Audio Engineering Society
Convention Express
Paper 362

Presented at the AES 159th Convention
2025 October 23–25, Long Beach, CA, USA

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Direct vs. Rendered Binaural Capture of Guitar Amplifier: A Comparative Study

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ABSTRACT

This paper presents a comparative study between direct binaural recording using a Neumann KU100 dummy head microphone and digitally rendered binaural audio derived from omnidirectional impulse responses captured with an Earthworks M50 measurement microphone. Impulse responses were acquired in a hemispherical measurement field surrounding a Fender Twin Reverb amplifier at radial distances of 2 and 6 feet, using a structured grid of elevation and azimuth angles. These datasets were integrated into a custom amplifier simulation plugin, enabling interactive spatial playback and A/B comparison between the KU100, M50 and binauralized M50 render outputs. Objective analysis compares both methods with the unprocessed M50 baseline, while subjective evaluation was conducted through a blind listening test with professional audio engineers from Bias Studios and American University's Audio Technology department. The results aim to assess the realism and applicability of digitally rendered binaural techniques relative to traditional physical binaural capture for guitar amplifier recording.

1 Introduction

Accurate spatial recording and rendering of musical instruments remains a significant focus in audio engineering. Traditional methods for capturing guitar amplifier sound typically rely on monophonic or stereophonic microphone techniques; however, these approaches often lack the ability to represent immersive spatial cues. Binaural microphones, such as the Neumann KU100, yield more convincing spatial attributes by capturing audio information filtered by the pinnae and shape of their enclosures.

Using a Neumann KU100 and an Earthworks M50 microphone, impulse responses (IRs) were collected over a hemispherical field around a Fender Twin Reverb guitar amplifier at fixed radii of 2 feet and 6 feet. The captured dataset serves as the foundation for two main areas of analysis: an objective directivity response comparison and a subjective listening test.

For objective comparison, the IRs of the KU100 and the HRTF spatialized M50 renders were analyzed against the unprocessed M50 impulse responses. This comparison aims to quantify the spatial differences introduced by each recording and rendering method. For subjective evaluation, a blind listening test was conducted with experienced audio engineers from Bias Studios and American University's Audio Technology department, where participants were asked to identify which

source has superior spatial attributes.

In order to aid in analysis, impulse responses have been implemented in a custom guitar amplifier simulation plugin allowing users to auralize the KU100, M50 and binauralized M50 render outputs in real-time. This plugin features an interactive graphical user interface where users can move a virtual listening point within the measured hemisphere. The listeners were asked a series of subjective test questions to assess the spatial accuracy of the binaural renderings in comparison to the captures of the KU100, as well as the applicability of the binaural guitar in comparison to the traditional mono capture. Through both objective and subjective assessments, this study aims to provide a critical evaluation of direct versus digitally rendered binaural techniques, offering new insights for engineers seeking more realistic methods for spatial guitar amp recording.

2 Background

2.1 Traditional Amplifier Recording Techniques

Guitar amplifiers have traditionally been recorded using close-positioned, directional mono microphones placed directly against the amplifier grille, occasionally supplemented by a distant or room microphone [1]. The influence of proximity effect, along with the balance between direct sound and ambient reflections, has led engineers to favor this technique. In addition, on-axis placement is commonly used to capture the high-frequency directional content of the amplifier.

2.2 Non-Traditional Recording Techniques

Although close mic placement is often considered the standard for recording electric guitar amplifiers, several notable commercial releases have been recorded using binaural techniques [2, 3, 4]. In addition to binaural efforts, over-the-shoulder mic techniques have been utilized to add realism and the percussive clarity of the unplugged electric guitar pick sound [5]. Over-the-shoulder configurations have also been used independant of the acoustic instrument itself to approximate the sonic properties of a guitar amp from the in-situ perspective of the guitarist [6]. These various methods highlight the importance of subjective listening positions in shaping what is perceived as an "authentic" guitar tone.

2.3 Interaural Time Differences (ITDs)

The three main auditory cues that allow the brain to locate sounds are: interaural time difference (ITD), interaural level difference (ILD), and spectral cues. Since spatial cues are derived from human anatomy, binaural microphones designed to replicate these features can capture these temporal and spectral changes.

ITDs describe the difference in arrival times between the ears. This is directly related to the azimuth of the source in relation to the observer. This discrepancy in microseconds plays a key role for horizontal plane localization. Theoretical models have described ITD as a function of the azimuth and a simplified geometric head shape such as Woodworth and Schlosberg's spherical head model [7]. This model is based on a rigid sphere whose radius is r and where the speed of sound is c. The ITD is defined by the difference in acoustic path lengths between the sound source and each ear [7] and is shown by:

$$W(\phi) = \frac{r}{c}(\phi + sin\phi) \qquad 0 \leq \phi \leq 90 \qquad (1)$$

$$\frac{r}{c}(180 - \phi + sin\phi) \qquad 90 \leq \phi \leq 180 \qquad (2)$$

2.4 Interaural Level Differences (ILDs)

ILDs describe the variation in sound pressure level caused by the head shadow effect. Above approximately 1.5 kHz, wavelengths become shorter than the head's diameter. The head will attenuate these high-frequency components producing an interaural sound pressure level disparity [8].

ITDs are most effective for localizing low-frequency sounds (below 1.5 kHz), where the wavelength of sound is longer than or comparable to the distance between the ears. In this range, the head produces little to no acoustic shadow, making ILDs negligible. At higher frequencies (above 1.5 kHz), the shorter wavelengths are more strongly attenuated by the head, and ILDs become the dominant spatial cue [8].

2.5 Directional Bands

In vertical and median plane localization, spectral cues introduced by the filtering characteristics of the pinnae become dominant. These high-frequency notches and peaks, typically above 6 kHz, vary with the elevation and azimuth of the source. They are essential for resolving ambiguities not addressed by ITD and ILD [8]. Directional bands have significant implications for the design and evaluation of binaural systems. A binaural system that fails to reproduce the appropriate spectral coloration, either due to poor HRTF modeling or microphone limitations, may cause spatial ambiguities, particularly in elevation or front/back localization [8].

In the context of this study, elevation cues play a more critical role than front/back localization when considering directional bands. This is due to both the KU100 and the M50 being consistently aligned to face the guitar amplifier's speaker cone regardless of changes in azimuth (ϕ) or elevation (θ). As a result, the typical conditions required to activate strong front/back perceptual differences were effectively neutralized by maintaining a constant on-axis alignment with the speaker.

2.6 Head-Related Transfer Function (HRTF)

Head-Related Transfer Functions describe the direction-dependent acoustic filtering produced by the listener's anatomy, combining interaural cues with reflections and diffraction from the head, pinnae, torso, and shoulders [9]. Because these physical features vary across individuals, HRTFs are inherently unique. In order to maintain consistency between our measured and rendered binaural auralizations, our M50 data set was rendered with a KU100 HRTF obtained from the main SOFA repository [10].

3 Methods & Procedure

3.1 Experimental Setup

All measurements were conducted in the Kreeger studios at American University, an acoustically treated environment designed by Walters-Storyk Design Group. The sound source was a Fender '65 Twin Reverb Reissue guitar amplifier, widespread use in both performance and recording contexts. This model delivers 85 watts RMS into a pair of 12-inch Jensen C-12K 4 Ohm speakers [11] and was set to a clean tone configuration with tone controls set flat. A 5-second logarithmic sine sweep ranging from 20 Hz to 20 kHz was played through the amplifier at 80 dBA. The sweep was routed to the amplifier via a Little Labs PCP Instrument Distro. Microphone signals were captured using SSL SuperAnalogue microphone preamplifiers. This preamp provided low harmonic distortion THD + N: < 0.0015 percent and low self noise [12].

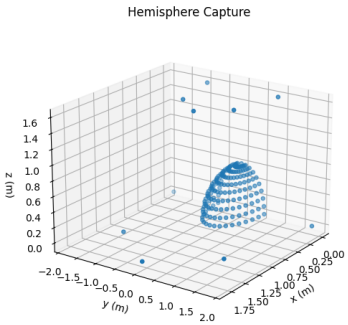


Fig. 1: Plot showing the locations of the measured microphone Impulse Responses.

3.2 Spatial Sampling Method

Impulse responses were recorded at radial distances of 2 and 6 feet from the amplifier's speaker cone. At 2 ft, measurements covered a hemispherical field (r, θ, ϕ), with elevation θ from 0° to 90° and azimuth ϕ from –90° to 90°, both in 10° steps. At 6 ft, recordings were limited to $\theta = 0°$ and 60°. At each coordinate, the KU100 or M50 microphone was aligned to the specified radial distance, by head orientation and capsule leveling respectively. Structure for the hemisphere capture of both microphones can be seen in Fig. 1.

3.3 Microphones and Signal Capture

The KU100 uses matched condenser capsules located in anatomically modeled ears and a solid head structure. The KU100 offers a frequency response of 20 Hz to 20 kHz (2.5 dB), 78 dB S/N ratio, and a sensitivity of 20 mV/Pa [13]. This microphone is well suited for high-resolution binaural capture. During the experiment, the KU100 was oriented so that the coronal plane remained perpendicular to the radius vector extending from the amplifier's speaker cone to the microphone position,

preserving consistent head orientation throughout the measurement grid.

Following the binaural measurements, the same procedure was repeated using the Earthworks M50, an omnidirectional pressure microphone with an extended flat frequency response from 3 Hz to 50 kHz ($\pm$ 1 dB). With a low self-noise level of 22 dB SPL (A-weighted) [14] and extremely fast impulse response characteristics, the M50 was used to obtain high-resolution mono IRs.

3.4 Repeatability Assessment

To evaluate the repeatability of the measurement procedure, second impulse responses were recorded at each coordinate. The process involved manually moving the microphone, returning it to its original position, realigning the capsule or head orientation, and verifying its placement using a tape measure. Reported error between successive measurements are low, with an equivalent median amplitude deviation of $\pm$ 1.3 dB for the KU100 and $\pm$ 1.6 dB for the M50.

4 Guitar Amplifier Plugin Design

To aid in creation of auralization files for subjective evaluation, an audio plugin was developed using the JUCE framework in conjunction with the SOFA C++ API to load and compare various physically captured and digitally rendered binaural methods. At its core, the plugin implements a WOLA convolution algorithm based on previous work [15, 16] that can perform low-latency interpolated binaural convolution suitable for arbitrary azimuth, elevation and depth queries. For each measurement, the plugin estimates per-ear ITD via a peak-relative onset threshold, time-aligns the IRs, and then resamples the HRTF field onto a 5° dense grid. Interpolation between IRs is 1-D linear when sharing an azimuth or elevation, otherwise barycentric over the three nearest neighbors. if multiple radii are present, it applies inverse-distance interpolation between radius layers to support depth control.

A preprocessing pipeline was set up in Python 3.9 to encode the IRs and their respective data into the SOFA files. Because there is no explicit convention for binaural amplifier captures, the SimpleFreeFieldHRIR convention was selected due to its spherical coordinate system. Radial distance, azimuth, and elevation measurements were extracted

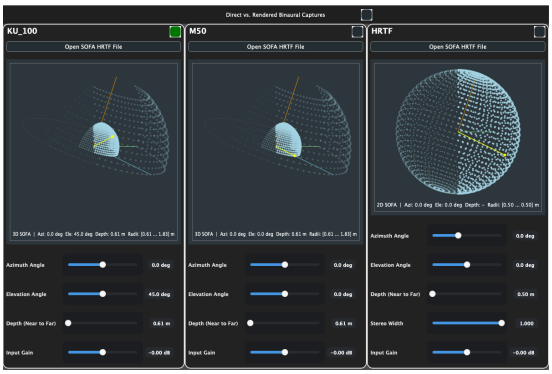


Fig. 2: GUI of the audio plugin used to generate and compare auralizations.

and encoded into each respective SOFA file. Code for the plugin, preprocessing and analysis can be found at: https://github.com/noahdeetzers/BinauralGuitarAmp.git.

5 Quantitative Analysis

Directivity graphs for both measurements shown in figures 3 and 4 align with previous literature [17, 18] analyzing the spectral directivity of guitar amplifiers, with lower frequencies exhibiting more omnidirectional radiation patterns, while higher frequencies maintain their directionality. Similarly to Roginska et al., our findings also indicate larger variability at higher frequencies, especially when analyzing the near field directivity of the amplifier.

When comparing the amp response to the generic KU100 HRTF, the amp response exhibits a higher average IACC mean than the HRTF with significantly less end-to-end variation. This effect seen in figures 5 and 6, is consistent with the observation that changing the IACC window length primarily shifts the absolute values while preserving the angular pattern, indicating that the amplifier's directivity dominates the shape while the room contributes a uniform downward offset. Possible contributors towards the less varied IACC are high frequency damping due to the directionality and shadowing caused by the amp speaker and enclosure, and the presence of strong first reflections (e.g. floor) that could not be windowed out.

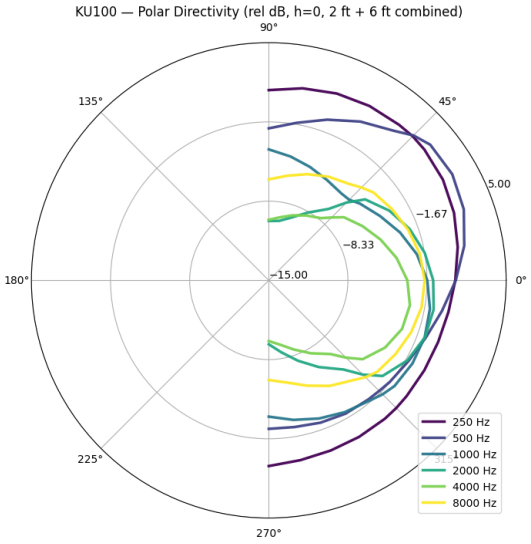


Fig. 3: Polar directivity of the measured KU100 microphone.

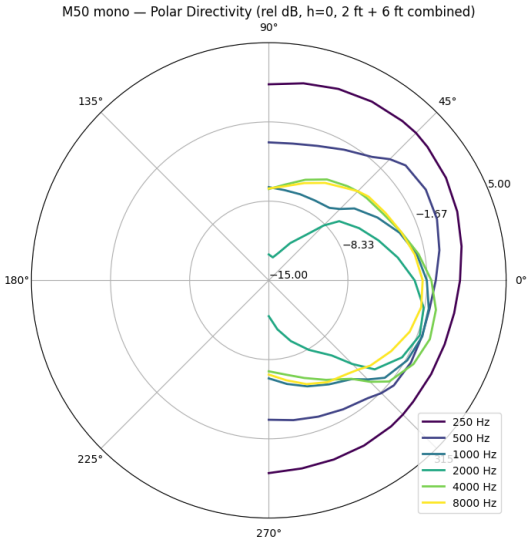


Fig. 4: Polar directivity of the measured M50 microphone.

6 Subjective Testing

6.1 Methods & Procedure

To subjectively compare the signals from the KU100, binauralized M50, and mono M50 data sets, a listening test was conducted with five professional audio engineers ages 25 to 40. The stimuli were administered via closed-back headphones in a controlled and quiet listening environment at Bias Studios, American University's Kreeger Studios, and at the participants' home studios.

Participants were presented with various guitar recordings and instructed to focus on azimuth, elevation, and distance. They answered the following prepared questions:

- Azimuth:

  1.) On a scale of 1–5, how clearly can you identify the sound's left-to-right position?

  2.) Could you perceive the full 180° horizontal movement of the sound source?

- Elevation:

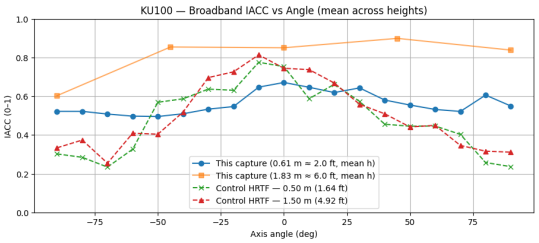


Fig. 5: Measured IACC values for the KU100 shown against a KU100 HRTF.

3.) On a scale of 1–5, how easy was it to tell if the sound was coming from above, below, or in front of you when comparing the different elevations?

4.) Did the sound feel as though it was coming from a consistent height at each elevation, or did the elevation shift during the -90° to 90° azimuth rotation?

- Distance:

  5.) How far away did the sound seem to be at 2 feet for the KU100, M50 render, and the M50? (A few inches away, a few feet away, or very far away)

  6.) How far away did the sound seem to be at 6

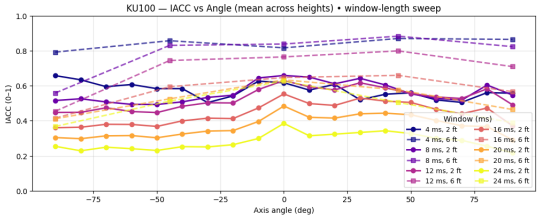


Fig. 6: Measured IACC values with respect to changing window size. Illustrates impact of amp directionality versus room reflections.

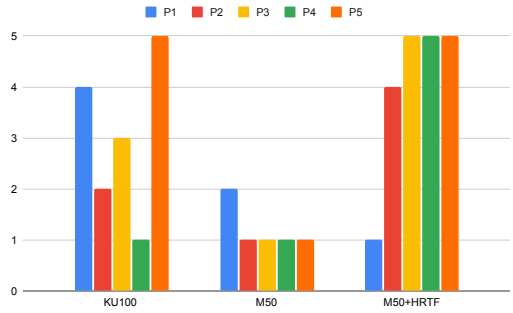


Fig. 7: Question 1: Left-to-Right Position

feet for the KU100, M50 render, and the M50? (A few inches away, a few feet away, or very far away)

- Applicability to Guitar Amplifier Representation:

  7.) Which technique best represented the guitar amplifier: KU100 capture, M50 binaural rendering, or traditional mono?

  8.) To what extent do you feel like the "insert measurement" portrays the sound of an amplifier in a room?

6.2 Subjective Test Results

Scale responses from 1-5 were listed and averaged across participants for each perceptual attribute.

The subjective testing showed some trends among the test participants. There were stark differences between the three captures across azimuth, elevation, distance, and applicability.

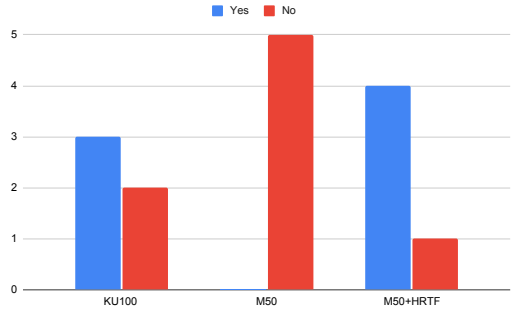


Fig. 8: Question 2: Horizontal Movement Perception

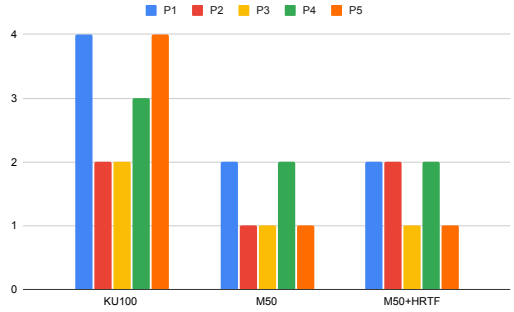


Fig. 9: Question 3: Above/Below Elevation Comparison

The azimuth perception was most consistently conveyed through the M50 + HRTF, which achieved the highest average ratings for horizontal localization with an average likert rating of 4.0 while the KU100 had an average score of 3.0 shown in figure 7. Both were perceived by the majority to have the full 180° motion across the amp as seen in figure 8. The M50 had the worst azimuth rating with a likert of 1.2 and was unanimously voted to have no perceptual continuous 180° horizontal arc.

Elevation perception further distinguished the KU100 from the other methods. Although the likert score for Question 3 for all three captures were low, the KU100 had an average score of 3.0 and was consistently rated higher for each participant (see figure 9). In contrast, both the raw M50 and its HRTF-rendered version yielded poor elevation performance, with multiple participants noting that there were no perceptual vertical changes.

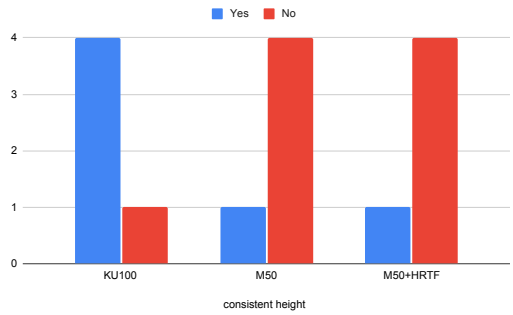


Fig. 10: Question 4: Elevation Shift

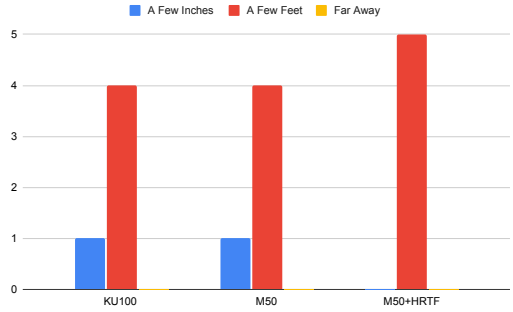


Fig. 11: Question 5: 2 ft Distance

In general, the perception of distance was less consistent at 6 ft. The KU100 most reliably portrayed the near and far distances. As seen in figures 11 and 12, most listeners perceived the source at “a few feet” away for both the 2 ft and 6 ft distances. In addition, some noted that the 6 ft felt slightly farther away while still being a few feet. In contrast, the M50 and binauralized M50 often distorted distance perception. At 2 ft, the results were almost all “a few feet” for all three captures, however, the M50 and M50 + HRTF were perceived as “far away” by the majority of testers while the KU100 was perceived as “a few feet” by four of the five subjects. Subjects felt that the M50 and M50 + HRTF are capturing and emphasizing more reflections than the direct sound making it seem further than it is.

Finally, three of the five participants selected the KU100 recordings as the most realistic representation of the sound of an "amplifier in a room". One participant preferred the M50 + HRTF rendering due to the accuracy in the azimuth localization. Another participant preferred the raw M50 for timbral reasons that were not applicable to localization cues. Despite falling short in comparison with the M50 + HRTF azimuth spatialization, the KU100 was the preferred method by the majority of participants. It provided the best elevation cues and spatial depth while still offering adequate azimuth perception.

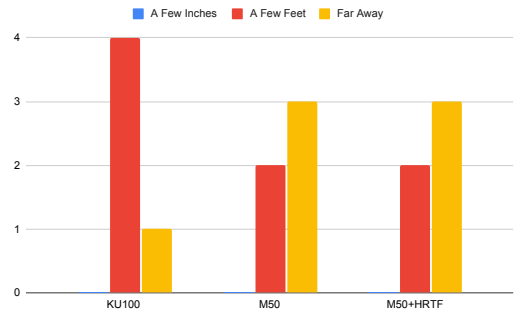


Fig. 12: Question 6: 6 ft Distance

6.3 Future Work

The current subjective test results show insight into the perceptual differences between KU100 and binauralized M50 recordings however, only five participants were included in this evaluation. Despite their expertise in the field of audio, the sample size for this experiment is too small to draw conclusions that can apply to the general population of professionals and consumers.

Future subjective testing should expand the number of participants and their backgrounds. Testing other audio related professionals such as musicians or the casual, untrained listener may add new perspectives to the results. Expanding the age range may help identify some age-related issues with spatial perception. Different sources such as dialogue, vocals, and acoustic instruments could affect the effectiveness of the KU100 and binaural renderings.

Procedural improvements include more dense data collection especially for the 6 ft radius, and additional radial distances to provide a more continuous representation of depth. A more anechoic environment where the amplifier could be suspended would aid in further understanding the effect that the amplifier geometry has on angled IACC measurements.

7 Conclusion

This study compared a direct binaural capture of a Fender Twin Reverb using the Neumann KU100 with an Earthworks M50 as well as the M50 processed through KU100 HRTFs. Objective analysis showed both the KU100 and the M50 reproduced the amplifier's spectral directivity patterns. The KU100 maintained more consistent results at higher frequencies and elevations but exhibited a higher IACC value than the generic HRTF. Subjective testing showed clear trends towards the KU100 providing the most accurate elevation and distance perception in the participants' answers. Despite the M50 + HRTF exhibiting superior azimuth localization, the KU100 was selected by the majority of participants to be the most accurate representation of an amplifier in a room.

Expanding subjective testing to a larger and more diverse participant pool, as well as applying the tested methods to acoustic instruments, could substantiate the findings of this paper and expand the applicability of binaural recordings using dummy heads such as the KU100. This project highlights both the strengths and current limitations of direct binaural recordings and digitally rendered binaural captures which reinforces the need for perceptual testing in conjunction with objective analysis in spatial audio research.

8 Acknowledgments

This work was made possible by American University, Bias Studios, and the support of our friends and family. A special thanks to Thomas Tyra, Matthew Murphy, Brian Jacobs Rivera, Matthew Twiford, Wayne Romero, and Robert Dawson.

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