Audio Engineering Society

Conference Paper

Presented at the AES 2026 International Conference on
Audio for Virtual and Augmented Reality and Immersive Games
2026 June 30 – July 3, Sorbonne University/d'Alembert & IRCAM/STMS, Paris, France

This conference paper was selected based on a submitted abstract and 750-word precis that have been peer reviewed by at least two qualified anonymous reviewers. The complete manuscript was not peer reviewed. This conference paper has been reproduced from the author's advance manuscript without editing, corrections, or consideration by the Review Board. The AES takes no responsibility for the contents. This paper is available in the AES E-Library (http://www.aes.org/e-lib), all rights reserved. Reproduction of this paper, or any portion thereof, is not permitted without direct permission from the Journal of the Audio Engineering Society.

Adapting to A Manipulated Acoustic Distance Law

Christian Scheer[1], Fabian Brinkmann[1], Lucas Schmitz[2], Marcus von Berg[2], and Stefan Weinzierl[1]

[1]*Audio Communication Group, Technische Universtität Berlin, Germany*
[2]*Institute of Sound and Vibration Engineering (ISAVE), Hochschule Düsseldorf, Germany*

Correspondence should be addressed to Christian Scheer (christian.scheer@tu-berlin.de)

ABSTRACT

This study investigates whether humans can adapt to manipulated auditory distance cues in virtual environments. While listeners have been shown to adapt successfully to modified directional auditory localization cues, it remains unclear whether similar processes apply to distance perception, particularly when acoustic cues are modified in a non-physical way. Virtual reality (VR) systems often employ distance laws of this kind to improve the intelligibility of distant sound sources, which can introduce conflicts between auditory and visual information. To examine perceptual adaptation under such conditions, we modified a binaural, real-time room acoustic simulation engine with six-degrees-of-freedom rendering. The manipulation consisted of holding the direct sound level constant across distance while applying a distance-dependent low-pass filter. Over four consecutive days, participants completed a training protocol combining alternating testing phases with gamified training sessions. Results show that participants successfully adapted to the altered distance cues, with most of the learning occurring within the first two days. Initial exposure to the manipulation severely disrupted distance perception, rendering participants unable to make reliable judgments. Following training, however, perceived distance functions approached veridical performance for far distances, exhibiting slopes close to unity. In contrast, judgments at close distances remained highly variable, suggesting that the available spectral cues were insufficient for accurate estimation in this range. These findings demonstrate that auditory distance perception can be recalibrated through short-term perceptual learning, even when initial perceptual mappings are strongly degraded.

1 Introduction

Humans rely on auditory spatial perception to navigate, communicate, and maintain safety in complex environments. This ability depends on acoustic cues that allow listeners to estimate the direction and distance of sound sources. While spatial hearing is generally robust, systematic mismatches between physical and perceived sound location can occur, leading to errors such as localization blur, front–back confusions, or distance misestimation [1, 2, 3].

A large body of work demonstrates that angular localization is highly plastic. Listeners can adapt to manipulated ILDs (by ear plugging [4]), ITDs (by delaying the sound on one ear [5]), and spectral cues (by inserting

ear-molds into the pinna [6, 7]), and relearn accurate directional mappings within days. These findings suggest that the auditory system can flexibly recalibrate spatial representations.

In contrast, auditory distance perception (ADP) remains less well understood. Distance judgments rely on multiple cues, including sound level, direct-to-reverberant ratio (DRR), and spectral changes. However, ADP is typically less accurate than directional hearing and exhibits systematic biases, with nearby sources often overestimated and distant sources underestimated [8, 3]. Whether these distance-related mappings can be recalibrated in a similar way as directional cues is still largely unknown.

This question is particularly relevant for virtual and augmented reality (VR/AR), where auditory distance cues are often intentionally modified to improve intelligibility or enhance user experience. Such manipulations may distort the natural relationship between distance cue and presented distance, potentially leading to perceptual inconsistencies if users cannot adapt.

The present paper is part of ongoing research investigating whether humans can learn a systematically altered acoustic distance laws and generalize this learning across environments. Here, participants completed a four-day VR-based training paradigm with real-time six-degrees-of-freedom binaural rendering, in which the level of the direct sound was kept constant across distances, while the distance-dependent high-frequency attenuation due to air absorption was exaggerated, making spectral cues salient even at short distances. Adaptation was assessed using an auditory distance placement task across repeated test and training sessions.

We test the following hypotheses: (H1) initial performance is degraded under the manipulated distance law; training improves performance within and across days for the physical (H2) and manipulated (H3) distance laws. By addressing these questions, this work contributes to a better understanding of auditory spatial plasticity in distance perception and informs the design of perceptually consistent VR/AR audio systems.

2 Methods

2.1 Participants

A total of 12 participants with self-reported normal hearing took part in the experiment. All were unaware of the study's purpose, provided informed consent for both participation and publication of the results, and received 200 Euro as compensation. Participants ranged in age from 20 to 36 years (M = 26, Mdn = 27, SD = 4.75). One participant indicated an acoustics-related profession or relevant educational background and may therefore be considered an experienced listener.

2.2 Setup

The experiment took place in a soundproof, acoustically treated mixing studio at Hochschule Düsseldorf (≈22 dB(A) background noise). It was controlled by a custom VR application built in Unreal Engine 5.4, which handled rendering, procedures, data logging, and communication with the real-time room acoustics software liveRAZR [9] via OSC. Participants sat at a table wearing an HTC VIVE Pro HMD tracked by three SteamVR Base Stations 2.0 and used an HTC Vive Controller 2.0 for input. SteamVR 2.3.5 interfaced the hardware with Unreal Engine. Audio was delivered through Sennheiser HD 600 headphones and the participants speech was captured via a Sennheiser MKE-1EW lavalier microphone. The instructor operated the experiment from outside the booth using a Windows 10 PC (64 GB RAM, AMD Ryzen 9 5950X CPU, NVIDIA RTX 3080 Ti GPU), with monitoring via headphones and a talkback microphone. All audio I/O was handled by an RME Fireface UFX II interface (48 kHz sampling rate, 512 samples block size).

2.3 VR Game and Experimental Procedure

To examine potential learning effects in distance perception, the experiment was conducted in a fully virtual environment (HMD with binaural audio) and divided into test and training scenarios. Two virtual rooms were used: a photorealistic "wet" room based on the TU Berlin Mixed Reality Lab and a modified "dry" version with an identical floor plan but a lower visual ceiling height and more strongly sound-absorbing and visually different ceiling and floor materials. Before starting, participants completed VR-based tutorials led by a virtual avatar that explained the procedure and controller mapping. The avatar's voice, generated via text-to-speech [10], was spatially rendered at its position. These tutorials ensured consistent preparation and facilitated familiarization to the virtual acoustic environment, which can improve auditory distance judgments

[11]. When needed, the instructor communicated via a talkback microphone, rendered as an intercom source inside the virtual scene.

The test scenario consisted of a placement task in which participants judged the distance of sounds presented without a visual reference from positions in front of them. They indicated the perceived distance by pressing buttons on a hand-held controller to move a visual marker (a red needle). A display on the back wall indicated progress. Each test comprised 45 trials (five audio contents $\times$ nine logarithmically spaced distances from 0.8 to 17.8 m).

The training scenario took the form of a gamified task designed to reinforce auditory distance perception. Participants controlled a sound-emitting "catcher" to intercept incoming projectiles from approaching enemies, earning or losing points based on performance. The difficulty increased across waves by disabling the visibility of the catcher from the second wave onward, thereby requiring participants to rely solely on auditory cues to score points in the game. Each training run lasted three minutes, with score, wave number, and remaining time displayed within the scene.

The experiment spanned four consecutive days. On the first day, participants were introduced to the setup, completed administrative steps, and were familiarized with the equipment before entering the VR environment. The session began with the test tutorial, followed by the *baseline block* using the physical rendering condition. Each block consisted of alternating test and training phases. Tests were preceded by an undisclosed lead-in of nine trials covering all distances in decreasing order to familiarize participants with the range of stimuli (excluded from statistical analysis). Training phases comprised three consecutive runs of the VR game. After the baseline block, the *learning block* was conducted using the manipulated rendering condition, following the same structure with one additional training and test. Days two to four repeated the learning block.

2.4 Binaural Rendering

Binaural rendering was carried out using liveRAZR (v0.6.0) [12], a real-time room acoustics engine that provides perceptually plausible binaural audio in six degrees of freedom. It assumes a shoebox-shaped room and models direct sound and early reflections via a closed-form image source model (ISM), whose output feeds a feedback delay network (FDN) to generate late reverberation. Within the ISM, both direct sound and reflections incorporate source directivity through direction-dependent FIR filters, along with surface-specific wall-reflection filters. Spatialization is achieved using HRTFs, with source and receiver directivities provided in SOFA format [13] and interpolated via vector base amplitude panning (VBAP). Wall-reflection filters can be defined either by specifying frequency-dependent absorption coefficients per surface or by assigning target reverberation times, in which case the corresponding absorption is computed and applied uniformly.

For the distance-law manipulation, liveRAZR's source code was modified to disable the frequency-independent $1/r$ distance attenuation, while high-frequency attenuation due to air absorption was exaggerated, enhancing spectral cues even at short ranges. Both manipulations were applied only to the direct sound. This modified version is referred to as the "Manipulated" condition, whereas the unaltered baseline is termed "Physical." Both versions simulated two rooms with identical dimensions (W = 19.8 m, L = 14.5 m, H = 3.56 m) but different absorption properties. Consistent with its visual design (see Sec. 2.3), the wet room replicated the real Mixed Reality Lab at TU Berlin, using frequency-dependent absorption coefficients. For the dry room, the lab's measured reverberation times were halved and applied as target values in liveRAZR. Fig. 1 shows the left ear binaural room transfer functions (BRTFs) of the wet room's acoustic simulation for both distance laws and all tested source distances. Under the physical distance law, the magnitude decreases approximately uniformly with increasing distance across the spectrum. Only at larger distances does the natural high-frequency attenuation due to simulated air absorption begin to slightly affect the spectral shape. In contrast, under the manipulated distance law, spectral changes over distance are dominated by the exaggerated air-absorption filter, which becomes progressively more pronounced. Consequently, no broadband, frequency-independent level decay with distance is observed.

2.5 Audio Content

To examine the effect of source familiarity on ADP, we used two types of audio content: three unidenti-

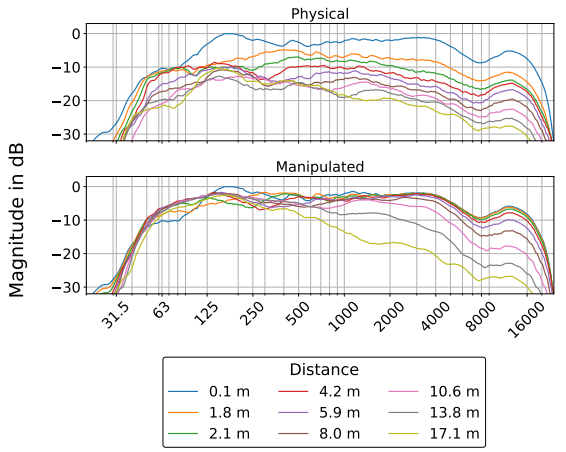


Fig. 1: Binaural room transfer functions (BRTFs, left ear) of the acoustic simulation for both distance laws ('Physical' and 'Manipulated'), exemplary for the wet room, displayed for each distance appearing in the test case of the listening experiment.

fiable sound objects (USOs) and two speech recordings. The USOs were designed to sound perceptually unfamiliar while preserving natural acoustic characteristics. They were created by combining anechoic recordings of everyday non-speech sounds from the RWCP Sound Scene Database [14]. In addition, two anechoic recordings of the same Harvard sentence (L1, S2), spoken by a female and a male American English speaker, served as familiar stimuli. To prevent learning of sound-specific distance cues, different stimulus subsets were used in the training scenario, randomly selected by the Unreal Engine application. In total, 96 USOs and 100 speech samples were available; the latter consisted of anechoic Harvard sentences (L1–L10) spoken by a female British English speaker.

2.6 Distance Error Measure

Performance in the test scenario was evaluated using accuracy $a(t)$, defined as the unsigned relative error,

$$a(t) = \begin{cases} \frac{r}{t} \cdot w(t), & r < t, \\ \frac{t}{r} \cdot w(t), & r \geq t \end{cases} \tag{1}$$

where t denotes the target distance, r the response distance, and $w(t)$ a distance-dependent weighting factor to compensate for the non-uniform spacing of target distances. It was computed from local distance intervals (via finite differences) and normalized by their mean to preserve the overall scale. A value of $a(t) = 1$ indicates perfect accuracy.

2.7 Statistical Analyses

We analyzed the results using generalized linear mixed-effects models (GLMMs) in `jamovi` and `R` (`GAMLj3` and `lme4` packages). Accuracy served as the dependent variable. Due to its skewed distribution, models assumed a Gamma distribution with a log-link function. Subject ID was included as a random intercept to account for repeated measures. Model evaluation was based on fixed effects, confidence intervals, and post-hoc comparisons at a 0.05 significance level. Predicted marginal means were used for visualization, and significant effects were further quantified using average marginal effects and standardized mean differences.

Three models were fitted to address different research questions: **Model 1 (Initial Performance):** Compared baseline performance between physical and manipulated distance laws, including distance law, stimulus type (speech vs. USO), and their interaction. **Model 2 (Learning – Physical):** Assessed learning effects across sessions under the physical condition, including session, stimulus type, and their interaction. **Model 3 (Learning – Manipulated):** Examined learning effects across sessions and days under the manipulated condition, including day, session, and their interaction.

3 Results

3.1 Initial Performance

Fig. 2A and 3A illustrate the performance of the first test of Day 1 with the physical and manipulated distance laws. A visual inspection of Fig. 2A reveals a slight overestimation of close sounds up to approximately 7.5 m for the physical distance law. Distances beyond these crossover points were persistently underestimated. Furthermore, under the manipulated distance law, the distance curve is almost flat and only starts to slightly bend upwards at about 10 m, suggesting responses clustered around approximately 2.5 m. Fig. 3A suggests that under the manipulated distance law, accuracy was worse than under the physical distance law.

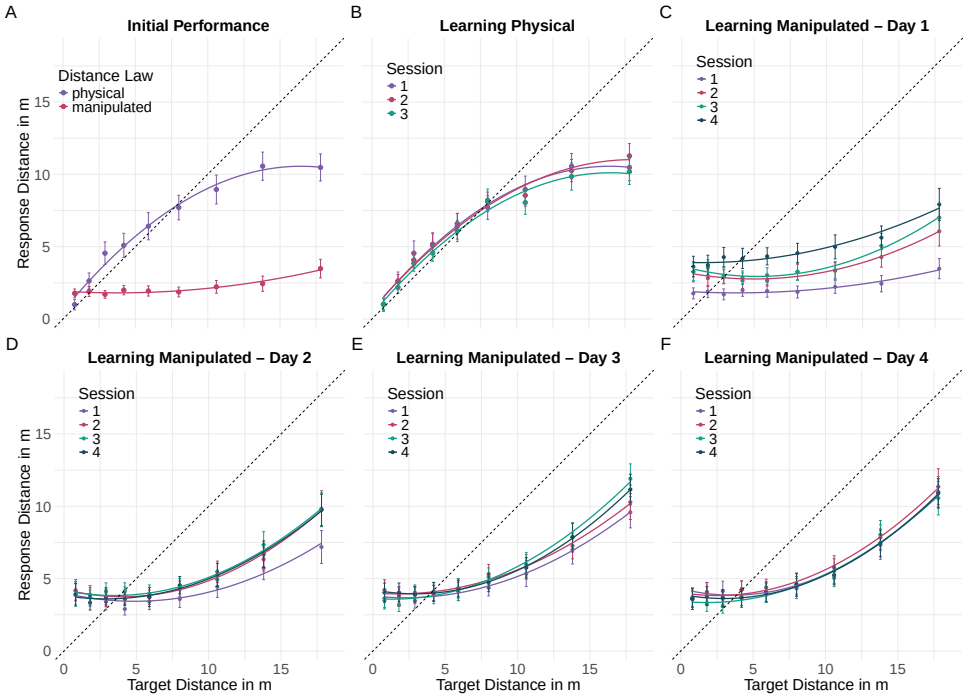


Fig. 2: Response distance as a function of target distance, averaged across participants and sound files. Points show means (95% within-subject CIs, Cousineau–Morey adjusted); curves show second-order polynomial fits.

Inferential analysis of Model 1 (ICC = 0.054) confirmed these impressions. The fixed-effects omnibus test shows a significant effect of distance law, $\chi^2(1) = 235.99$, $p < .001$, stimulus, $\chi^2(1) = 25.68$, $p < .001$, and their interaction, $\chi^2(1) = 4.15$, $p = .042$. The estimated effect of distance law at the reference is $\beta = 0.94, \mathrm{SE} = 0.06$, $z = 15.36$, $p < .001$, AME = .361, SMD = .611. However, this effect is smaller for USO stimuli, as indicated by a significant distance law × stimulus interaction, $\beta = -0.16$, SE = 0.08, $z = -2.04$, $p = .042$, resulting in AME = .362 and SMD = .612 for USO, and an AME = .360 and SMD = .610 for speech. There was also an overall significant difference between accuracy of stimuli, $\beta = 0.28$, SE = 0.06, $z = 5.07$, $p < .001$, AME = .076, SMD = .128, with USOs obtaining higher accuracy.

3.2 Learning of the Physical Distance Law

Fig. 2B and 3B illustrate the performance on Day 1, for all tests with the physical distance law. A visual inspection of Fig. 2B reveals that there were only minor differences in the average response distance and no differences in the fitted curves over sessions. Fig. 3B suggests there was only a slight improvement in accuracy from Session 1 to Session 2 and an even smaller decline from Session 2 to Session 3. Furthermore, accuracy was again slightly higher for USOs than for speech.

Inferential analysis of Model 2 (ICC = 0.011) confirmed these impressions as there was no significant effect of session, indicating that ADP was already as accurate as possible in this specific scenario and setup. A fixed-effects omnibus test showed only a significant effect of stimulus, $\chi^2(1) = 9.86$, $p = .002$, with USOs again yielding more accurate performance as indicated by a significant estimated effect of stimulus at the reference level, $\beta = 0.10, \mathrm{SE} = 0.03$, $z = 3.14$, $p = .002$, AME = .062, SMD = .112.

3.3 Learning of the Manipulated Distance Law

Fig. 2C–F illustrate the performance with the manipulated distance law over all four days and sessions. A visual inspection of Fig. 2C (Day 1) reveals substantial changes in response distance over sessions. For all

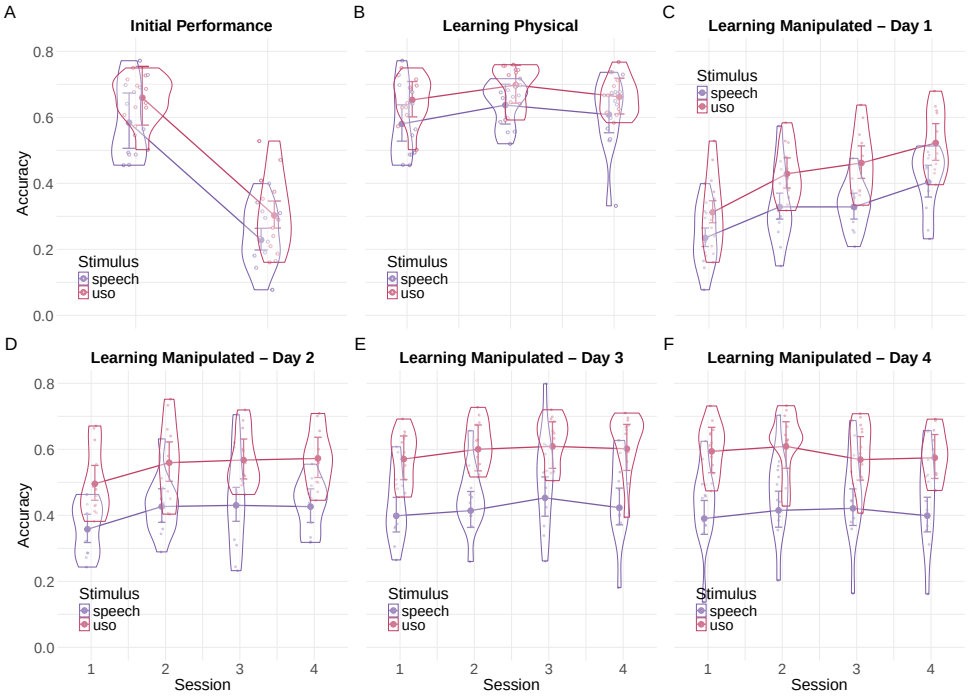


Fig. 3: Accuracy per condition. Error bars show model-predicted marginal means ± 95 % CIs from the models. Data points represent arithmetic mean for accuracy per participant, with violin plots showing distributions.

target distances, the average response increases over sessions. For Day 2 and Day 3, a slight improvement of localization performance for distances beyond 5 – 10 m can be seen, whereas the adaptation seems to be completed on Day 4 where no further improvement is observed. Fig. 3C indicates a similar increase of accuracy over sessions. According to Model 3, Day 1 begins with an average accuracy of 0.23/0.31 (Speech/USO) in Session 1 and ends with an average accuracy of 0.40/0.52 (Speech/USO), indicating improvement of 74/67 % (Speech/USO). Day 2 began with an average accuracy of 0.36/0.50 (Speech/USO), much higher than Session 1 of the previous day, and ended at 0.43/0.57 (Speech/USO). From Day 3 onward, the average accuracy stopped increasing and remained around 0.5 until the end of Day 4. From Day 1, Session 1 to Day 4, Session 4, there was an overall improvement in accuracy of approximately 83 %.

Inferential analysis of Model 3 (ICC = 0.021) mostly confirmed these impressions. A fixed-effects omnibus test showed significant effects of day, $\chi^2(3) = 134.87$, $p < .001$, session, $\chi^2(3) = 47.27$, $p < .001$, stimulus, $\chi^2(1) = 363.45$, $p < .001$, and the day × session interaction, $\chi^2(9) = 34.65$, $p < .001$.

A significant difference was observed between Day 1 and Day 2, $\beta = 0.24$, SE = 0.03, $z = 7.23$, $p < .001$, AME = .104, SMD = .165. However, no significant effect emerged between Day 2 and Day 3 and between Day 3 and Day 4. Finally, post-hoc pairwise comparisons revealed a significant difference between Day 1 and Day 4, $\beta = 0.72$, SE = 0.02, $z = 15.41$, $p_{\text{Holm}} < .001$, AME = .148, SMD = .235, indicating a substantial increase in accuracy over days.

A significant difference was observed between Session 1 and Session 2, $\beta = 0.16$, SE = 0.03, $z = 4.73$, $p < .001$, AME = .058, SMD = .092. No significant differences were found between Session 2 and Session 3 or between Session 3 and Session 4. Furthermore, post-hoc pairwise comparisons revealed a significant difference between Session 1 and Session 4, $\beta = 0.83$, SE = 0.02, $z = 8.70$, $p_{\text{Holm}} < .001$, AME = .075, SMD = .119, indicating a substantial general increase in accuracy over sessions within a day. However, day-specific post-hoc pairwise comparisons between Session 1 and Session 4 revealed

that this within-day improvement only reached significance for Day 1, $\beta = 0.60$, SE $= 0.03$, $z = 11.91$, $p_{\text{Holm}} < .001$, AME $= .226$, SMD $= .359$, and for Day 2, $\beta = 0.86$, SE $= 0.04$, $z = 3.57$, $p_{\text{Holm}} = .026$, AME $= .081$, SMD $= .128$.

Furthermore, similar to Model 1, there was a significant effect of stimulus, $\beta = 0.29$, SE $= 0.02$, $z = 19.06$, $p < .001$, AME $= .140$, SMD $= .222$, indicating higher accuracy for USOs compared to speech.

4 Discussion

In the current study, we investigated if humans can adapt to a manipulated acoustic distance law through training in audio-visual virtual reality. The results showed a drastic decrease in distance localization performance upon first encounter of the manipulated distance law. Localization accuracy significantly improved through interactive and gamified training sessions, showing that humans can adapt to a manipulated distance law. While localization accuracy significantly increased from Day 1 to Day 2, most of the learning took place during the first training sessions of Day 1, indicating a quick adaption to the manipulated distance law. The effects were close to identical for speech and USOs with significantly higher localization accuracy for USOs.

Localization performance after training fundamentally differed between the physical and manipulated distance law. For the physical law, participants showed an almost linear relation between target and response distances for close sources up to approximately 7.5 m, indicating a good localization accuracy in this region. Beyond this distance, the curve flattens out, indicating a decreased localization accuracy. This is completely opposite for the manipulated distance law, where the responses show a flat curve for close sources up to approximately 5 – 7.5 m, and an almost linear relation above approximately 10 m.

This behavior can most likely be explained by the acoustic distance cues that were available to the participants. Under the physical distance law, the direct sound level and DRR might be the most salient distance cues that change more drastically for close than for far sources due to the $1/r$ distance attenuation of the direct sound. The effect of this emerges as a broad band attenuation of the BRTFs shown in Fig. 1 (top). For the manipulated distance law, the $1/r$ distance attenuation of the direct sound was disabled in favor of an exaggerated air attenuation. This resulted in a low-pass like effect that affected the spectral shape of the direct sound and changed more drastically for sound sources farther away (cf. Fig. 1, bottom).

Previous research has introduced the concept of the *auditory horizon* as the distance beyond which listeners can no longer perceive changes in the distance of a sound source. This phenomenon is believed to occur because the gradients of all auditory distance cues become smaller at greater distances [15, 3, 16]. At the same time, many studies on ADP have reported a growing underestimation of far distances even before the auditory horizon is reached [3]. In contrast, our synthetic manipulation of distance cues resulted in a largely linear increase in perceived distance at greater distances. This demonstrates the listeners' successful adaptation to non-physical cues. At the same time, it demonstrates the potential of the specific spectral manipulations carried out to induce differences in distance perception even at greater perceived distances—differences that would be difficult to achieve using physical cues alone.

References

[1] Blauert, J., *Spatial Hearing: The Psychophysics of Human Sound Localization*, The MIT Press, 1996, ISBN 978-0-262-26868-4.

[2] Xie, B., editor, *Head-Related Transfer Function and Virtual Auditory Display*, J. Ross Publishing, second edition, 2013, ISBN 978-1-60427-070-9 978-1-60427-741-8 978-1-68015-491-7.

[3] Kolarik, A. J., Moore, B. C. J., Zahorik, P., Cirstea, S., and Pardhan, S., "Auditory Distance Perception in Humans: A Review of Cues, Development, Neuronal Bases, and Effects of Sensory Loss," *Attention, Perception, & Psychophysics*, 78(2), pp. 373–395, 2016, doi:10.3758/s13414-015-1015-1.

[4] Kumpik, D. P., Kacelnik, O., and King, A. J., "Adaptive Reweighting of Auditory Localization Cues in Response to Chronic Unilateral Earplugging in Humans," *The Journal of Neuroscience*, 30(14), pp. 4883–4894, 2010, doi:10.1523/jneurosci.5488-09.2010.

[5] Trapeau, R. and Schönwiesner, M., "Adaptation to Shifted Interaural Time Differences Changes Encoding of Sound Location in Human Auditory Cortex," *NeuroImage*, 118, pp. 26–38, 2015, doi:10.1016/j.neuroimage.2015.06.006.

[6] Trapeau, R., Aubrais, V., and Schönwiesner, M., "Fast and Persistent Adaptation to New Spectral Cues for Sound Localization Suggests a Many-to-One Mapping Mechanism," *The Journal of the Acoustical Society of America*, 140(2), pp. 879–890, 2016, doi:10.1121/1.4960568.

[7] Friedrich, P. and Schönwiesner, M., "Adaptation Rate and Persistence across Multiple Sets of Spectral Cues for Sound Localization," *The Journal of the Acoustical Society of America*, 157(3), pp. 1543–1553, 2025, doi:10.1121/10.0036056.

[8] Zahorik, P., Brungart, D. S., and Bronkhorst, A. W., "Auditory Distance Perception in Humans: A Summary of Past and Present Research," *Acta Acustica united with Acustica*, 91, pp. 409–420, 2005.

[9] De Haas, K., Schutte, M., and Ewert, S., "Real-Time Virtual Environment and Room Acoustics Simulator," in *Proceedings of the 11th Convention of the European Acoustics Association Forum Acusticum / EuroNoise 2025*, pp. 6533–6540, European Acoustics Association, 2025, doi:10.61782/fa.2025.0729.

[10] ttsMP3.com, "Free AI Text-To-Speech and Text-to-MP3 for English," `https://ttsmp3.com/ai`, 2025, accessed: 2025-07-40.

[11] Calcagno, E. R., Abregú, E. L., Eguía, M. C., and Vergara, R., "The Role of Vision in Auditory Distance Perception," *Perception*, 41(2), pp. 175–192, 2012, doi:10.1068/p7153.

[12] Sommerfeldt, J., Arend, J. M., Brinkmann, F., Ewert, S. D., and Weinzierl, S., "Source Directivity Implementation for Real-Time Room Acoustic Simulation with liveRAZR," in *Proceedings of the 50th DAGA*, volume 50, pp. 1616–1618, 2024.

[13] Majdak, P., Zotter, F., Brinkmann, F., De Muynke, J., Mihocic, M., and Noisternig, M., "Spatially Oriented Format for Acoustics 2.1: Introduction and Recent Advances," *Journal of the Audio Engineering Society*, 70(7/8), pp. 565–584, 2022, doi:10.17743/jaes.2022.0026.

[14] Nakamura, S., Hiyane, K., Asano, F., Nishiura, T., and Yamada, T., "Acoustical Sound Database in Real Environments for Sound Scene Understanding and Hands-Free Speech Recognition," in *Proceedings of the International Conference on Language Resources and Evaluation*, pp. 965–968, 2000.

[15] Bronkhorst, A. W. and Houtgast, T., "Auditory Distance Perception in Rooms," *Nature*, 397(6719), pp. 517–520, 1999, doi:10.1038/17374.

[16] Larsen, E., Iyer, N., Lansing, C. R., and Feng, A. S., "On the Minimum Audible Difference in Direct-to-Reverberant Energy Ratio," 124(1), pp. 450–461, 2008.