SOUND STRENGTH IN ACTIVE ACOUSTIC SYSTEMS

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1 INTRODUCTION

Active acoustic systems (AAS), also known as acoustic enhancement systems, have gained increasing prominence in multipurpose venues and rehearsal rooms in recent years. The decreasing cost of system components has facilitated their adoption in smaller halls. The main purpose of AAS is to alter room acoustic parameters like reverberation time or sound strength to provide adequate acoustics for various formats. The importance of an optimal balance between reverberation and sound strength for satisfactory musical performances has been emphasized by Rindel[1]. Specifically, small concert halls often struggle to accommodate symphonic music due to a common dilemma: achieving a desired reverberation time frequently results in excessively high sound strength, leading to a perception of excessive loudness. Conversely, when sound strength is at an appropriate level, the reverberation time tends to be too short. This inherent limitation restricts the versatility of such venues.

This paper investigates the behavior of sound strength (G) in three distinct room types: a small, medium, and large room, all equipped with an active acoustic system. To ensure high sound quality and the absence of artifacts, commonly used and thoroughly tested system presets, approved by engineering staff, the audience and artists, were employed for each venue. Room acoustic measurements were conducted to evaluate both reverberation times and sound strength. The measured results are then compared with theoretical predictions, and any observed discrepancies are highlighted. Previous research2 has indicated that sound strength (G) in small rooms equipped with purely recursive active acoustic systems does not consistently conform to theoretical expectations. This paper extends this research to hybrid systems and larger rooms.

2 THEORY

2.1 Reverberation Time (T)

Reverberation time (T) is widely recognized as a fundamental and arguably the most crucial metric in room acoustics. It quantifies the duration required for sound energy in a room to decay by 60 dB. An appropriate reverberation time is essential for a satisfactory perception of musical performances. An inadequate reverberation time, whether in terms of its duration or frequency response, can result in perceived sonic issues such as muddiness or shrillness, or a loss of intimacy and clarity if too long. Conversely, an excessively short reverberation time can lead to an audibly disjointed sound, characterized by insufficient sound blending and a sensation of excessive directness. It's important to note that while an adequate reverberation time is a prerequisite for a pleasant acoustic experience, numerous other parameters also contribute to these qualitative descriptions.

The measurement of impulse responses offers a robust and repeatable method, which is employed in this study. In addition to the frequency response of the reverberation time, the value for mid frequencies T_m is given for quick comparison between presets:

$$T_m = \frac{T_{500Hz} + T_{1kHz}}{2},$$

where T_{500Hz} and T_{1kHz} are the reverberation times of the 500 Hz and the 1 kHz octave band respectively[3]. To arrive at a comparable value for each preset, the values are averaged over all measurement positions. The resulting spatial mean reverberation time for mid frequencies is denoted $\bar{T}_m$.

2.2 Sound Strength (G)

Sound strength (G) quantifies the amplification provided by a room's acoustics. Its calculation involves comparing the integrated squared impulse response measured within the room to the free-field impulse response of the measurement system at a distance of 10 m.[3] The formula for G is given by:

$$G = 10 \cdot \log\left(\frac{\int_0^\tau p^2(t)dt}{\int_0^\tau p_{10}^2(t)dt}\right),$$

where $p(t)$ represents the measured impulse response in the room, $p_{10}(t)$ denotes the free field reference impulse response at a 10 m distance from the source, and τ is the time at which the impulse response level has decayed by 30 dB. As values for G are highly dependent on the position, they are not averaged over measurement positions in this work. For easier comparison the values for mid frequencies are calculated from the 500 Hz and 1 kHz octave bands, similarly to T_m, resulting in G_m.

The relationship between sound strength, reverberation time, and room volume is described by various theoretical frameworks. This study employs the revised diffuse field theory, as formulated by Barron and Lee[4]. they derived a source-receiver distance-dependent description:

$$G = 10 \cdot \log\left(\frac{100}{r^2} + 31200 \cdot \frac{T}{V} \cdot e^{-0.04 \cdot \frac{r}{T}}\right),$$

where r is the source-receiver distance, T the reverberation time, and V the room volume. The model takes into account that due to the attenuated direct sound and weaker early reflections in the rear sections of a concert hall, the sound level decreases towards the back, even within the reverberant sound field

Expanding upon the work of Barron and Lee, Aretz[5] further elucidated this dependency and its significance in the context of small concert halls. Additionally, Aretz demonstrated that mechanical variable acoustic systems (curtains and turning panels) can adapt both reverberation time and sound strength in accordance with the aforementioned dependencies.

2.3 Active Acoustic Systems (AAS)

Active Acoustic Systems (AAS) are electro-acoustic systems designed to extend the sound energy decay within a room by capturing the existing sound field and subsequently reproducing an altered version of it. AAS philosophies broadly fall into two categories based on their approach to feedback:

- Recursive systems intentionally maintain stable acoustic feedback to extend reverberation by re-injecting energy through loudspeakers.

- In-line systems suppress feedback through careful positioning of microphones, adding reverberation primarily through signal processing algorithms.

A third category, hybrid systems, combines elements of both recursive and in-line philosophies to leverage their respective advantages. In this paper, recursive and hybrid systems were measured. Therefore, in-line systems are left out in the following system descriptions.

Recursive systems primarily capture the existing reverberant sound field to generate additional reverberation. This means the inherent character of the passive acoustic energy decay is maintained while being extended. Recursive systems lower the absorption coefficient[6,7] and, therefore, decay curves are altered in their slope, not their form[2,6,7]. There are two primary principles for recursive AAS:

- 1-to-1 approach: Each microphone is independently connected to a single loudspeaker channel. This design preserves channel independence and permits medium to large distances between microphones and loudspeakers, decorrelating microphone inputs and facilitate maintaining stability.

- N-to-M approach: Every microphone is connected to every loudspeaker via a signal processing matrix. While sacrificing channel independence, this approach allows for a quadratically increasing channel count with added microphone-loudspeaker pairs, and distances between microphones but loudspeakers can vary considerably.

Hybrid systems strategically combine both AAS philosophies simultaneously, aiming to merge the immersive qualities of recursive systems with the predictable, algorithmically generated reverberation of in-line systems. Several approaches exist for this system architecture fusion.

One strategy involves operating two independent systems: a recursive AAS and an in-line AAS. Another approach integrates an algorithmic reverberation unit directly into the signal processing chain of a recursive system, thereby offering both recursive reverberation generation and algorithmic reverberation. Hybrid system with an algorithmic reverberation unit in the signal processing path show a similar behavior as coupled rooms[7].

3 EXPERIMENTAL SETUP AND RESULTS

Measurements were conducted in three distinct acoustic environments, varying in characteristics and volume: an office space, a medium-sized experimental concert venue, and a larger shoebox theater. All rooms were equipped with an Active Acoustic System (AAS) capable of operating in in-line, recursive, and hybrid modes (Amadeus Acoustics).

Measurements from the smallest room, Amadeus Hub, stem previous work[2] and were conducted in accordance with ISO 3382-1[3]. For both larger rooms, measurements were performed based on ISO 3382-1, employing six microphone positions and a single sound source position. Constraints in experimental time precluded the implementation of additional source positions. The excitation signal utilized in all measurements was an exponential sinus sweep, with a duration of 1.6 seconds per octave. The measurement software was RoomCapture v1.67. Acoustic instrumentation included six Behringer ECM8000 microphones, a 01dB dodecahedron loudspeaker as the sound source, and a Roland Octa-Capture audio interface. The entire measurement chain was calibrated for G (sound strength) measurements in an anechoic room[a]. The measured rooms are described in detail in the following subsection.

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[a] For the first measurement, the setup was calibrated in a reverberation chamber. Due to the bias of the measurement results for G, the calibration was redone in an anechoic chamber, between the first and both other measurements.

3.1 Measurement Environments

The initial measurements, part of a previous study[2], were conducted in the Amadeus Hub, an office space and sound laboratory belonging to Amadeus Acoustics in Vienna. This room, with a volume of $V_{AH} = 180\ m^3$, serves as a dedicated test environment. Its installed AAS comprises eight SoundTube IPD-RS62-EZ pendulum speakers, 24 Genelec 4410A wall-mounted speakers, and four Genelec F Two subwoofers. Acoustic capture is facilitated by 12 DPA 4098 super-cardioid microphones suspended from the ceiling. For these measurements, the AAS was configured in a purely recursive setting.

Figure 1: Rooms: Amadeus Hub (left), Klangtheater (middle), Halle E&G (right).

The second measurement environment was the Klangtheater, an experimental concert stage located at the University of Music and Performing Arts Vienna (mdw). This $V_{KT} = 1700\ m^3$ venue is designed for diverse performances, ranging from electro-acoustic music and orchestra rehearsals to chamber and jazz concerts. The installed AAS integrates 12 DPA 4098 microphones, 58 d&b 5S loudspeakers, and six d&b 18S subwoofers. Measurements in this venue were performed with the AAS configured in three distinct settings: one purely recursive, and two hybrid configurations.

The final experimental location was Halle E, an adaptable multi-purpose hall within Vienna's Museumsquartier. Spanning a volume of $V_{HE} = 17400\ m^3$, it can accommodate up to 1144 attendees, and its configurable seating arrangements facilitate a diverse calendar of events, ranging from orchestral performances over opera and theater to galas. The hall's AAS integrates 32 Electro-Voice SL12-2V loudspeakers positioned on walls to cover the audience, supplemented by Kling & Freitag CA1215 loudspeakers for ceiling and stage reinforcement. A d&b audiotechnik Y-Series main PA, along with frontfill and infill speakers, completes the AAS infrastructure. Overhead, multiple Audio-Technica U853 microphones capture ambient sound, while six DPA 4017 shotgun microphones are dedicated to on-stage pickup. The microphone array can be expanded with an additional six AKG CK98 units, and five Schoeps MK41 microphones are available for precise stage-front capture. A hybrid AAS configuration was employed for the measurements conducted in this venue.

All rooms are measured with two engineers present but without audience. The rooms were furnished as depicted in Figure 2.

3.2 Results – Reverberation Times (T_{30})

Reverberation times were determined from measured impulse responses, as previously described. For each experimental space, reverberation times were quantified for all investigated Active Acoustic System (AAS) presets, as well as for the inherent passive room acoustic condition. Figure 3 presents the measured reverberation times across frequencies. For the Amadeus Hub, measurements are displayed in octave bands to align with the representation in Ref.[1]. Conversely, measurements for the Klangtheater and Halle E are presented in 1/3-octave bands.

The upper-left panel of Figure 3 illustrates the reverberation times within the Amadeus Hub, the smallest of the three analyzed venues. The passive reverberation time (blue) exhibited a mid-frequency value of $\bar{T}_{m,off} = 0.39\,s$, with a slight increase observed at lower frequencies. Upon activation of the recursive active acoustic system, reverberation times increased across all octave bands (orange). At mid-frequencies, reverberation times rose to $\bar{T}_{m,on} = 0.56\,s$, representing a 44% augmentation. The increase was less pronounced at high frequencies (23% at the 2 kHz octave), while lower frequencies demonstrated a more substantial increase of 82%. It is pertinent to note that this experimental configuration was optimized for research objectives, and the observed increase in low-mid frequencies was attributed to minor sound coloration[1].

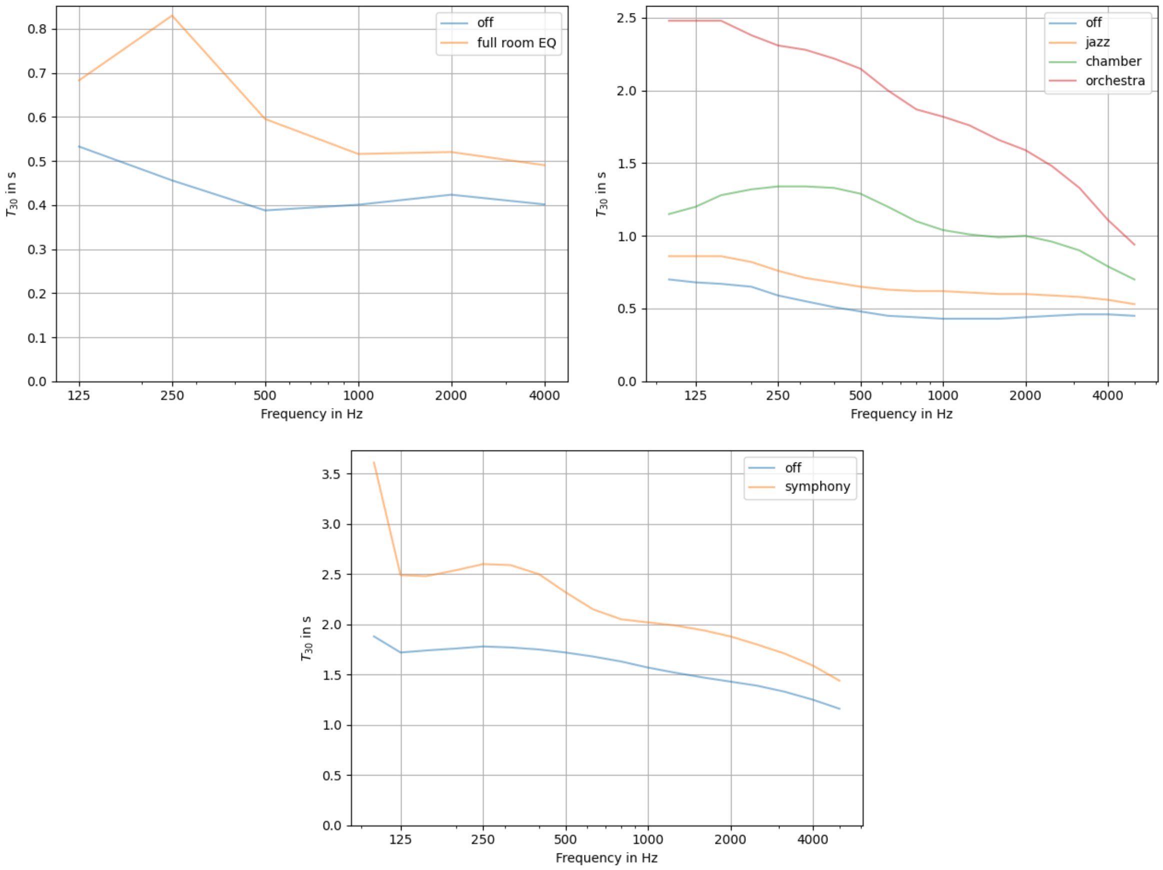

Figure 2: Mean reverberation times $\bar{T}_{30}$ over frequency in different AAS settings. Amadeus Hub (upper left), Klangtheater (upper right) and Halle E (lower).

Reverberation time measurements of the Klangtheater are presented in the upper-right panel of Figure 3. For this environment, one recursive and two hybrid AAS settings were evaluated in addition to the passive room condition. The mid-frequency reverberation time for the passive room (blue) was measured at $\bar{T}_{m,off} = 0.46\,s$. The employed AAS settings correspond to standard presets routinely utilized for performances within this venue. For each preset, a progressive increase in reverberation time relative to the preceding preset was observed across all 1/3-octave bands. The presets are designated according to their typical genre application: "Jazz" for jazz concerts, "chamber" for chamber ensembles, and "orchestra" for symphony orchestras. The mid-frequency reverberation times for these presets were $\bar{T}_{m,jazz} = 0.63\,s$ (orange), $\bar{T}_{m,cham} = 1.16\,s$ (green) and $\bar{T}_{m,orch} = 1.97\,s$ (red), respectively. These values correspond to relative increases of 37%, 152% and 328% at mid-frequencies when compared to the passive room condition. For the "jazz" preset, the increase was consistent across frequencies. In contrast, the other presets exhibited a greater increase at lower frequencies and a lesser increase at higher frequencies, which was intentional in this case.

The lower panel of Figure 3 illustrates the 1/3-octave band reverberation times within Halle E. The passive reverberation time (blue) at mid-frequencies was $\overline{T}_{m,off} = 1.64\ s$, with a decreasing trend towards higher frequencies. Activation of the hybrid active acoustic system resulted in an increase in reverberation times across all octave bands (orange). At mid-frequencies, reverberation times increased to $\overline{T}_{m,sym} = 2.18\ s$, representing a 33% increase. The increase in reverberation time was relatively constant at high frequencies, whereas a more pronounced increase was observed at lower frequencies.

3.3 Results – Sound Strength (G_{mid})

Sound strength values were derived from measured impulse responses, as previously detailed. Mid-frequency sound strength values were compared against theoretical predictions based on the model by Barron and Lee[4], which accounts for room volume and, in this work, mean mid-frequency reverberation time. This comparison is presented in Figure 4 for all venues. For each venue, the comparison includes every active acoustic system (AAS) preset and the passive room condition. The theoretical relationship is depicted as a continuous line, while measured sound strength values at each measurement position are marked as discrete points. Source-receiver distances for the measurement positions ranged from 1 m to 5 m for the Amadeus Hub, 5 m to 10 m for the Klangtheater, and 10 m to 30 m for Halle E.

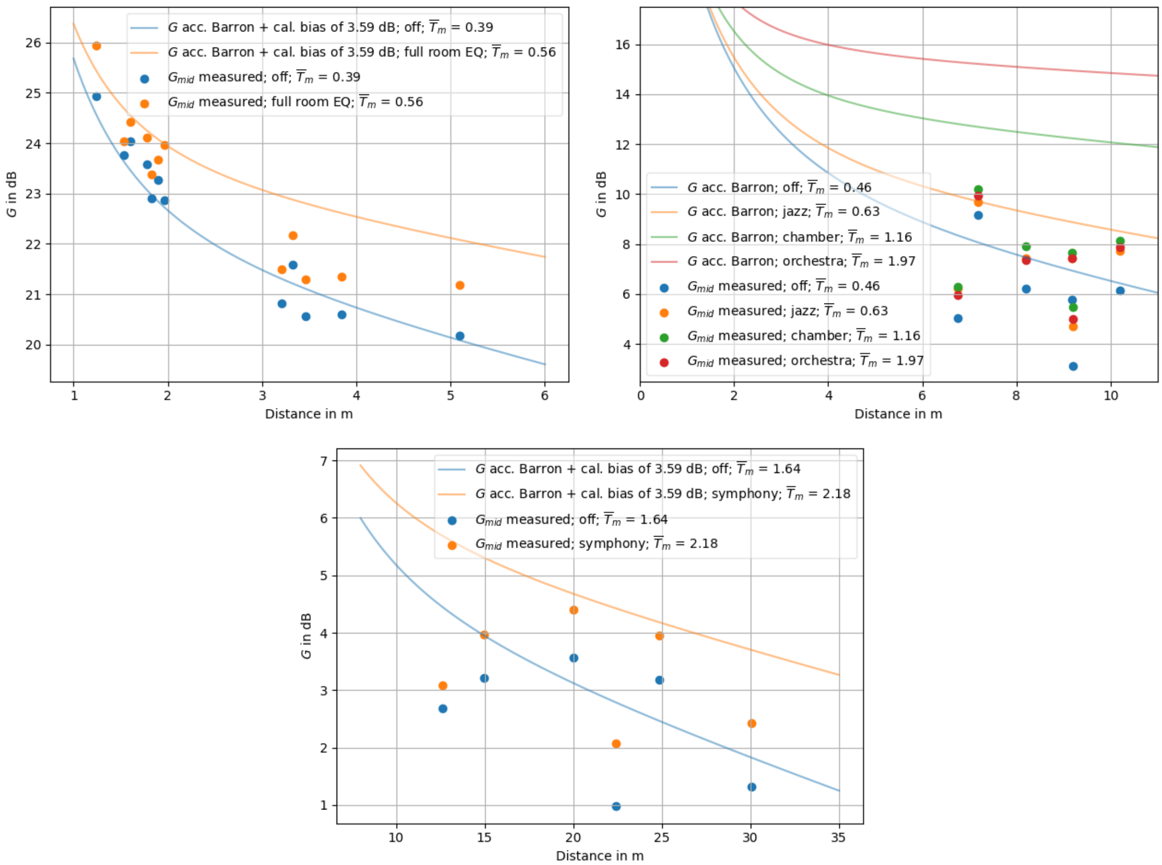

Figure 3: Sound strength G over source-receiver distance in different AAS settings. Amadeus Hub (upper left), Klangtheater (upper right) and Halle E (lower).

The upper-left panel of Figure 4 displays the results for the Amadeus Hub. Measured sound strength values for the passive room (blue dots) demonstrate good agreement with the theoretical predictions (blue line)[b]. However, with the recursive AAS activated, the increase in measured sound strength values (orange dots) was less pronounced than suggested by the theoretical relationship, which was calculated using the adjusted reverberation time and original room volume (orange line). While the reverberation time increased by 44%, which is more than eight times the just noticeable difference (JND) of 5%[3], sound strength increased by $1\ dB$, which is the JND[3].

A similar relationship was observed for the Klangtheater, as shown in the upper-right panel of Figure 4. The measured sound strength values for all AAS presets fell within a span of $\Delta G = 2.5\ dB$. In contrast, the theoretical dependency for the passive room would predict a span of up to $\Delta G = 8\ dB$ for the "orchestra" preset, which exhibited the highest mean mid-frequency reverberation time. Therefore, an increase of reverberation time by 328% resulted in an increase of G by $2.5 \cdot \mathrm{JND}$.

For Halle E, depicted in the lower panel of Figure 4, the measured sound strength values for the passive room (blue dots) corresponded well with the theoretical predictions (blue line). Similar to the Amadeus Hub, the measured increase in sound strength values with the recursive AAS activated (orange dots) was less than anticipated by the theoretical relationship, derived from the new reverberation time and room volume (orange line). An increase of reverberation time of 33% resulted in an increase of sound strength of $1\ dB$ $(1 \cdot \mathrm{JND})$.

4 CONCLUSION

This study investigated the impact of Active Acoustic Systems (AAS) on the reverberation time and sound strength within three distinct venues: the Amadeus Hub, Klangtheater, and Halle E. Reverberation times were consistently observed to increase with the activation of AAS presets across all venues, demonstrating the efficacy of these systems in altering the acoustic decay characteristics of a space.

Specifically, in the Amadeus Hub, the recursive AAS significantly increased reverberation times, with mid-frequencies experiencing a 44% rise. The Klangtheater demonstrated the versatility of AAS, where different presets ("jazz," "chamber," "orchestra") yielded progressively longer reverberation times, reaching up to a 328% increase at mid-frequencies for the "orchestra" preset relative to the passive room. This illustrates the ability of AAS to create a range of acoustic environments tailored to specific performance genres. In Halle E, one hybrid configuration (there would have been others with more and less reverberation gain) increased reverberation times, with a 33% increase at mid-frequencies.

Regarding sound strength, the measurements generally aligned with the theoretical predictions for the passive room conditions, confirming the validity of the model by Barron and Lee. However, a notable observation across all venues was that the increase in sound strength with the active AAS was less than predicted by theoretical relationships calculated solely based on the altered reverberation times and physical room volume. This suggests that the relationship between reverberation time modification by AAS and the resulting sound strength is more complex than a simple direct correlation with theoretical models. Factors beyond just reverberation time and room volume, potentially related to the specific implementation or energy distribution within the actively modified acoustic field, may play a significant role in determining the final sound strength.

[b] Note: A calibration bias of 3.59 dB was applied to the calculated sound strength curves, resulting in a consistent shift of both theoretical curves by this amount. Consequently, absolute sound strength values may differ from those presented; however, the relative differences discussed herein remain valid as all measurements within this venue were conducted under identical settings.

In conclusion, AAS effectively modifies reverberation times across frequencies and room sizes, offering substantial control over the acoustic character of a space. While reverberation times could be increased significantly, the expected increase in sound strength could not be observed in recursive nor hybrid systems. It was shown in Ref.[1] that the course of G over distance for the active system has the same slope as the passive room but shifted parallel. For the active system sound strength decays faster over distance than predicted by the model of Barron and Lee[4]. This suggests that natural reflections have a greater influence on sound strength than additional reflections added by AAS. Whereas Aretz[5] has shown that the Barron and Lee model fits for conventional variable acoustics, the model does not hold for active acoustic systems. However, our results suggest that in small halls, reverberation time can be significantly extended without a significant increase in sound strength as suggested by conventional theory. The highest sound strength increase was found to be below $\Delta G \leq 2.5 \cdot \mathrm{JND}$ for quadrupling the reverberation time in a medium sized room (1700 m³). Consequently, active acoustic systems offer substantial benefits for smaller venues. These spaces could be acoustically designed for a desired sound strength and a correspondingly short reverberation time, which can then be extended to the preferred value without substantially elevating the sound strength. This capability enables the successful performance of symphonic music in small concert halls with the desired acoustic characteristics and also presents significant advantages for rehearsal room acoustics.

Future research should be conducted to investigate the underlying mechanisms influencing sound strength in actively controlled acoustic environments to refine predictive models for AAS and optimize AAS design for specific acoustic outcomes. Furthermore, G_{early} and G_{late}, as well as EDT, should be compared to investigate the temporal influence of AAS on sound strength.

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