

# ROOM ACOUSTICS MISMATCHES OF REHEARSAL SPACES AND CONCERT HALLS AND THEIR IMPACT ON MUSIC PERFORMANCE

G Dedousis      Laboratory of Music Acoustics & Technology (LabMAT), NKUA  
K Bakogiannis   Laboratory of Music Acoustics & Technology (LabMAT), NKUA  
A Andreopoulou   Laboratory of Music Acoustics & Technology (LabMAT), NKUA  
A Georgaki        Laboratory of Music Acoustics & Technology (LabMAT), NKUA

## 1 INTRODUCTION

The acoustic experience of audiences in concert halls<sup>1</sup>, along with the appropriate terms for describing it<sup>2</sup>, has undergone extensive research. However, less research has been done to understand what performers experience onstage. While musicians and listeners might have similar expectations about the qualities of sound, the formers' aural perception differ as they also need to take into consideration, not only the sound of their instrument but, also, the sound produced by other musicians, and how the performance room affects it<sup>3</sup>. Additionally, as conductors can influence the sound produced by the orchestra, they may have their own preferences, such as performing on stages with non-reflective surfaces above the ensemble, while, oftentimes, they may agree with the audience and musicians, such as preferring narrow and tall stages<sup>4</sup>.

In addition to the above, not only is it uncommon for rehearsals to take place in performance stages, but these two settings may also have different acoustic qualities. While this may sometimes be desirable<sup>5</sup>, research suggests certain guidelines for the rehearsal spaces. For vocal rehearsals, it is recommended to take place in moderately dampened rooms with low reverberation time to facilitate error detection<sup>6</sup>. Keeping it under one second can provide performers with confidence and a reference point while singing<sup>7,8</sup>. Despite this, there are examples such as vocational training courses in Turkey held in acoustically inadequate rooms<sup>9</sup> or in Finland, where renovated spaces seem unsuitable for holding loud music lessons<sup>10</sup>. Since classrooms are often used for both music instruction/lectures and rehearsals, this situation is predictable. Thus, the attempt to adjust acoustics to meet the requirements of both speech and music appears impractical, due to their differing acoustic needs<sup>11</sup>.

Consequently, particularly regarding vocal performance, several strategies have been developed to assist with the transition from the acoustics of rehearsal spaces to those present in performance venues<sup>5,12,13</sup>. Among these strategies, Virtual and Augmented Reality (VR/AR) technologies have been suggested for investigating how room acoustics and auditory experiences affect performance, and for assisting performers in adjusting to the acoustic characteristics of performance venues, even when physically absent<sup>14–16</sup>. The current study revisits the mismatch between the acoustics of rehearsal and performance spaces and the adaptation strategies singers use to manage this mismatch. It examines how virtual spatial audio technology can serve as a tool to assist performers in navigating this transition and presents initial feedback on this approach.

## 2 ADAPTING TO ROOM ACOUSTICS

Numerous studies have extensively examined how room acoustics affect musicians' live performances, especially the acoustical disparities among concert venues that lead to variations in musical execution<sup>17,18</sup>. Musicians often modify their approach to accommodate such acoustic differences. For instance, in spaces with long reverberation time, instrumentalists tend to shorten the length of staccato notes, enhancing sound clarity<sup>19</sup>. In general, when faced with long reverberation times, individual musicians, or small ensembles, tend to adopt a slower tempo for their performance<sup>20</sup>.

Akin adjustments may occur in virtual acoustic simulations, where musicians adjust staccato timing, sound volume, tempo, timbre, and vibrato intensity based on the reverberation time of the virtual environment<sup>21,22</sup>. Notably, these adaptation strategies, whether in physical or simulated settings, may not always be a conscious decision made by the musicians<sup>23</sup>.

Singers and choristers seem to employ similar strategies as instrumentalists. They are more content and achieve improved clarity in both vocal enunciation and musical rendition when performing in spaces characterized by early reflections with significant high-frequency content<sup>24</sup>. However, early reflections longer than 40ms appear to render vocal performances more difficult<sup>25</sup>. Furthermore, there seems to exist a correlation between the length of reverberation time and vocal comfort, with singers generally favoring spaces with shorter reverberation times<sup>26</sup> (with 'drier' rooms providing a better environment for maintaining tempo and rhythmic accuracy).

It has also been observed that the dynamic range and the sound pressure level of a singer's voice relates to the reverberation time<sup>19</sup>. On the other hand, it appears that tonal accuracy is unaffected by this<sup>26</sup>. As the duration of reverberation decreases and spatial absorption increases, the vocal output level also tends to increase<sup>12,19,27</sup>. Moreover, the acoustic characteristics of the performance space can significantly affect the timbre and vocal quality. Singers may opt to enhance their voice's resonances<sup>19</sup> or, in 'drier' rooms, adjust their formant frequencies higher<sup>27</sup>.

Studies on small vocal groups suggest that strong early reflections can benefit the performance of fast-paced repertoire<sup>28</sup>. Additionally, reverberation time can potentially define the whole repertoire<sup>19</sup>. However, there exist studies with conflicting results, for example on whether tonal accuracy is affected in different acoustic environments<sup>12</sup>, such as a rehearsal room and a performance hall, or not<sup>26</sup>.

Vocalists and choristers, like instrumentalists, employ individual strategies to adapt to different room acoustics<sup>29</sup>, which can be influenced by various factors, ranging from objective ones, such as the visual and auditory feedback of the performance space, to subjective, such as emotional state and physical condition<sup>14,15,19,30</sup>. Furthermore, formal singing lessons and accumulated performance experience may influence vocalists' strategic approaches in different scenarios<sup>31</sup>.

Although these strategies are typically unconscious<sup>22</sup> and highly individual<sup>29</sup>, research indicates they remain consistent regardless of whether the performance takes place in physical or virtual acoustic environments<sup>32</sup>. This finding highlights the potential value of using virtual acoustic simulations as effective substitutes for physical performance spaces when investigating on-stage acoustics and their influence on the quality and precision of performances.

### 3 PERFORMING IN VIRTUAL PLACES

Many of the musical performances during the COVID-19 pandemic were conducted remotely via the web using virtual reality technology<sup>33</sup> with relevant research gaining momentum<sup>34</sup>. However, comparable performances had already been conducted using systems<sup>35</sup> demonstrating the capacity to assist performers with rehearsing and performing in a manner that mitigates the social and performance anxieties that live performances can sometimes induce<sup>14,16,35</sup>. Furthermore, users of this technology seem to have positive views when using them<sup>14,36</sup>.

Music projects in the realm of virtual, augmented, mixed, and extended reality, along with augmented virtuality, can be classified as "Musical Extended Reality" (Musical XR)<sup>34</sup>. These projects emphasize the immersive experience of both visual and auditory aspects in remote music interactions<sup>14</sup>, while also evaluating the effectiveness of virtual music instruction<sup>36</sup>. The Virtual Concert Hall (VCH) combines visual signals and dynamic binaural sound to create simulated performance settings<sup>37</sup>, while VR Rehearse & Perform utilizes VR headsets and headphones to virtually place musicians in spaces of their choice<sup>16</sup> and was developed using ongoing feedback from musicians and experts.

While many projects rely on binaural sound, the use of microphones and loudspeakers has also been investigated<sup>15</sup>.

Music XR technology is increasingly being used to study how musicians perceive and perform in various acoustic environments. It also offers the means to analyze musicians' interactions, both among themselves and with the virtual performance spaces, in the context of music<sup>34,38</sup>. This study investigates the use of Music XR technology to assist singers in familiarizing themselves with the on-stage acoustic conditions in their selected performance venue, by situating themselves in different positions in a virtual choir, performing the repertoire of their preference. The research follows previous practices, utilizing continuous feedback obtained from singers, conductors, and music educators.

## 4 CHORISTERS' INQUIRY

Twenty-two ( $N = 22$ ) choristers, all undergraduate students from the Department of Music Studies (NKUA), completed a questionnaire regarding their perceptions of the sound produced by their choir in rehearsal and performance spaces. The participants had a median age of 22 years (min: 18, max: 30 years). The length of time they had spent singing in a choir ranged from 2 months to 17 years (median: 9 years). 14 of them (64%) had taken formal singing lessons, with a median duration of 1,75 years.

One of the rooms that the participants rehearse is shown in Figure 1. It was recently acoustically treated and repurposed as a music classroom. The room measures 10,98m (d) x 6,08m (w) x 3,04m (h). On one end, there are windows with blinds and several wooden bookcases, while the other end has a high bookcase and sound absorption panels. The same is true for the rear wall (not depicted in Figure 1). On the opposite wall, there is a wooden door with curtains in front of it. Sound absorption panels are also on the ceiling and the floor is made of wood. Although the windows and the wooden surfaces suggest that this is a 'live' room, its sound characteristics seem to be suitable for a rehearsal space, as will be discussed later in this chapter.

The University's choir performs at various venues, including the Great Hall (shown in Figure 2), situated in the Main Building of the National and Kapodistrian University of Athens, located in the center of Athens. The space has limited sound treatment, with only a carpet on the floor, and, as such, can be considered a very 'live' room. Except for the walls, wood, marble, and windows make up the majority of the surfaces. The primary level has a length of 37,39m, a width of 9,6m, and a height range between 7,14m and 7,93m. The two elevated sides, which rise 1,40m from the floor, measure 21,72m (l) x 3,4m (d) x 5,9m (h).

As depicted in Figure 3, choir rehearsals may take place in different types of spaces. The most common are standard classrooms, typically used for lectures, and music classrooms, such as the one shown in Figure 1, which are specifically designed for musical instruction. Some participants rehearse in concert halls (32%), while a smaller fraction in other spaces such as ballet rooms (4,5%) and recording studios (4,5%). These findings are consistent with previous research indicating that music rehearsals commonly occur in multi-purpose classrooms<sup>11</sup>. Notably, three of the four most common responses referred to spaces acoustically treated for music (music classroom, concert hall, recording studio). This unexpected finding might reflect the conductor's attempts to achieve acoustically optimal rehearsals. Further research, with a larger and more diverse group of participants, could potentially shed more light on this matter.

Figure 4 presents choristers' perspectives on the differences in sound perception between rehearsal and performance spaces. The participants seem to be aware of the sound they produce during rehearsals, with about 1/3 expressing moderate satisfaction with the space they rehearse, and the remainder expressing high to complete satisfaction. This could be because most of their rehearsals occur in the sound-treated music classroom depicted in Figure 1. However, the majority of participants report a significant difference (ranging from very to extremely) in the sound they perceive while singing



Figure 1. Rehearsal space (Classroom 917, NKUA).



Figure 2. Performance space (Great Hall, Main Building NKUA).

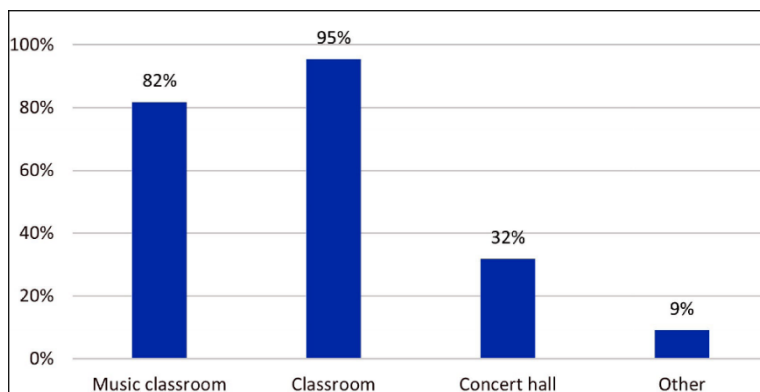


Figure 3. Choristers' usual rehearsal space.

in a performance space relative to that experienced during rehearsals, with less than 1/3 stating otherwise. These results align with prior research on the topic <sup>5,12</sup>.

Combining the response distributions in Figures 3 and 4 can lead to the conclusion that, the alteration in the perceived acoustic impression is not limited to the transition between rehearsal and performance venues. Even in cases of rehearsals taking place within performance halls, a significant contrast in the auditory experience persists between rehearsals and performances. Given the preliminary nature of this study, further empirical evidence is needed to gain a deeper understanding of the factors this is happening, its potential impact on choristers, and the necessary strategies to facilitate a smooth transition between these auditory environments.

Figure 5 illustrates choristers' adaptation strategies to adjust for dissimilar room acoustics, including modifications to loudness (95%), intonation (73%), timbre (64%), tempo (41%), and other (directivity, singing technique, chorister's position in the choir, layout of the choir, etc.). It should be noted that those most frequently cited, such as alterations in loudness, intonation, timbre, and tempo, are in line with previous research<sup>12,19–22,26,27,29</sup>. Vocal technique adjustments, mentioned by 4,5% of participants,

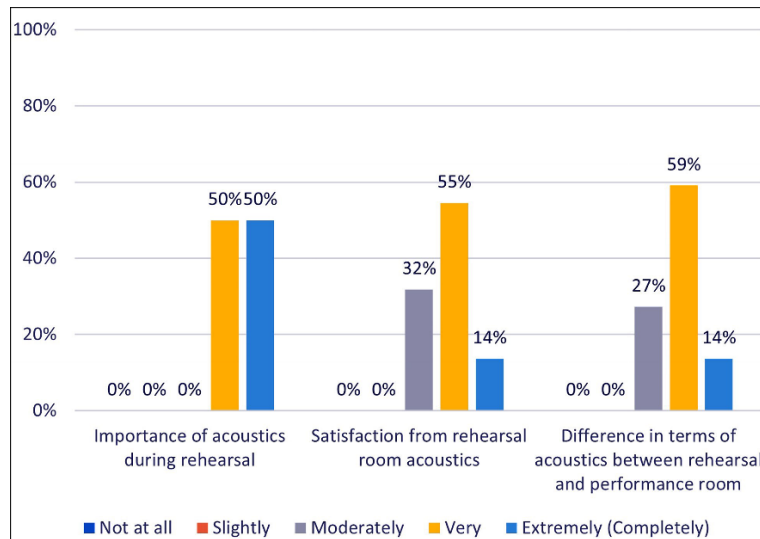


Figure 4. Choristers' responses.

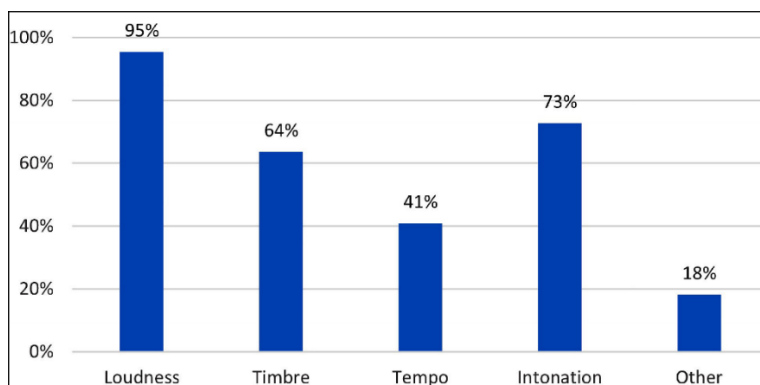


Figure 5. Choristers' adaptation strategies.

refer to the methods, such as efficient breathing, acquired through singing training. This is in line with the literature which suggests that experienced singers tend to choose spaces with different reverberation times than novices<sup>19</sup>. The spatial arrangement of choristers and height differences among them, which often involves risers, significantly impacts auditory perception<sup>39</sup>. A small group (4,5%) confirms altering choir position or even layout (4,5%) for this purpose.

## 5 DEVELOPMENT AND ASSESSMENT

### 5.1 Development of the prototype

The above presents a preliminary report on choristers' sound perception across varied rooms and the strategies they employ to adapt. The research idea behind this project is to design a tool to facilitate their transition from rehearsal to performance spaces, allowing for a virtual selection of rooms and moving between various positions within a virtual choir, performing the repertoire of their choice.

Using the Max/MSP programming environment, a prototype tool (Figure 6), was designed featuring ambisonics choir recordings, from physical concert halls and rehearsal spaces, which were captured using 3 first-order ambisonics microphones positioned in fixed locations within a choir (far-left front, far-right front, center back). Currently, these recordings feature the acoustic properties of the room without any option for modification, but our plan is to replace them with anechoic recordings providing users the ability to apply different room characteristics using Room Impulse Responses (RIR).

At present, the recorded content is binauralized for headphone audition using a non-individualized, generic Head-Related Transfer Function (HRTF), statically (i.e., no head-tracking). The result is a fixed audio auralization where users can be virtually situated within three pre-determined positions in the virtual choir, facing the conductor.

Although this version of the tool is limited in terms of repertoire, it includes diverse music genres, including classical music, Greek folk songs, popular music, and children's tunes, enabling initial evaluations of usability and usefulness by field experts.

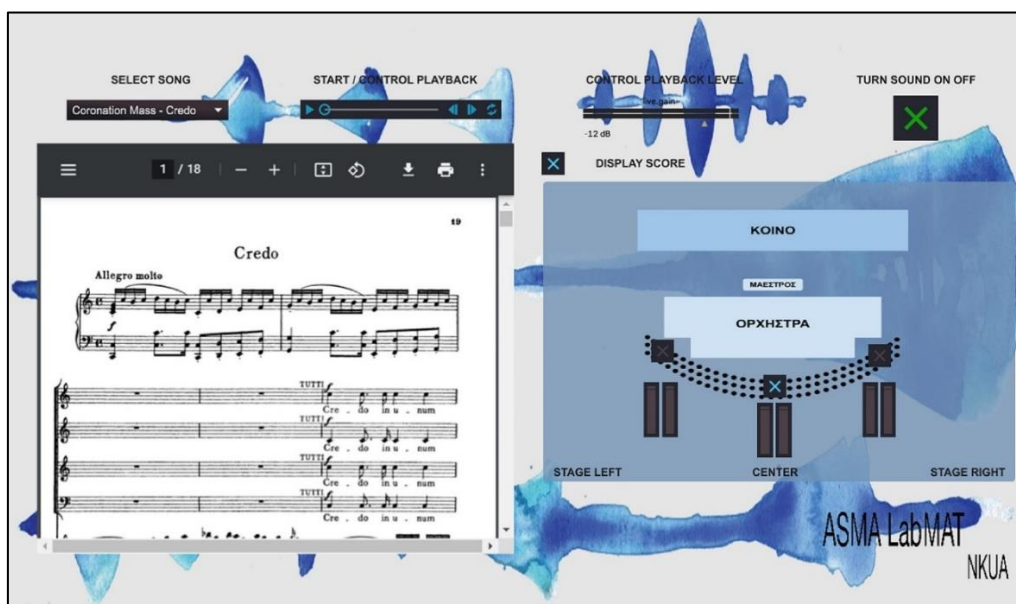


Figure 6. User interface of the preliminary version of the tool.

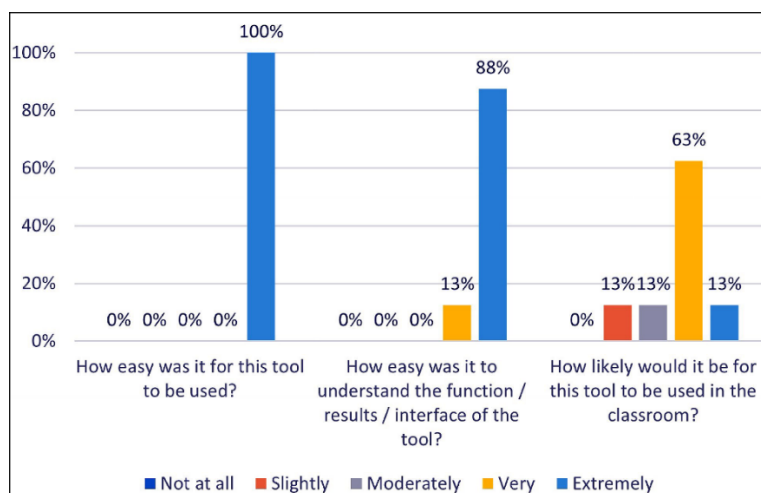


Figure 7. Music teachers' and conductors' responses.

## 5.2 Preliminary evaluation

After completing the initial development phase of the tool, an alpha-version testing was conducted by making an open call to music educators and conductors. Participants were fully introduced to the tool's concept and functionality, and, after using it, they completed an evaluation questionnaire. A total of eight questionnaires (N=8) were completed. This initial study focused primarily on the usability,

functionality, and potential classroom application of the tool, rather than immersion and realism due to uncontrollable listening conditions (the audition space and type of headphones used by each participant were not fixed). The formal evaluation study will investigate these aspects.

Figure 7 shows that the tool's usability and functionality received notably positive ratings, suggesting that its design is headed in the right direction. However, evaluations on the tool's appropriateness for classroom use were less definitive, perhaps because of the Greek schools' limited music curriculum (1 hour per week) and conservatories, the latter mainly following a curriculum that was established in 1957 (Greek Law 229/A/1957), which, as participants noted, allows for minimal time for such tools.

Other comments from participants included 4 primary topics as identified in the open-ended questions section. 38% of the participants expressed the desire for enhanced (free) navigation within the virtual environment, enabling them to isolate each singer or instrument, a feature that requires, as mentioned earlier, different data collection methods. Moreover, 25% of the participants advocated expanding the tool's capabilities to accommodate different ensembles. Figure 6 illustrates the interface of the prototype which was asked to become as intuitive as possible by 25% of the participants, while 13% of them expressed interest in a multi-user simultaneous function. In general, the educational perspectives of the tool were favorably mentioned by the participants.

## **6 CONCLUSIONS AND FUTURE WORK**

This study investigated the potential impact of acoustic differences between rehearsal spaces and concert halls on music performance, with a focus on singers. It also examined the adaptation and compensation mechanisms they employ to address these differences. Additionally, the study explores the use of XR Music technology in this context, as a basis for conceptualizing and exploring a tool. This tool aims to familiarize singers with the on-stage acoustic conditions of a chosen concert hall. Through virtual positioning within a virtual choir and the ability to perform a selected repertoire, choristers can adapt to varying acoustic environments and enhance their integration within a choir using auditory spatialization. Currently, users can virtually immerse themselves among fellow musicians in predetermined choir positions using headphones and static, non-individualized binaural audio content. This enables them to understand how positioning and on-stage acoustics affect auditory feedback.

Future work involves integrating higher-order ambisonics and dynamic binaural rendering through head-tracking and personalized HRTF data. This will allow choir members to maneuver freely and in real-time throughout the ensemble, virtually placing themselves in a broader range of concert halls with simulated acoustics. The next phase includes gathering data, which involves music recordings in anechoic rooms and Room Impulse Response (RIR) recordings from various performance venues and practice rooms to simulate individualized acoustic spaces. The musical selection will increase in quantity and variety. The last stage of this project envisions incorporating visual cues, a significant step towards creating an XR Music educational tool.

### **Acknowledgments**

Part of this research work was supported by the Hellenic Foundation for Research and Innovation (HFRI) under the "First Call for HFRI Research Projects to support Faculty members and Researchers and the procurement of high-cost research equipment grant" (Project Number: HFRIFM17- 3832).

## **7 REFERENCES**

1. M. Barron, *Auditorium Acoustics and Architectural Design*, 2nd ed. (Spon Press, 2009).
2. A. Kuusinen and T. Lokki, "Wheel of Concert Hall Acoustics," *Acta Acustica united with Acustica* 103(2), 185–188 (2017).

3. J. J. Dammerud, "Stage Acoustics for Symphony Orchestras in Concert Halls," University of Bath (2009).
4. J. Meyer, "Acoustical Demands for the Conductor's Location," *Building Acoustics* 15(2), 79–94 (2008).
5. N. G. Patrick and C. R. Boner, "Acoustics of School-Band Rehearsal Rooms," *The Journal of the Acoustical Society of America* 41(1), 215–219 (1967).
6. J. A. Bartle, *Sound Advice: Becoming a Better Children's Choir Conductor* (Oxford University Press, USA, 2003).
7. J. Kramme, "Applications of Acoustical Principles to Selected Problems Arising During Choral Rehearsals," *The Choral Journal* 18(7), 5–13 (1978).
8. Ö. Sinal and S. Yilmazer, "A Comparative Study on Indoor Sound Quality of the Practice Rooms upon Classical Singing Trainees' Preference," in *Proceedings of Euronoise 2015*, C. Glorieux, ed. (2015), pp. 697–702.
9. M. Gök and Ç. Sen, "Evaluation of the Physical and Acoustical Competences of Vocational Music Education Institutions in Terms of the Requirements of Music Education," *International Online Journal of Education and Teaching* 9(1), 284–307 (2022).
10. H. Koskinen, E. Toppila, and P. Olkinuora, "Facilities for Music Education and Their Acoustical Design," *International Journal of Occupational Safety and Ergonomics* 16(1), 93–104 (2010).
11. A. Aslan, A. Oktav, and B. Metin, "Determination of the acoustical performance of multipurpose music classrooms," *Architectural Science Review* 0(0), 1–15 (2022).
12. K. S. Hom, "The effect of two different rooms on acoustical and perceptual measures of SATB choir sound," PhD Thesis, University of Kansas (2013).
13. L. S.-J. Tsaih, "Soundscape of music rehearsal in band room," Ph.D., University of Florida (2011).
14. L. Aufegger, R. Perkins, D. Wasley, and A. Williamon, "Musicians' perceptions and experiences of using simulation training to develop performance skills," *Psychology of Music* 45(3), 417–431 (2017).
15. E. K. Canfield-Dafilou, E. F. Callery, J. S. Abel, and J. Berger, "A Method for Studying Interactions between Music Performance and Rooms with Real-Time Virtual Acoustics," in *Audio Engineering Society Convention 146* (Audio Engineering Society, 2019).
16. S. Ppali, V. Lalioti, B. Branch, C. S. Ang, A. J. Thomas, B. S. Wohl, and A. Covaci, "Keep the VRhythm going: A musician-centred study investigating how Virtual Reality can support creative musical practice," in *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems, CHI '22* (Association for Computing Machinery, 2022), pp. 1–19.
17. Z. S. Kalkandjiev and S. Weinzierl, "The influence of room acoustics on solo music performance: An empirical case study," *Acta Acustica united with Acustica* 99(3), 433–441 (2013).
18. J. Berg, S. Jullander, P. Sundkvist, and H. Kjekshus, "The Influence of Room Acoustics on Musical Performance and Interpretation - A Pilot Study," in (Audio Engineering Society, 2016).
19. K. Kittimathaveenan and M. Park, "The influence of stage acoustics on the singers' performance and perception: A pilot study," in *Audio Engineering Society Convention 151* (Audio Engineering Society, 2021).
20. J. Berg, "Concert Hall Acoustics' Influence on the Tempo of Musical Performances," in (Audio Engineering Society, Inc., 2019).
21. K. Kato, K. Ueno, and K. Kawai, "Effect of Room Acoustics on Musicians' Performance. Part II: Audio Analysis of the Variations in Performed Sound Signals," *Acta Acustica united with Acustica* 101(4), 743–759 (2015).
22. Z. S. Kalkandjiev and S. Weinzierl, "The influence of room acoustics on solo music performance: An experimental study," *Psychomusicology* 25(3), 195 (2015).
23. Z. S. Kalkandjiev and S. Weinzierl, "Room acoustics viewed from the stage: Solo performers' adjustments to the acoustical environment," in *International Symposium on Room Acoustics* (2013), pp. 9–11.
24. D. B. Fry, "The singer and the auditorium," *Journal of Sound and Vibration* 69(1), 139–142 (1980).



25. A. H. Marshall and J. Meyer, "The Directivity and Auditory Impressions of Singers," *Acta Acustica united with Acustica* 58(3), 130–140 (1985).
26. T. Fischinger, K. Frieler, and J. Louhivuori, "Influence of virtual room acoustics on choir singing.," *Psychomusicology: Music, Mind, and Brain* 25(3), 208 (2015).
27. S. Ternström, "Long-time average spectrum characteristics of different choirs in different rooms," *Voice (UK)* 2, 55–77 (1993).
28. D. Noson, S. Sato, H. Sakai, and Y. Ando, "SINGER RESPONSES TO SOUND FIELDS WITH A SIMULATED REFLECTION," *Journal of Sound and Vibration* 232(1), 39–51 (2000).
29. P. Luizard, J. Steffens, and S. Weinzierl, "Singing in different rooms: Common or individual adaptation patterns to the acoustic conditions?," *The Journal of the Acoustical Society of America* 147(2), EL132–EL137 (2020).
30. R. Parncutt and G. McPherson, *The Science and Psychology of Music Performance: Creative Strategies for Teaching and Learning* (Oxford University Press, 2002).
31. Ö. Sinal and S. Yilmazer, "Effects of perceived singing effort on classical singers' reverberation time preferences towards music practice rooms," *Applied Acoustics* 136, 132–138 (2018).
32. P. Luizard, E. Brauer, and S. Weinzierl, "Singing in Physical and Virtual Environments: How Performers Adapt to Room Acoustical Conditions," in (Audio Engineering Society, 2019).
33. B. Mróz, P. Ody, and B. Kostek, "Creating a Remote Choir Performance Recording Based on an Ambisonic Approach," *Applied Sciences* 12(7), 3316 (2022).
34. L. Turchet, R. Hamilton, and A. Çamcı, "Music in Extended Realities," *IEEE Access* 9, 15810–15832 (2021).
35. S. Serafin, A. Adjorlu, L. Andersen, and N. Andersen, "Singing in Virtual Reality with the Danish National Children's Choir," in *Perception, Representations, Image, Sound, Music*, R. Kronland-Martinet, S. Ystad, and M. Aramaki, eds., *Lecture Notes in Computer Science* (Springer International Publishing, 2021), pp. 563–574.
36. K. Pedersen, V. Hulusic, P. Amelidis, and T. Slattery, "Spatialised Audio in a Custom-Built OpenGL-based Ear Training Virtual Environment," *IEEE Computer Graphics and Applications* 40(5), 67–81 (2020).
37. H.-J. Maempel and M. Horn, "The Virtual Concert Hall—A Research Tool for the Experimental Investigation of Audiovisual Room Perception," *International Journal on Stereo & Immersive Media* 1(1), 78–98 (2017).
38. J. Brereton, "Music perception and performance in virtual acoustic spaces," in *Body, Sound, and Space in Music and Beyond: Multimodal Explorations*, C. Wöllner, ed., 1st ed., *SEMPRE Studies in The Psychology of Music* (Routledge, 2016), pp. 211–234.
39. J. F. Daugherty, M. L. Grady, and R. C. Coffeen, "Effects of choir spacing and riser step heights on acoustic and perceptual measures of SATB choir sound acquired from four microphone positions in two performance halls," *Journal of Research in Music Education* 67(3), 355–371 (2019).