoxon, F. (1945) Individual Comparisons by Ranking Methods. *Biometrics Bulletin*, **1**, 80-83. https://doi.org/10.2307/3001968

[37] Xiao, B., Zhou, B., Ye, J., Chen, Q. and Zhang, C. (2023) On the Performance Limits of Array-Based Acoustic Source Localization. *IEEE Sensors Journal*, **23**, 23303-23316. https://doi.org/10.1109/jsen.2023.3303216

[38] Haragopal, H., Dorkoski, R., Pollard, A.R., Whaley, G.A., Wohl, T.R., Stroud, N.C., *et al*. (2020) Specific Loss of Neural Sensitivity to Interaural Time Difference of Unmodulated Noise Stimuli Following Noise-Induced Hearing Loss. *Journal of Neurophysiology*, **124**, 1165-1182. https://doi.org/10.1152/jn.00349.2020

[39] Nearity Team (2024) The Importance of Noise Reduction in Hearing Aids: How to Reduce Background Noise. https://www.nearity.co/blog/the-importance-of-noise-reduction-in-hearing-aids

[40] Dincer D'alessandro, H., Sennaroğlu, G., Yücel, E., Belgin, E. and Mancini, P. (2015) Gli effetti squelch binaurale e ombra nei bambini con impianto cocleare monolaterale e protesi acustica controlaterale. *Acta Otorhinolaryngologica Italica*, **35**, 343-349. https://doi.org/10.14639/0392-100x-497

[41] Loiselle, L.H., Dorman, M.F., Yost, W.A., Cook, S.J. and Gifford, R.H. (2016) Using ILD or ITD Cues for Sound Source Localization and Speech Understanding in a Complex Listening Environment by Listeners with Bilateral and with Hearing-Preservation Cochlear Implants. *Journal of Speech, Language, and Hearing Research*, **59**, 810-818. https://doi.org/10.1044/2015_jslhr-h-14-0355

[42] Ha, J., Kim, H., Lee, J.H. and Park, H.Y. (2022) Sound Localization in Patients with a Unilateral Hearing Aid: Discordance between the Right and Left Ears. *Laryngoscope Investigative Otolaryngology*, **7**, 599-603. https://doi.org/10.1002/lio2.769

[43] Ellinger, R.L., Jakien, K.M. and Gallun, F.J. (2017) The Role of Interaural Differences on Speech Intelligibility in Complex Multi-Talker Environments. *The Journal of the Acoustical Society of America*, **141**, EL170-EL176. https://doi.org/10.1121/1.4976113

[44] Armstrong, A.G., Lam, C.C., Sabesan, S. and Lesica, N.A. (2021) Compression and Amplification Algorithms in Hearing Aids Impair the Selectivity of Neural Responses to Speech. *Nature Biomedical Engineering*, **6**, 717-730. https://doi.org/10.1038/s41551-021-00707-y

[45] May, T., Kowalewski, B. and Dau, T. (2020) Scene-aware Dynamic-Range Compression in Hearing Aids. In: Blauert, J. and Braasch, J., Eds., *The Technology of Binaural Understanding*, Springer International Publishing, 763-799. https://doi.org/10.1007/978-3-030-00386-9_25

[46] Kerber, S. and Seeber, B.U. (2012) Sound Localization in Noise by Normal-Hearing Listeners and Cochlear Implant Users. *Ear & Hearing*, **33**, 445-457. https://doi.org/10.1097/aud.0b013e318257607b

[47] Spencer, N.J., Tillery, K.H. and Brown, C.A. (2019) The Effects of Dynamic-Range Automatic Gain Control on Sentence Intelligibility with a Speech Masker in Simulated Cochlear Implant Listening. *Ear & Hearing*, **40**, 710-724. https://doi.org/10.1097/aud.0000000000000653

[48] Wu, Y., Stangl, E., Chipara, O., Hasan, S.S., Welhaven, A. and Oleson, J. (2018) Characteristics of Real-World Signal to Noise Ratios and Speech Listening Situations of Older Adults with Mild to Moderate Hearing Loss. *Ear & Hearing*, **39**, 293-304. https://doi.org/10.1097/aud.0000000000000486

[49] Marin-Hurtado, J.I. and Anderson, D.V. (2012) Preservation of Localization Cues in BSS-Based Noise Reduction: Application in Binaural Hearing Aids. In: Naik, G.R., Ed., *Independent Component Analysis for Audio and Biosignal Applications*, InTech, 209 p. https://doi.org/10.5772/48241

[50] Llave, A., Leglaive, S. and Séguier, R. (2020) Localization Cues Preservation in Hearing Aids by Combining Noise Reduction and Dynamic Range Compression. 2020 *Asia-Pacific Signal and Information Processing Association Annual Summit and Conference* (*APSIPA ASC*), Auckland, 7-10 December 2020, 686-693. https://ieeexplore.ieee.org/abstract/document/9306420

[51] Kolarik, A.J., Moore, B.C.J., Zahorik, P., Cirstea, S. and Pardhan, S. (2015) Auditory Distance Perception in Humans: A Review of Cues, Development, Neuronal Bases, and Effects of Sensory Loss. *Attention*, *Perception*, *& Psychophysics*, **78**, 373-395. https://doi.org/10.3758/s13414-015-1015-1

[52] Oxenham, A.J. (2018) How We Hear: The Perception and Neural Coding of Sound. *Annual Review of Psychology*, **69**, 27-50. https://doi.org/10.1146/annurev-psych-122216-011635

[53] National Guideline Centre (UK) (2018) Hearing Loss in Adults: Assessment and Management. National Institute for Health and Care Excellence (NICE). https://www.ncbi.nlm.nih.gov/books/NBK536536/

[54] Nelissen, R.C., Agterberg, M.J.H., Hol, M.K.S. and Snik, A.F.M. (2016) Three-Year Experience with the Sophono in Children with Congenital Conductive Unilateral Hearing Loss: Tolerability, Audiometry, and Sound Localization Compared to a Bone-Anchored Hearing Aid. *European Archives of Oto-Rhino-Laryngology*, **273**, 3149-3156. https://doi.org/10.1007/s00405-016-3908-6

[55] Lawrence, B.J., Jayakody, D.M.P., Henshaw, H., Ferguson, M.A., Eikelboom, R.H., Loftus, A.M., *et al*. (2018) Auditory and Cognitive Training for Cognition in Adults with Hearing Loss: A Systematic Review and Meta-Analysis. *Trends in Hearing*, **22**. https://doi.org/10.1177/2331216518792096