Auditory and Vestibular Research

Intensity as the Dominant Cue for Minimum Audible Angle in Young Adults

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Highlights

- Stimulus intensity is the strongest predictor of minimum audible angle
- Spectrally rich complex tones improve auditory spatial discrimination
- Virtual spatial audio provides a valid tool for assessing Minimum Audible Angle

Abstract

Background and Aim: The Minimum Audible Angle (MAA), defined as the minimum perceivable angular disparity among sound sources, is the most frequently used measure of spatial acuity in psychophysics. While conventionally free-field loudspeaker arrangements measure MAA, virtual auditory methods offer flexible alternatives. The study aimed to determine which stimulus characteristic—intensity level, type, or duration—most influences MAA in normally hearing young adults.
Methods: Using a repeated-measures design with 30 healthy adults aged 18-30 years, spatialized stimuli generated by the 3D Tune-In Toolkit were presented over headphones at three levels (45-, 55-, and 65-dB SPL), durations (250, 500, and 1000 ms), and stimulus types (complex tone, pure tone, and white band noise). MAA thresholds were determined using a psychometric staircase procedure with a two-down one-up rule in a three-interval forced-choice task.
Results: Three-way repeated-measures ANOVA showed significant main effects of stimulus type and intensity level ($p < 0.001$), while duration had no significant effect but interacted with level and stimulus type ($p < 0.001$). Post hoc comparisons revealed eight significant stimulus-type pairs and nine level pairs after Bonferroni correction ($\alpha = 0.02$), with complex tones and higher intensity producing lower MAA thresholds. Multiple regression showed only stimulus intensity significantly predicted MAA.
Conclusion: The findings demonstrate that higher intensities yield optimal spatial acuity and confirm the reliability of virtual headphone-based methods.
Keywords: Minimum Audible Angle; Spatial Hearing; Virtual Acoustics; Stimulus Complexity.

Introduction

The precise localization of sounds by the human auditory system underlies efficient interaction with the environment. One of the most common psychoacoustic tests for auditory spatial resolution measurement is the Minimum Audible Angle (MAA), which is defined as the minimal inter-source angular distance that a listener can differentiate with reliability. The MAA indirectly gauges listener's sensitivity to interaural time differences (ITDs) and interaural level differences (ILDs), which are cues to localization in the horizontal plane.

Scientists have explored a range of stimuli for measuring MAA, including pure tones, broadband noise, and more ecologically relevant complex sounds [1]. Their findings revealed that spatial acuity is considerably affected by the temporal properties of a stimulus, such as sound duration, rather than its frequency-related characteristics. Shorter sound durations can elevate MAA thresholds because they do not allow time for the auditory system to completely process binaural cues [2]. Perrott and Saberi [1] also reported better spatial localization performance with increased duration of stimuli, emphasizing that spatial perception requires temporal windows. In addition, factors such as intensity and plane of presentation influence spatial

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discrimination. Although higher intensities may enhance the salience of interaural differences, they can also increase masking or loudness summation, resulting in nonlinear changes in spatial acuity [3]. Mills [4] was one of the earliest researchers to report that spatial discrimination improved with increasing intensity in the range of approximately 50 dB sensation level (SL) above the minimum audible field. Similarly, Perrott and Saberi in 1990 found that increasing presentation levels (intensity) reduced MAA thresholds in free-field conditions, with stimuli presented at a 52 dB A-weighted sound pressure level (SPL). More recently, [5,6] reported that stimulus intensity significantly influenced MAA thresholds in headphone-based virtual environments, particularly at the midline azimuths. MAA thresholds are typically lowest (i.e., best) when sound is from frontal locations and linearly it gets poorer/increase in the lateral and rear directions [3,4,]. This directional dependence, or anisotropy, is attributed to head geometry, which creates an acoustic shadow that affects the availability and reliability of binaural cues.

MAA can be measured using two main approaches: in the free-field (real) using loudspeakers, and in closed-field or virtual settings using headphones. In free-field methods, participants are situated in a sound-treated room surrounded by spatially oriented loudspeaker arrays that emit sound stimuli [1,4]. In contrast, the virtual approach involves delivering spatialized audio through headphones using individualized or generic Head-Related Transfer Functions (HRTFs) to simulate sound source positions in space [5,6,7]. With advances in virtual auditory environments, databases of HRTFs have facilitated the stimulation of spatial audio over headphones. Several widely used HRTF datasets include ambisonics-based rendering, the CIPIC database, and the LISTEN HRTF database [8]. High-fidelity simulation software such as SPARTA , SLAB 3D, and 3D Tune-In Toolkit (3DTI) [9] now provide researchers with precise control over spatial presentation and stimulus generation, enabling highly reproducible and adaptable auditory testing paradigms [5,10]. Utilizing this technique, we assessed MAA thresholds in normal-hearing listeners as a function of varying intensity levels, durations, and types of stimuli.

The study has three primary objectives: 1) to identify the auditory state(s) that produce the lowest MAA thresholds, indicating optimal conditions for assessing auditory spatial resolution; 2) to examine the extent to which stimulus intensity, stimulus type, and stimulus duration influence MAA; and 3) to determine the combination of these factors that most effectively enhances spatial discrimination in normal-hearing individuals. By systematically varying these acoustic parameters and measuring their effects on spatial acuity, this study aims to advance the understanding of auditory spatial processing. This knowledge can help design training protocols and auditory displays for both technological and clinical applications.

Methods

Research design: A within-subject design with purposive sampling was used.

Participants

A total of 30 clinically normal-hearing young adult participants aged 18 to 28 years (mean age: 22.4 years) volunteered for the study. Recruitment was carried out via notices posted in the campus buildings of the institute, and informed consent was provided by all participants after a description of the purpose and nature of the experiment. Consistent with conventional recommendations and previous psychoacoustic and spatial hearing studies, a sample size of 30 participants was considered adequate to allow stable estimation of effects and to provide acceptable statistical power for within-subject experimental designs. Ethical committee approval was obtained from the Institutional Review Board (no. SH/IRB/M.1-20-2024-25). Participation was voluntary.

The inclusion criteria were as follows: young adults aged 18–28 years with normal hearing who volunteered to participate in all testing conditions, had no prior auditory training, and were naïve to MAA tasks. Pure-tone audiometry was performed using the modified Hughson-Westlake method with a step size of 5 dB. Air-conduction thresholds were obtained using TDH-39 supra-aural headphones in a sound-treated room that conformed to ANSI standards. Individuals with pure-tone hearing thresholds within 15 dB HL at octave frequencies in the range of 250–8000 Hz in both ears were included in the study. Only participants with symmetrical hearing were included, defined as interaural threshold differences of ≤ 10 dB HL at octave

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frequencies from 250 Hz to 8000 Hz [11,12]. The mean thresholds of the participants for both ears across the audiometric frequency range are shown in Figure 1.

None of the participants had a history of ear disease, neurological disorders, or ototoxic drug use. None of them had undergone any auditory, yoga, or musical training that might benefit spatial processing. The entire testing was performed in a sound-treated room meeting ANSI standards for levels of ambient noise, and each session took approximately 90 to 120 minutes, including breaks and familiarization.

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Stimuli

Three stimulus types were selected to represent increasing levels of spectral richness and ecological validity in the study. The first was a pure tone at a frequency of 500 Hz, a tone positioned in the low-frequency region, in which interaural time differences (ITDs) are most noticeable for localization [13]. Pure tones have a controlled frequency make-up, but because they only have limited spectral cues, they can limit fine-grained localization [14]. The second was a complex tone with multiple pure-tone components from 300 to 1000 Hz in steps of 100 Hz. This was designed to mimic a more natural sound with some spectral complexity, which allows both ITDs and interaural level differences (ILDs) to operate [15]. The third was white noise, which was characterized by a broad, flat spectral pattern over frequencies. White band noise stimuli have great value in spatial experiments because they provide rich binaural cues, and in most cases, they are accompanied by the highest localization accuracy because a high range of frequency-based spatial information is available [16]. The spectra corresponding to each of the three stimulus variants are presented in Figure 2.

To investigate the extent to which temporal summation occurs over time, each type of stimulus was presented for three durations: 250, 500, and 1000 ms. These time frames were used to include a perceptually meaningful range of short-to-moderately long auditory events [1]. By comparing these three-time windows, the current study sought to identify potential gains in spatial resolution as a function of extended time availability. In addition to temporal modifications, stimuli also varied in three intensity levels: 45 dB SPL, 55 dB SPL, and 65 dB SPL. The levels were calibrated in RMS SPL using a precision sound level meter coupled to an artificial ear coupler matched to that used in the experiment. The rationale for presenting more than one level was to determine whether higher levels improved spatial discrimination by making interaural level differences and interaural time differences more noticeable or whether higher levels could introduce the effects of masking or loudness summation to compromise performance. The levels used were comfortably within the range of all participants and were in agreement with previous experiments investigating the effects of intensity on auditory spatial resolution.

All stimuli were spatially produced using the 3D Tune-In Toolkit, a computer-based virtual auditory environment system that enables real-time binaural spatialization using nonindividualized head-related transfer functions (HRTFs). The toolkit supports flexible stimulus control and integration with external software, such as MATLAB, and is capable of simulating azimuthal sound locations across the horizontal plane. In the present study, all three stimuli were first generated using Adobe Audition (Adobe Systems Inc., 2024). Spatial simulation was performed using the Listen HRTF dataset within the 3D Tune-In Toolkit, applying a source-image model to render static azimuthal locations across the horizontal plane without reverberation or head-tracking. Totally 13 spatialized stimuli were generated limited to the horizontal plane, with discrete azimuth positions ranging from 0° (midline), 1^0, 2^0, 3^0, 4^0, 5^0, 10^0, 15^0, 20^0, 25^0, 30^0, 35^0 and 40° to simulate varying inter-source angles in the frontal plane. All audio files were saved in an uncompressed ".wav" format at a sampling rate of 44.1 kHz and 16-bit resolution to ensure high-fidelity. Calibration was performed using a Brüel & Kjær Type 1 precision sound level meter (Model 831C; Brüel & Kjær, Denmark) with the headphone placed over a 6cc coupler and sealed using an external weight. The stimuli were played through a laptop, and output levels of 45-, 55-, and 65-dB SPL were verified by adjusting the laptop volume based on the SLM readings.

For each condition in the current study, spatialized stimuli were presented through a user-built MATLAB interface. A full factorial design was implemented, comprising 27 distinct auditory conditions (three stimulus types × three durations × three intensity levels). The presentation order was randomized across the trials to reduce the order effects. In each condition, totally This comprehensive setup enabled a systematic evaluation of how each acoustic parameter and its interactions influence MAA thresholds in young adults with normal hearing.

Equipment and procedure

Experiments were conducted in the Psychoacoustic Acoustic Laboratory at the Department of Audiology of the institute. Ambient noise levels were continuously monitored to ensure that they remained below 30 dB(A) using the NEERI Sound Level Meter mobile application (Version 5), developed by the CSIR–National Environmental Engineering Research Institute (NEERI), Nagpur and the NEERI Sound Level Meter mobile application (Version 5) was used only for preliminary monitoring of sound levels. Final calibration and verification of stimulus intensity were performed using a calibrated professional sound level meter (Model 831C; Brüel & Kjær, Denmark). The SLM-based measurements were used as the reference standard to ensure accurate and reliable sound pressure level verification. Mobile application measurements were not used for final calibration decisions. As mentioned before, experiments were conducted in Psychoacoustic Lab of institute which is one of the best labs in INDIA, so the ambient noise levels were strictly followed and the app is used just comparison and for normal feedback. Stimulus presentation and response recording were performed using a customized program with a graphical user interface implemented in MATLAB (version R2024b, The MathWorks Inc., Natick, MA). Modular MATLAB functions managed the stimulus selection, trial randomization, adaptive control, and real-time feedback.

Spatialized auditory stimuli were delivered via Sennheiser HD 280 Pro circumaural headphones through a 6.3 mm jack adapter. The headphones had a dynamic, closed-back design with a frequency response of 8 Hz to 25000 Hz, a maximum sound pressure level of up to 113 dB SPL at a frequency of 1 kHz, a distortion level of less than 0.1%, and an impedance of 64 ohms. Before each testing session, the headphones were calibrated using a Type 1 precision sound level meter with an artificial ear coupler connected to an SLM (Knowles) to accurately produce target sound pressure levels (45, 55, and 65-dB SPL). The participants sat comfortably facing a computer screen, maintaining a natural, fixed head posture throughout the testing. Head movements were not permitted during the stimulus presentation but were allowed during the response acquisition phase. On-screen instructions at the commencement of each block and feedback indicating the accuracy of responses after each trial were used to maintain engagement in the task.

The experimental procedure comprised two phases: familiarization and testing. During the familiarization phase, the participants completed a psychoacoustic three-alternative forced-choice (3 AFC) task in which they were instructed to identify the sound source that differed in lateralization from a reference standard (0^0). From the stimulus module, a random ".wav" file corresponding to one of the 27 conditions (three stimulus types × three durations × three intensity levels) was chosen randomly and presented to the participant. Four reversals were employed to verify the participants' understanding of the task and response method. The participants received immediate visual feedback after each response to support learning and orientation. A schematic overview of the procedure used to track the MAA thresholds is shown in Figure 3.

In the test phase, the same 3 AFC paradigm was applied, using a 2-down, 1-up staircase adaptive tracking procedure [17], to converge on the MAA threshold at 70.7% of the correct responses. The participant was asked to select the trail that produced lateralization, different from the midline (0^0) standard stimulus. This was performed using a mouse click. The condition order was randomized by a trial controller to ensure balanced occurrence across trials.

The task began with stimuli that had a larger angular separation between the sound sources. The task started with 20^0 angle separation. If the participant responded correctly, the angular separation between the stimuli was reduced to a smaller degree difference to 15^0 angles in the subsequent trial with 5^0 angle decrements and then to 1^0 decrements, increasing task difficulty. Conversely, for incorrect responses, the angular separation was increased by 5^0 angles, making the task easier. This adaptive staircase procedure was continued until ten reversals were obtained. A reversal was defined as the point at which the adjustment direction of angular separation changed from increasing to decreasing or vice versa, based on participant responses. Participants continued to respond using the 3 AFC method until 10 reversals, and immediate visual feedback was provided after each response to maintain engagement and task accuracy. The last four reversals were averaged to obtain the MAA threshold. The behavioral data were logged automatically and stored in an Excel sheet for later analysis.

Data Analysis

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Data analyses were conducted using the Statistical Package for the Social Sciences (SPSS) version 26. Normality in the distribution of data was determined using the Shapiro–Wilk test. The main effects of stimulus type, duration, and intensity level, as well as their interactions, on the MAA threshold were evaluated using a three-way repeated-measures ANOVA (3 stimulus types × 3 durations × 3 intensity levels). Effect sizes (η_p^2) were reported for all significant main and interaction effects. Wherever appropriate, post-hoc pairwise comparisons were performed using paired t-tests with Bonferroni correction for multiple comparisons. A multiple linear regression analysis was conducted to examine the extent to which stimulus intensity, stimulus type, and stimulus duration predicted MAA.

Results

A two-way analysis of variance (ANOVA) with frequency and ears as fixed factors and participant thresholds as a random factor revealed no significant main [Ear: $F(1,31) = < 0.001$, $p = 0.985$; Frequency: $F(5, 155) = 0.134$, $p = 0.984$] and interaction [Ear × Frequency: $F(5,155) = 0.030$, $p = 1.00$] effects, indicative of symmetrical hearing thresholds between the two ears across frequencies.

Shapiro Wilk's test revealed that the data was normally distributed ($p > 0.05$). The descriptive statistics, including the mean and standard deviation for the three factors (stimulus type, duration, and intensity level), are depicted in Figure 4. MAA thresholds decreased with increasing SPL and stimulus duration under all conditions. Among the stimulus types, complex stimuli consistently yielded lower thresholds than pure tones and white band noise. The white band noise showed the highest thresholds, especially at lower SPLs.

The results of the three-way repeated-measures ANOVA revealed a significant main effect of intensity [F (2,58) – 25.66, η_p^2 – 0.47] and stimulus type [F (2,58) – 10.23, η_p^2 – 0.26] on the MAA thresholds. However, the main effect of duration was not statistically significant ($p > 0.05$). Among the interaction effects, a significant interaction between intensity and stimulus type was observed. Additionally, a significant three-way interaction was found between stimulus type, duration, and intensity level. No significant interaction was observed between the stimulus type and duration or between the duration and intensity level.

To further examine the most effective stimuli that yielded the lowest MAA, specific condition-level differences were analyzed using post hoc paired-sample *t*-tests across all possible combinations of stimulus and intensity levels (i.e., 27 stimulus-type pairs and 27 intensity level pairs), and the results are shown in Tables 1 and 2. A Bonferroni correction was applied to adjust for multiple comparisons, resulting in an adjusted significance threshold of $\alpha = 0.0166$. Among the stimulus-type comparisons, eight pairs showed statistically significant differences. Similarly, for the presentation-level comparisons, nine pairs were found to be statistically significant. The remaining comparisons did not reach an adjusted level of significance.

On multiple linear regression analysis, the regression model was statistically significant, $F(3, 806) = 8.692$, $p < .001$, but accounted for only 3.1% of the variance in MAA scores ($R^2 = .031$, adjusted $R^2 = .028$). Examination of the predictors revealed that intensity level was a significant predictor of MAA ($\beta = –0.170$, $p < .001$) whereas stimulus type ($\beta = 0.037$, $p = .286$) and stimulus duration ($\beta = –0.034$, $p = .328$) were not statistically significant. These findings suggest that higher intensities are associated with smaller MAA values.

Discussion

The findings of the present study confirm and extend prior observations that MAA decreases with increasing stimulus level. Importantly, by adopting a multifactorial design and rigorous calibration procedures, we demonstrate how the effects of stimulus type and duration modulate this level effect, offering novel insights that build on the work of [18] and other spatial hearing investigations. These detailed patterns of effects enhance our understanding of auditory spatial discrimination beyond simple level dependence. Although minimum audible angle (MAA) is classically defined for small angular deviations near the midline, larger azimuthal positions were incorporated in the present study to facilitate perceptual anchoring and stable spatial reference during adaptive tracking. The adaptive procedure adjusted angular separation relative to a reference position, allowing estimation of discrimination thresholds while maintaining perceptual clarity across conditions. The inclusion of larger azimuths ensured robust spatial perception and reduced uncertainty in virtual spatial rendering.

The Minimum Audible Angle (MAA) task, originally specified by Mills [4], is one of the most consistent psychoacoustic measures for auditory spatial resolution assessment. Early studies in free-field conditions

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reported MAA thresholds as low as 1° under optimal conditions using pure tones of frontal azimuth. Recent studies have investigated the applicability of the MAA in headphone-based virtual environments using spatial simulation software with head-related transfer functions (HRTFs). [5] achieved average MAA thresholds of 5.6° (±7.3°) at 0° azimuth with headphone-based testing using 300–1200 Hz broadband noise, reporting these findings to be equivalent to free-field testing with KEMAR dummy-head recordings. Similarly, [19] utilized amplitude-based virtual panning methods and reported MAA values of 1.1° for broadband stimuli in young adults. These findings attest to the consistency of headphone-based MAA tests as an alternative to traditional loudspeaker arrays, offering portability and environmental control benefits with minimal compromise in the accuracy of spatial discrimination measurements.

The present study demonstrated a clear improvement in spatial discrimination with increasing intensity level, with 65 dB SPL yielding significantly lower MAA thresholds than 45 and 55 dB SPL. Mills [4] initially demonstrated that increased intensity enhances spatial resolution, attributing it to the greater salience of ILD cues. Similarly, [1] described nonlinear relationships in which spatial performance improved with intensity until an asymptote. At higher sound levels, more auditory nerve fibers are recruited and fire at higher rates, improving the encoding of ITDs and ILDs. Increased intensity also sharpens phase-locking and synchrony across neurons within the superior olivary complex and inferior colliculus, both of which are critical for spatial cue integration [20]. [5] documented that stimulus intensity modulated headphone-based MAA performance, particularly near the midline.

However, not all studies have reported a consistent benefit of increased intensity on spatial acuities. For example, [6] found that improvements in localization with higher levels were minimal beyond a certain threshold, particularly for complex or broadband stimuli. [2] also observed that intensity level did not significantly impact MAA in some conditions, suggesting that binaural processing may reach a ceiling effect with moderately intense stimuli. These contrasting findings indicate that while increased loudness often enhances localization, the relationship is not strictly linear and may depend on the stimulus type, azimuth, or individual listener factors. The present findings reaffirm the general trend toward improved spatial resolution at higher intensities but should be interpreted in light of these considerations.

The nature of the stimulus had a significant effect on MAA thresholds, with complex tones eliciting the best (lowest) thresholds, followed by white band noise (WBN) and pure tones. As shown in Figure 2, the pure tone (A) displays a single frequency component, the complex tone (B) comprises harmonics, and the white band noise (C) exhibits a broad and dense spectral distribution. Complex tones and WBN stimulate broader regions of the cochlea, enhancing the availability of ITDs and ILDs by engaging a wider range of auditory nerve fibers [3,19,21]. This differential cochlear activation is further integrated into the inferior colliculus, which is sensitive to spectral and temporal binaural cues for localization, resulting in better spatial resolution with spectral richness. In contrast, pure tones activate confined cochlear regions, thereby offering limited spatial information. Both noise-oriented and complex stimuli demonstrate better MAA performance in young and older adults than narrowband or pure-tone stimuli. The poorer performance with WBN in the present study may indicate a lack of spectral specificity or susceptibility to temporal masking in the virtual environment. Although broadband noise is typically associated with optimal spatial resolution in free-field conditions due to the availability of wide-band spectral and temporal cues, the present findings demonstrated improved MAA performance with complex tones compared to white band noise. Several factors may account for this observation. First, spectral weighting effects may have enhanced the salience of interaural time difference (ITD) cues within specific frequency regions of the complex tones, potentially leading to more robust binaural processing. Second, stimulus rendering through non-individualized HRTFs may have altered the spectral cues available in the broadband noise condition, thereby reducing the effective spatial information conveyed. In headphone-based virtual spatial paradigms, inaccuracies in individualized pinna filtering can disproportionately affect broadband stimuli. Third, complex tones may provide more stable phase relationships across frequency components, potentially enhancing temporal fine-structure processing and spatial discrimination under controlled laboratory conditions. Together, these factors may explain why complex tones yielded superior MAA performance in the present study despite traditional expectations favoring broadband noise.

Although the duration variable did not produce a statistically significant main effect in this experiment, it was revealed to interact with other parameters. This aligns with the temporal coding properties of the auditory system, where temporal summation saturates beyond approximately 300 ms [22]. This may limit

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the spatial benefits of longer durations. Spatial cues are primarily extracted within the early part of the stimulus, as binaural processing in the brainstem relies on rapid, synchronized inputs [20], making extended durations less critical once sufficient temporal information becomes available.

A significant three-way interaction was found between stimulus type, intensity, and duration, suggesting that the finest spatial resolution is obtained through a combination of spectrally different stimuli at high intensities for adequate durations. Complex tones at 65 dB SPL intensity and 500 ms duration, for instance, yielded some of the optimal Minimum Auditable Angle (MAA) thresholds. These findings are consistent with the multidimensional nature of spatial hearing, where temporal, frequency, and intensity cues interact to permit precise localization [1,3]. This result is highly applicable to virtual and clinical tests of spatial hearing, where optimized sets of these parameters can maximize test sensitivity. Regression analysis indicated that among the tested parameters, only stimulus intensity significantly predicted MAA, with higher intensities yielding smaller audible angles. Stimulus type and duration did not emerge as meaningful predictors, suggesting their limited role in influencing localization accuracy within the tested range.

Although the regression model was statistically significant, the predictors accounted for only 3.1% of the variance in MAA, indicating that the tested stimulus parameters explain only a small proportion of individual differences in spatial acuity. This finding is consistent with previous reports that MAA is influenced more strongly by listener-specific factors—such as age, audiometric thresholds, binaural cue sensitivity, and cognitive abilities—than by basic manipulations of stimulus intensity, spectral content, or duration. Other variables not examined here, individualized head-related transfer function (HRTF) characteristics, and training effects, are also known to modulate spatial localization accuracy and may account for the remaining variance [18,23]. The present results therefore suggest that, while stimulus intensity exerts a measurable influence on MAA, comprehensive prediction models will require the integration of both stimulus- and listener-related factors. Although stimulus intensity was identified as a statistically significant predictor, the regression model accounted for only a limited proportion of the overall variance in MAA performance. This suggests that spatial discrimination is influenced by additional factors beyond stimulus-level characteristics. Listener-related variables, including individual differences in binaural sensitivity, temporal fine-structure processing, attentional mechanisms, and spatial cue integration strategies, are likely to contribute substantially to variability in MAA thresholds. Such inter-individual differences are well documented in spatial hearing literature and may explain the residual variance observed in the present study.

Conclusion

This study clarifies the strong effects of stimulus type and intensity level on MAA thresholds in young adults with normal hearing, with complex tones and high intensity levels being determinants of the best spatial discrimination abilities. Although duration per se had no effect on MAA thresholds, its interaction with other acoustic parameters suggests an advanced spatial auditory processing function. These findings further attest to the validity of virtual auditory simulations, in this instance, headphone-based MAA measurement, as a valid and practical means of assessing spatial hearing. The results highlight the diagnostic utility of using complex stimuli for MAA to best gauge spatial resolution. A limitation of the present study is that it used generic (nonindividualized) head-related transfer functions (HRTFs), which can reduce spatial realism in certain listeners. Future studies should focus on the benefits of using individualized HRTFs, age differences, and performance in noisy real-world environments.

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Author declarations

Conflicts of interest: The author/s have no conflicts of interest to disclose regarding this article.

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References

1. Perrott DR, Saberi K. Minimum audible angle thresholds for sources varying in both elevation and azimuth. J Acoust Soc Am. 1990;87(4):1728-31. [DOI:10.1121/1.399421]
2. Strybel TZ, Fujimoto K. Minimum audible angles in the horizontal and vertical planes: effects of stimulus onset asynchrony and burst duration. J Acoust Soc Am. 2000;108(6):3092-5. [DOI:10.1121/1.1323720]
3. Grantham DW, Hornsby BW, Erpenbeck EA. Auditory spatial resolution in horizontal, vertical, and diagonal planes. J Acoust Soc Am. 2003;114(2):1009-22. [DOI:10.1121/1.1590970]
4. Mills AW. On the Minimum Audible Angle. J Acoust Soc Am. 1958;30:237-46. [DOI:10.1121/1.1909553]
5. Alzaher M, Serrano P, Tardieu J, Barone P, Marx M, Nieto P. Contribution of a method of assessing minimum audible angle in headphones. Eur Ann Otorhinolaryngol Head Neck Dis. 2021;138(5):333-6. [DOI:10.1016/j.anorl.2020.12.006]
6. Alzaher M, Valzolgher C, Verdelet G, Pavani F, Farnè A, Barone P, et al. Audiovisual Training in Virtual Reality Improves Auditory Spatial Adaptation in Unilateral Hearing Loss Patients. J Clin Med. 2023;12(6):2357. [DOI:10.3390/jcm12062357]
7. Rønne FM, Laugesen S, Jensen NS, Pedersen JH. Minimum Audible Angles Measured with Simulated Normally-Sized and Oversized Pinnas for Normal-Hearing and Hearing-Impaired Test Subjects. Adv Exp Med Biol. 2016;894:207-17. [DOI:10.1007/978-3-319-25474-6_22]
8. Kayser H, Ewert SD, Anemüller J, Rohdenburg T, Hohmann V, Kollmeier B. Database of multichannel in-ear and behind-the-ear head-related and binaural room impulse responses. EURASIP J Adv Signal Process. 2009;2009(1):298605. [DOI:10.1155/2009/29860]
9. Cuevas-Rodríguez M, Picinali L, González-Toledo D, Garre C, de la Rubia-Cuestas E, Molina-Tanco L, et al. 3D Tune-In Toolkit: An open-source library for real-time binaural spatialisation. PLoS One. 2019;14(3):e0211899. [DOI:10.1371/journal.pone.0211899]
10. Meng R, Xiang J, Sang J, Zheng C, Li X, Bleeck S, et al. Investigation of an MAA Test With Virtual Sound Synthesis. Front Psychol. 2021;12:656052. [DOI:10.3389/fpsyg.2021.656052]
11. Shub DE, Carr SP, Kong Y, Colburn HS. Discrimination and identification of azimuth using spectral shape. J Acoust Soc Am. 2008;124(5):3132-41. [DOI:10.1121/1.2981634]
12. Thavam S, Dietz M. Smallest perceivable interaural time differences. J Acoust Soc Am. 2019;145(1):458. [DOI:10.1121/1.5087566]
13. Smith RC, Price SR. Modelling of human low frequency sound localization acuity demonstrates dominance of spatial variation of interaural time difference and suggests uniform just-noticeable differences in interaural time difference. PLoS One. 2014;9(2):e89033. [DOI:10.1371/journal.pone.0089033]
14. Macpherson EA, Middlebrooks JC. Listener weighting of cues for lateral angle: the duplex theory of sound localization revisited. J Acoust Soc Am. 2002;111(5 Pt 1):2219-36. [DOI:10.1121/1.1471898]
15. Horvath D, Lesica NA. The effects of interaural time difference and intensity on the coding of low-frequency sounds in the mammalian midbrain. J Neurosci. 2011;31(10):3821-7. [DOI:10.1523/JNEUROSCI.4806-10.2011]
16. Leino S, May PJ, Alku P, Liikkanen LA, Tiitinen H. The contribution of high frequencies to human brain activity underlying horizontal localization of natural spatial sounds. BMC Neurosci. 2007;8:78. [DOI:10.1186/1471-2202-8-78]
17. Levitt H. Transformed up-down methods in psychoacoustics. J Acoust Soc Am. 1971;49(2):Suppl 2:467+. [DOI:10.1121/1.1912375]
18. Romigh GD, Brungart DS, Stern RM, Simpson BD. Efficient Real Spherical Harmonic Representation of Head-Related Transfer Functions. IEEE J. Sel. Top. Signal Process. 2015;9(5):921-30. [DOI:10.1109/JSTSP.2015.2421876]
19. Liberman MC, Dodds LW. Single-neuron labeling and chronic cochlear pathology. III. Stereocilia damage and alterations of threshold tuning curves. Hear Res. 1984;16(1):55-74. [DOI:10.1016/0378-5955(84)90025-x]
20. Joris P, Yin TC. A matter of time: internal delays in binaural processing. Trends Neurosci. 2007;30(2):70-8. [DOI:10.1016/j.tins.2006.12.004]
21. Yin TCT, Smith PH, Joris PX. Neural Mechanisms of Binaural Processing in the Auditory Brainstem. Compr Physiol. 2019;9(4):1503-75. [DOI:10.1002/cphy.c180036]
22. Zwislocki J. Theory of Temporal Auditory Summation. J Acoust Soc Am. 1960;32(8):1046-60. [DOI:10.1121/1.1908276]
23. Planinec V, Planinec V, Reijniers J, Horvat M, Jambrošić K. The Accuracy of Dynamic Sound Source Localization and Recognition Ability of Individual Head-Related Transfer Functions in Binaural Audio Systems with Head Tracking. Appl Sci. 2023;13(9):5254. [DOI:10.3390/app13095254]

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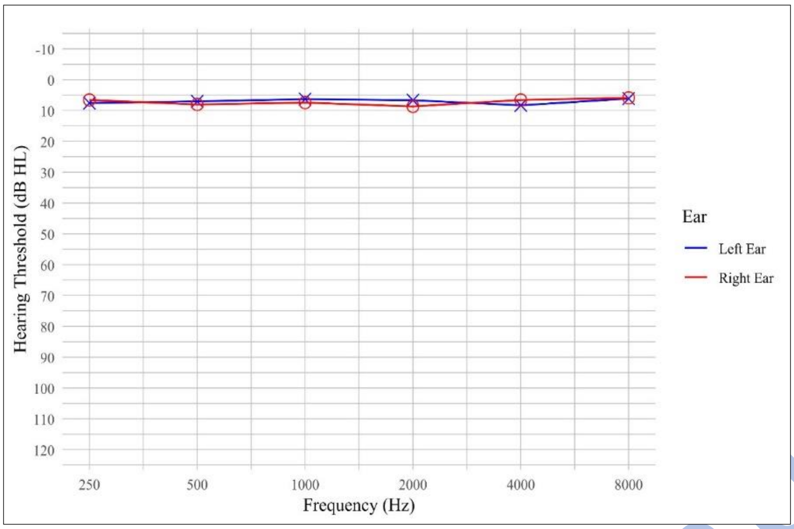

Fig 1. Mean Pure-Tone Audiogram for 30 participants Showing Average Hearing Thresholds Across Frequencies for Left and Right Ears

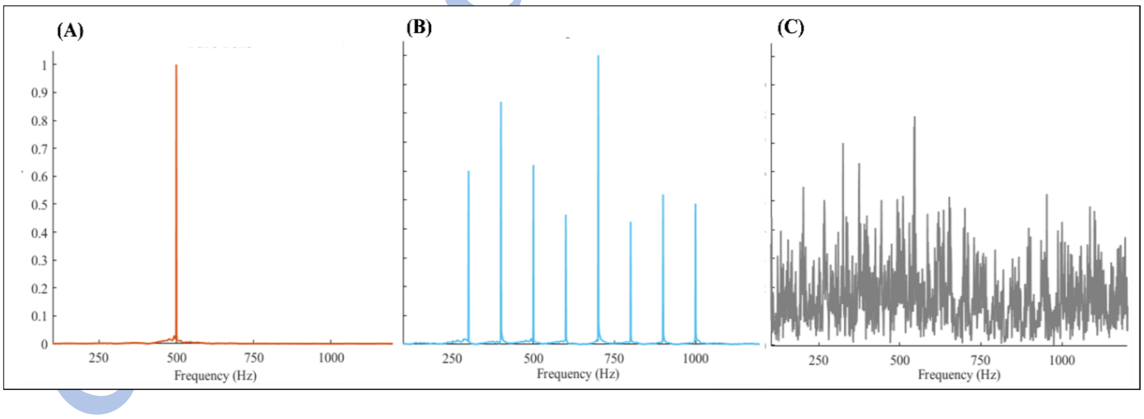

Fig 2. Frequency spectrum of three types of auditory spatially simulated at 0°azimuth:(A) pure tone, (B) complex tone, and (C) white band noise.

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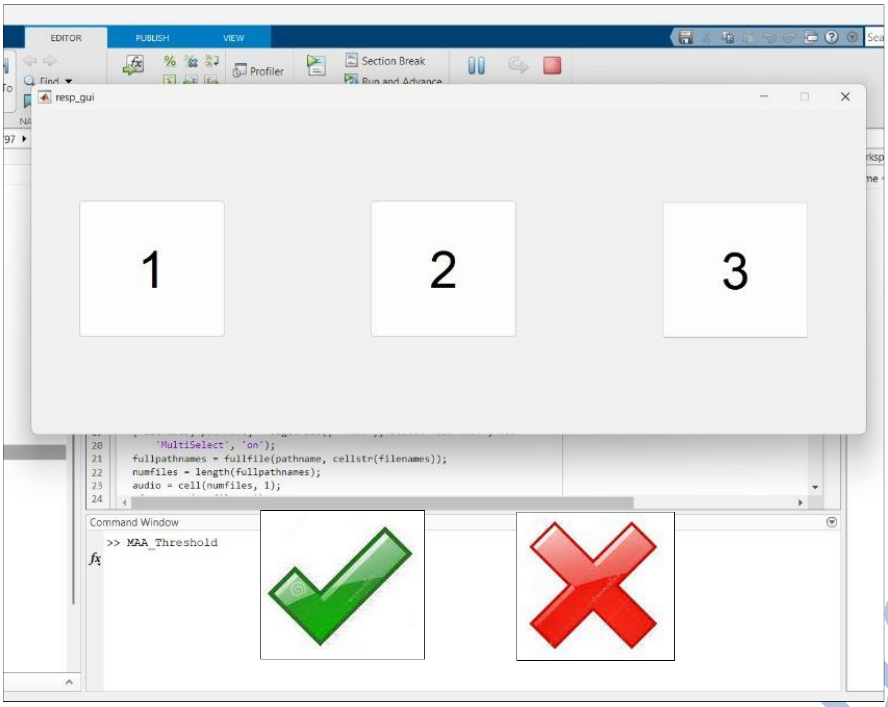

```
'MultiSelect', 'on');
fullpathnames = fullfile(pathname, cellstr(filenames));
numfiles = length(fullpathnames);
audio = cell(numfiles, 1);
```

```
>> MAA_Threshold
```

Fig 3. Alternative Forced Choice (3AFC) Interface with Immediate Visual Feedback for Correct and Incorrect Responses

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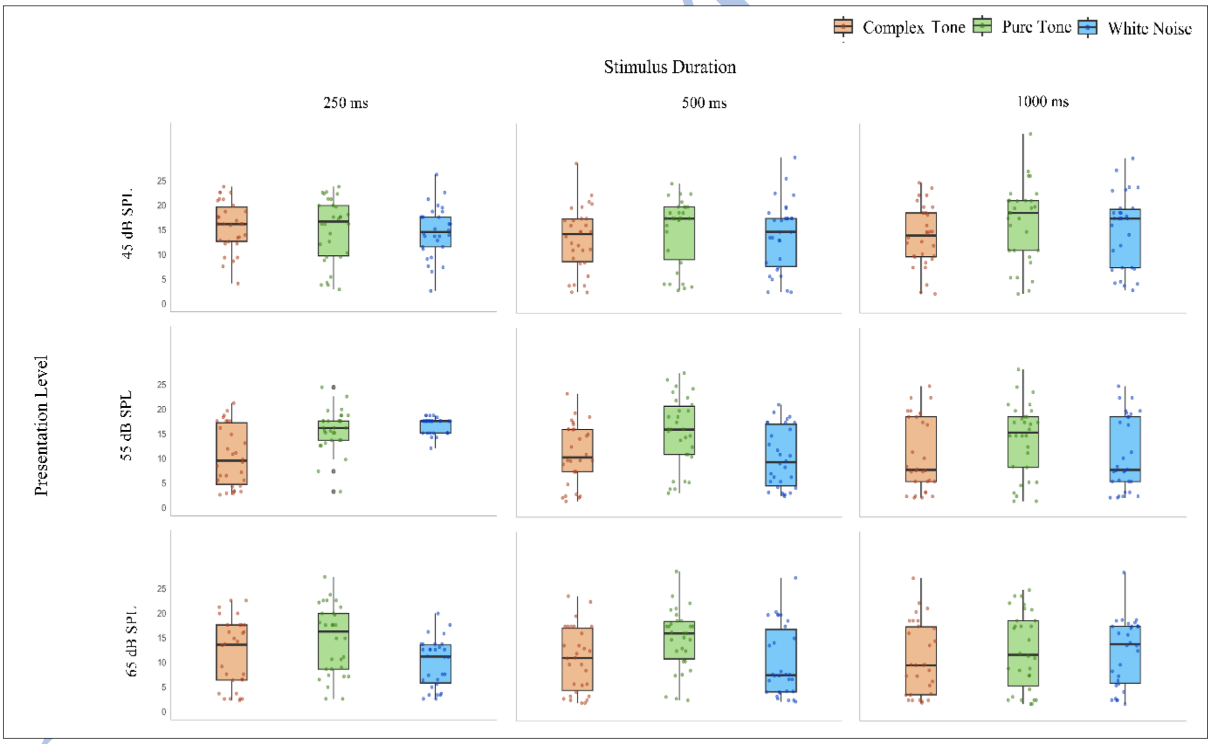

Fig 4. “Mean ± SD plot” depicting the mean and standard deviation (SD) of responses for the three stimulus types: Complex Tone (blue), Pure Tone (green), and White Noise (orange). Data are shown across three stimulus durations (250, 500, and 1000 ms) and three intensity levels (45, 55, and 65 dB SPL). Each box represents the mean response, with the box height indicating ±1 SD. The individual data points are overlaid as dots.

Table 1. Significant post hoc paired-sample t-test results for stimulus-type comparisons across all durations and intensity levels. Only comparisons that remained statistically significant after Bonferroni correction (α = 0.0166) were included. Each entry presents the t (29) value and corresponding *p*-value. Here conditions (Stimulus 1 and 2) are represented in the format “StimulusType_Duration_PresentationLevel” where C = Complex tone, P = Pure tone, WBN = White Band Noise.

Stimulus 1	**Mean (SD)**	**Stimulus 2**	**Mean (SD)**	***t* (29)**	***p***	***Cohen’s d***
Complex_250_55	10.31(6.15)	Puretone_250_55	15.69(4.17)	4.78	**<0.001**	1.02
Complex_250_55	10.31(6.15)	WBN_250_55	16.70(1.67)	5.62	**<0.001**	1.42
Complex_250_65	11.62(6.90)	Puretone_250_65	14.47(7.02)	2.69	0.012	0.41
Puretone_250_65	14.47(7.01)	WBN_250_65	9.86(4.91)	3.47	0.002	0.76
Complex_500_55	11.17(6.14)	Puretone_500_55	15.53(7.13)	3.86	0.001	0.66
Puretone_500_55	15.53(7.13)	WBN_500_55	10.31(6.15)	5.71	**<0.001**	0.79
Complex_500_65	10.79(6.58)	Puretone_500_65	14.86(6.24)	3.23	0.003	0.63
Puretone_500_65	14.86(6.24)	WBN_500_65	10.22(7.16)	2.88	0.007	0.69

Table 2. Significant post hoc paired-sample *t*-test results for presentation-level comparisons within each stimulus type and duration. Only comparisons that remained statistically significant after Bonferroni correction (α = 0.0166) are shown. Each row compares the MAA thresholds between two intensity levels (45, 55, or 65-dB SPL) for the same condition, along with the corresponding *t*(29) values and *p*-values.

Stimulus_Duration	**PL 1**	**Mean (SD)**	**PL 2**	**Mean (SD)**	***t* (29)**	***p***	***Cohen’s d***
Complex tone_250	45	15.73 (5.01)	55	10.37 (6.15)	4.89	**<0.001**	0.97
	45	15.73 (5.01)	65	11.62 (6.90)	3.33	0.002	0.68
Complex tone_1000	45	13.87 (6.19)	65	10.80 (7.39)	2.63	0.014	0.45
Pure tone_1000	45	16.62 (7.93)	65	12.56 (7.84)	2.88	0.007	0.51
WBN_250	45	14.52 (5.17)	65	9.86 (4.91)	4.64	**<0.001**	0.92
	55	16.70(1.67)	65	9.86 (4.91)	7.05	**<0.001**	1.86
WBN_500	45	13.90 (7.06)	55	10.31(6.15)	2.86	0.008	0.55
	45	13.99 (7.06)	65	10.22 (7.16)	2.55	0.016	0.53
WBN_1000	45	15.14 (7.55)	55	10.96 (7.47)	2.91	0.007	0.56

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