Audio Engineering Society

Convention Express Paper 392

Presented at the AES 159th Convention

2025 October 23–25, Long Beach, CA, USA

This Express Paper was selected on the basis of a submitted synopsis that has been peer-reviewed by at least two qualified anonymous reviewers. The complete manuscript was not peer reviewed. This Express 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.

Virtual acoustics for choir singers: Exploring the impact of choir spacing on singer perception

Kajornsak Kittimathaveenan[1], Jakob Alfredsson[1], Munhum Park[2], and Sten Ternström[1]

[1]*Division of Speech, Music and Hearing, KTH Royal Institute of Technology, Stockholm, Sweden*

[2]*Institute of Music, Science and Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand*

Correspondence should be addressed to Kajornsak Kittimathaveenan (kkit@kth.se)

ABSTRACT

Choir spacing—the physical arrangement and distance between singers—is known to influence both ensemble sound and individual singing experience. However, systematic perceptual studies remain limited due to the challenges of conducting controlled experiments with full choirs. This study presents a virtual acoustics system designed to investigate spacing effects under repeatable and controlled conditions. Anechoic recordings were combined with binaural room impulse responses (BRIRs) simulated in Room Acoustics for Virtual ENvironments (RAVEN) to recreate a concert hall environment. In each session, one participant sang live with spatialized pre-recorded choir voices rendered over closed-back headphones, with EQ compensation applied to their own voice. Thirty-nine experienced choir singers performed under three spacing conditions: Close, Lateral, and Circumambient. After each condition, participants completed a questionnaire assessing perception of self and others, vocal production, and overall preferences. Results indicated that spread formations (Lateral and Circumambient) significantly improved self-monitoring and tuning. Perception of other sections showed mixed results and was not consistently affected by spacing. Vocal effort ratings did not differ significantly, while vocal technique adjustments were border-line significant, with greater adjustment reported in the closer formation. Most singers preferred spread formation for concert settings. The study demonstrates the feasibility of using virtual acoustics to explore spacing effects in choral performance.

1 Introduction

Research in choir acoustics faces several challenges when experiments are conducted in physical spaces. These include logistical complexity, limited control over acoustic conditions, difficulty in randomizing stimuli, and the need for consistent performance across repetitions with all singers and the conductor [1–5]. Such constraints make it difficult to carry out controlled and repeatable studies with a full choir. This is why Virtual Acoustic Environments (VAEs) have been adopted, offering greater experimental control and repeatability. Several studies have used VAEs to investigate both individual singers [6–10] and vocal ensembles [11–16].

Choir spacing, referring to the physical arrangement and spacing among singers, is among the main topics in choral research. It is known to influence both the acoustic properties of the ensemble sound and singers' individual experiences [2, 17–18]. However, systematic studies on choir spacing remain limited, due to the logistical challenges of conducting controlled experiments with live choirs.

This study introduces a virtual acoustics system designed to examine how choir spacing influences singers' perception and vocal production. Using anechoic recordings, simulated room acoustics, and spatial audio rendering, the system enables a single singer to perform their part while hearing spatialized

recordings of other choir members through headphones.

Section 2 describes the implementation of the virtual acoustics system, the experimental protocol, and the perceptual survey. Section 3 presents and discusses the results. Conclusions and directions for future work are provided in Section 4.

2 Methods

2.1 Virtual acoustic environment

This study employed a virtual acoustic environment to simulate choir performance in a large concert hall. The system was designed to allow one singer at a time to perform live while hearing the spatialized voices of the other choir members rendered in real time. The simulation combined anechoic recordings, binaural room impulse responses (BRIRs) generated by using the Room Acoustics for Virtual ENvironments (RAVEN, version 2019.v3) software [19–20], and real-time signal processing to create a hybrid ensemble experience over headphones.

The following subsections describe the simulation of virtual singers in the model of the Concertgebouw, the design of the choir formations, and the auralization and recording setup of both the virtual choir and the participant's live voice.

2.1.1 Virtual choir construction

To construct the virtual choir, the system combined pre-recorded anechoic recordings of individual singers with BRIRs generated from sources to receiver positions in a geometrical model of the Concertgebouw in Amsterdam, provided with RAVEN.

Each source position represented a virtual choir singer, while the receiver position corresponded to the participant's listening location during the experiment. One receiver was used per session, placed at the listening location corresponding to the participant's voice part (e.g., in the Soprano section). Across sessions, four receiver positions were simulated to represent Alto, Tenor, and Bass listening perspectives.

The BRIRs were then convolved with dry recordings of singers, resulting in signals representing how the participant would have heard each choir member from their respective position. These spatialized signals were used to simulate the voices of the other choir members in a virtual choir setting.

Simulation of virtual singers:
To recreate the singing situation, the interaural center of the binaural receiver was positioned 10 cm behind and 6 cm above each source, following the configuration in [11]. This configuration was then applied to 15 of the 16 virtual choir singers, each modeled as an individual sound source with one position intentionally left unoccupied to represent the participant's location.

At each source position, singer directivity was applied, and at the receiver position, head-related transfer functions (HRTFs) were included to render spatial characteristics. For the 15 virtual choir sources, the BRIRs included the direct sound along with early reflections and late reverberation. For the participant's voice, however, the direct sound was excluded from the BRIR. The rendering of the participant's live voice is described in Section 2.1.2.

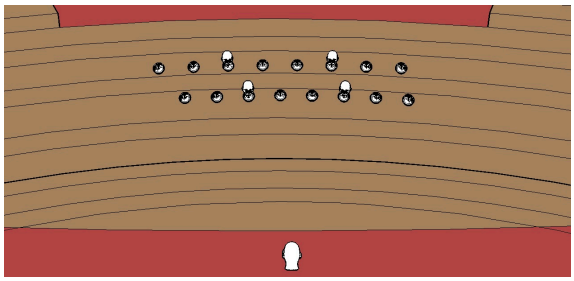
All simulation parameters followed those described in [11], including an image source order of 2, a total of 150,000 ray tracing particles, a detection sphere radius of 1 m, time bins of 15 ms, and a maximum energy loss of 78 dB.

Choir formation design:
Three spacing conditions were designed: Close (CL), Lateral (LA), and Circumambient (CA), adapted from choral formations described by Daugherty [18]. The ensemble was divided into two rows of eight singers, arranged in a front–back configuration. In all formations, the four leftmost sources in the front row (from the conductor's perspective) were sopranos and the four rightmost were altos; the back row consisted of basses (left) and tenors (right). This SATB layout simplified Daugherty's original three-row design while preserving left–right sectional separation. The formation also corresponds to the so-called "Scandinavian" formation described in [25], in which sopranos are positioned in front of basses, and altos in front of tenors.

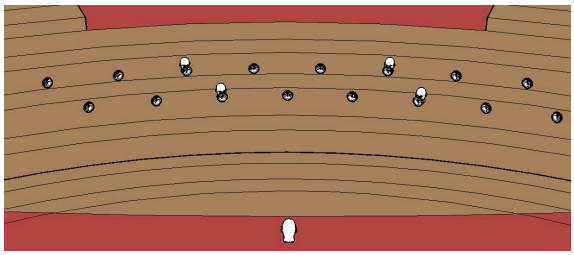
For the CL formation, the spacing between adjacent singers on the same row was 45 cm for women and 50 cm for men. These values correspond to the average bideltoid breadth of Swedes as measured in [21], plus the 1 inch (~2.5 cm) spacing used in Daugherty's close formation. The row spacing was set to 46 cm, matching the 18-inch front–back separation in the original design.

In the LA formation, the same row spacing of 46 cm was retained, while the side-to-side spacing between adjacent singers was increased to 103 cm in the front row and 109 cm in the back row.

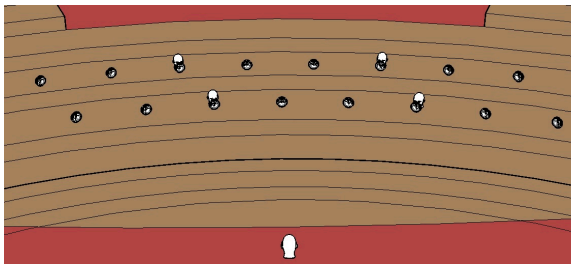
The CA formation used the same side-to-side spacing as LA but increased the row spacing to 91 cm. In all formations, a consistent 30 cm height difference was applied between the front and back rows (see Fig. 1(a–c)). The receiver shown in the conductor's position was included in visualizations but was not used in the simulation.



(a)



(b)



(c)

Fig. 1: Three virtual choir formations used in the simulation: (a) Close (CL), (b) Lateral (LA), and (c) Circumambient (CA). The layouts were rendered in the Concertgebouw model and reflect spatial formations adapted from Daugherty [18].

2.1.2 Auralization and recording setup

The experimental setup involved two types of signals: (1) the input signals delivered to the participant, consisting of the auralization of the virtual choir together with the participant's live singing, and (2) the output signals recorded, consisting of multi-channel recordings of both the participant's voice (self) and the virtual choir (others).

Auralization:
Fifteen pre-convolved tracks (the virtual choir) were imported into the digital audio workstation REAPER [version 7.33, www.reaper.fm] and played back along with a synchronized video of the conductor on the same timeline. This allowed the participant to follow both auditory and visual cues during the performance. The participant's live singing voice was captured using a headset microphone (4266, DPA), convolved in real time with a BRIR [22] corresponding to the participant's position (excluding direct sound), using the ReaVerb plugin in REAPER, and rendered over headphones.

Closed-back headphones (DT 1770 Pro, Beyerdynamic) were used to isolate the participant from the studio environment and minimize playback leakage into the recording microphones. In a practical application, a participant will want to hear the simulated room only, and not the actual one. As the headphones also blocked the airborne path from mouth to ears, the participant's own voice was perceived primarily through bone conduction, resulting in an unnatural and occluded auditory impression.

To improve self-monitoring, a low-latency EQ compensation filter was applied in the Fireface UCX II (RME, www.rme-audio.com) to the live mic signal before routing it to the headphones via the Fireface UFX (RME). This arrangement aimed to approximate the natural vocal feedback as if no headphones were worn (see [29] for details).

Recording setup:
The participant's voice (self) was captured by the same headset microphone together with the three additional microphones: a front-facing microphone (ECM8000, Behringer), placed 30 cm in front of the participant to capture a reference signal, and binaural microphones (4560, DPA), worn under the headphones to capture the sound arriving from the virtual choir (others), see Fig. 2.

All signals were recorded via the Fireface UFX interface into REAPER at a sampling rate of 44.1 kHz and 24-bit resolution. A block size of 256 samples was chosen to minimize latency, resulting in an end-to-end system latency of approximately 20 ms for rendering the participant's performance together with the simulated acoustics. This latency applied only to the processed signals (simulated acoustics of the participant's voice and the virtual choir), while the direct self-voice feedback (unprocessed voice) was unaffected. The 20 ms latency is well below the perceptual threshold for real-time vocal feedback in singing, within the thresholds reported for effective real-time musical collaboration [23] (see Fig. 3).

We report here the perceptual survey results. Singing performances were also recorded, for subsequent analysis as part of an ongoing larger study.



Fig. 2: Participant equipped with headset (beige) and binaural microphones (black).

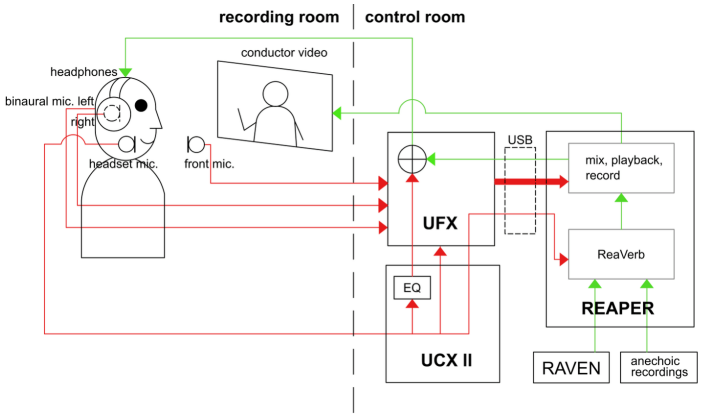


Fig. 3: Schematic diagram of signal routing and auralization setup used for playback and recording (green: input signals to the participant, red: output signals from mics).

2.2 Experimental protocol

Thirty-nine experienced choir singers participated in the study (N = 39), consisting of 9 sopranos, 9 altos, 9 tenors, and 12 basses. All had at least four years of ensemble singing experience, and most were current or former members of the KTH university choir, Kongl. Teknologkören (KTK). Each singer performed the first verse of *Strålande Helgonfé*, a four-part homophonic piece arranged by Helene Stureborg, together with the virtual choir under all three spacing conditions, presented in randomized order. All performances were sung from memory, following a video of the conductor, without the use of sheet music.

At the beginning of each session, participants were equipped with a headset microphone, binaural microphones, and closed-back headphones. A brief calibration was then performed to adjust the headset microphone level, using the front and binaural microphones as references.

Participants began by singing their part solo twice with the conductor video, providing baseline performances for later audio analysis. For each spacing condition, the participant first listened to the first phrase of the virtual choir without singing. The track was then restarted, and the participant sang along with the virtual choir three times per condition, for a total of nine performances during the participant's session. The three spacing conditions (CL, LA, CA) were presented in a balanced randomized order, with participants distributed evenly across six possible sequences.

After each condition, the participant completed a per-condition survey. Once all three conditions were completed, the solo singing task was repeated one final time. The participant was then assisted in removing the equipment and completed an end-of-experiment survey outside the studio. Each session lasted approximately 50 minutes, and each participant received a gift voucher for SEK 150 as an honorarium.

2.3 Perceptual survey

The perceptual survey consisted of both closed and open-ended questions and focused on three main aspects: (1) perception of self and others, (2) vocal production, and (3) overall impressions and preferences. The per-condition section included questions on self-monitoring, hearing of other voice parts, intonation, vocal effort, and vocal technique adjustment. The final section addressed overall

preferences and evaluated the realism and usefulness of the virtual environment for home practice.

3 Results and discussion

The survey responses were collected on ordinal Likert-type scales, so non-parametric statistical methods were employed. A Friedman test was used to evaluate the effect of spacing condition on each survey question. When a significant main effect was found, Conover pairwise comparisons were conducted with Holm's correction for multiple comparisons. All analyses were performed in JASP [version 0.19.3, www.jasp-stats.org] using the procedures described above.

3.1 Perception of self and others

Responses to the question on ***Self-perception*** ("I could hear my own voice [not at all / slightly / moderately / clearly / very clearly]") revealed a clear effect of spacing. Median ratings increased across formations (CL < LA < CA), indicating that wider spacing improved singers' ability to monitor their own voice (see Fig. 4). A Friedman test confirmed a significant main effect ($p < .001$), and Conover post hoc tests showed that CL differed significantly from both LA ($p = 0.003$) and CA ($p < .001$), while LA and CA did not differ ($p = 0.140$). These results are consistent with prior findings [18] that lateral or circumambient formations enhance self-monitoring.

This trend was manifest also in the direct comparison question on ***Self-monitoring***. In response to "Which condition made it easiest for you to hear your own voice?", 41% of participants selected LA and 49% selected CA, reinforcing the preference for more spread formations.

By contrast, results for ***Section hearing*** ("I could hear the following voice parts [same scale]") were more mixed. On average, the perception of other parts was not consistently affected by spacing. Increases in clarity for one section often coincided with decreases for others. For all parts except basses, participants most clearly heard their own section in the CL formation.

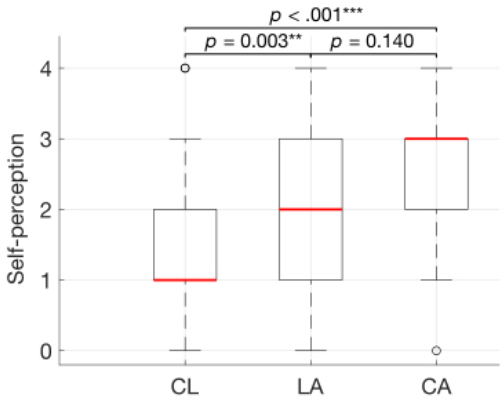


Fig. 4: Boxplots show self-perception ratings across spacing conditions. Scale: 0 = *not at all*, 1 = *slightly*, 2 = *moderately*, 3 = *clearly*, 4 = *very clearly*.

3.2 Vocal production

Perceived tuning with the group was evaluated using the ***Intonation*** question ("I felt my tuning with the group was [very difficult / difficult / moderate / easy / very easy]"). As shown in Fig. 5, median ratings improved with increased spacing. A Friedman test indicated a significant effect of spacing ($p < .001$). Post hoc comparisons revealed that tuning ratings in CL were significantly lower than in both LA ($p < .001$) and CA ($p < .001$), while no significant difference was found between LA and CA ($p = 0.936$).

These findings suggest that wider spacing may enhance singers' ability to tune with the ensemble, potentially due to more balanced auditory feedback between self and others. This aligns with previous research on the importance of maintaining an appropriate *Self-to-Other Ratio* (SOR) [24] in choral singing (e.g., [25–27]). Howard [27] further notes that when singers are close together, the Other part of the Self-to-Other ratio is typically too loud, making it difficult for the singer to hear themselves. This incites singers to over-sing to compensate. Achieving appropriate SOR throughout the choir is critical for enabling good overall intonation, blend, vowel matching and timing of consonants.

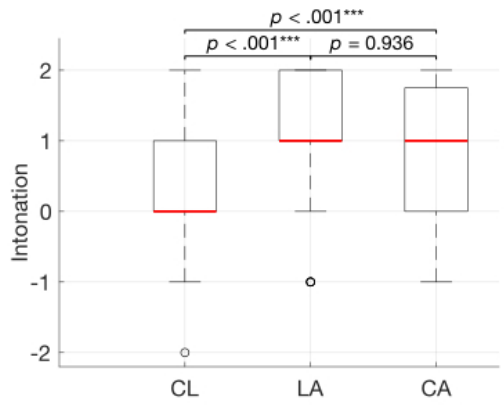


Fig. 5: Boxplots show intonation ratings across choir spacing conditions. Scale: –2 = *very difficult*, –1 = *difficult*, 0 = *moderate*, 1 = *easy*, 2 = *very easy*.

Ratings on ***Vocal effort*** ("I sang with [much less / less / normal / more / much more] vocal effort") did not differ significantly across conditions ($p = 0.448$), although slightly higher effort was reported in the CL formation. Although the difference was not statistically significant, the first and second authors observed during the sessions that several singers appeared to sing louder when moving from wider to closer formations. This observation may reflect a tendency for singers to underestimate the loudness of their own voice, as noted in prior studies [6, 28]. The planned acoustic analysis will shed light on this issue.

Responses to the ***Vocal technique*** adjustment question ("In response to the environment, my vocal technique was [not adjusted / slightly adjusted / moderately adjusted / clearly adjusted / strongly adjusted]") were border-line significant ($p = 0.052$). Ratings tended to decrease from CL to LA and CA, suggesting that singers were more likely to believe that they adjusted their vocal technique in closer formation. This trend suggests that spacing may subtly influence vocal production strategies, as discussed in [27].

Interestingly, when considering the results from both Section 3.1 (*Perception of self and others*) and Section 3.2 (*Vocal production*), statistically significant effects were found primarily in perceptual responses (e.g., self-perception, self-monitoring), while fewer effects emerged in performance responses (e.g., vocal effort, vocal technique adjustment). This raises the question of whether singers might have adapted their vocal production without being fully aware of it.

To explore this further, audio feature analysis of the recorded performances is planned as part of an ongoing larger study, that will assess the potential correlations between singers' perceptual ratings and their vocal production.

3.3 Preferences and overall impressions

When asked to rank the three formations based on their ***preference for performing in a real concert setting***, 87% of participants selected a spread formation as their most preferred option, with 46% choosing LA and 41% choosing CA. Additionally, 62% of participants ranked the CL formation as their least preferred.

Responses to the ***Audio realism*** question ("The overall sound environment in the virtual model felt realistic [strongly disagree / disagree / neutral / agree / strongly agree]") indicated general agreement. A majority of participants found the virtual environment convincing, with 47% selecting "Agree" and 15% selecting "Strongly agree," while 21% disagreed and none selected "Strongly disagree."

However, ratings on ***Headphone transparency*** were more mixed. Many participants disagreed or strongly disagreed with the statement "The headphone sound felt similar to how it sounds when I sing without wearing headphones," although a few participants expressed agreement. These results prompted the authors to initiate a parallel study on *How to make closed-back headphones transparent for the direct sound of a singer's own voice* (see [29] for details).

Regarding ***Future applicability***, the system was positively received as a training tool. In response to the statement "I believe that this virtual environment could be a useful tool for home practice," 89% of participants (32 out of 36) selected "Agree" or "Strongly agree." These responses indicate strong support for the system's potential as a tool for individual home practice.

4 Conclusions

This study introduced a virtual acoustics system to investigate how choir spacing affects singers' perception and vocal production under controlled conditions. Thirty-nine experienced choir singers performed with a spatialized virtual ensemble in three spacing conditions using closed-back headphones with EQ-compensated applied to the singer's own voice.

Survey results showed that spread formations (LA or CA) improved self-monitoring and tuning. Perception of other sections showed mixed results with no consistent effect of spacing. Vocal effort ratings did not differ significantly, while vocal technique adjustment showed a trend toward significance, with greater adjustment reported in the closer formation. Most singers preferred spread formation for concert settings.

The virtual system was generally perceived as realistic, although ratings on headphone transparency were more mixed. Nonetheless, the system was positively evaluated for its potential use in individual home practice. Audio recordings collected during the experiment will be analyzed in a larger study to examine correlations between singers' perceptual ratings and their vocal production.

Acknowledgement

Author K.K. acknowledges support from a doctoral stipend awarded by the Royal Thai Government (OCSC no. 1018.2/1218) and Karl Engver's foundation (grant no. VT-2023-0048), and Author M.P. from the King Mongkut's Institute of Technology Ladkrabang research grant (KREF046818). The authors are grateful to the singers of the KTH university choir, Kongl. Teknologkören (KTK), for their participation in the experiment. They also wish to thank Prof. Harald Jers for his valuable input and helpful comments on the experimental design and methodology, as well as Lukas Aspöck for his generous support and technical assistance with the RAVEN software. The authors also thank Jidapa Leekamnerdthai for drawing the illustration in Fig. 3.

References

[1] Zhang, M. M., *Investigations into choral singers' perception of stage acoustics during an Australian tour*, Tech. Rep., Marshall Day Acoustics Research & Development Fund NZ Trust, Rp 001 20220963, 2024.

[2] Daugherty, J. F., Grady, M. L., and Coffeen, R. C., "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), pp. 355–371, 2019.

[3] Hom, K. S., *The effect of two different rooms on acoustical and perceptual measures of SATB choir sound*, M.Ed. Thesis, University of Kansas, 2013.

[4] Ternström, S., "Self-to-other ratios measured in choral performance," in Proc. *15th International Congress on Acoustics*, 1995.

[5] Ternström, S., "Long-time average spectrum characteristics of different choirs in different rooms." *Voice* (UK), 2, pp. 55–77, 1993.

[6] Park, M. and Kittimathaveenan, K., "Singing in virtual environments: Exploring vocal adaptations to congruent audiovisual scenes of performance venues," *Applied Acoustics*, 241, Art. no. 110974, 2026.

[7] Fernandez, C., Lawless, M. S., Poirier-Quinot, D., and Katz, B. F. G., "Virtual acoustic environment rehearsal and performance in an unknown venue," *Virtual Worlds*, 4(3), 35, 2025.

[8] Wingfield, C. J., Redman, Y. G., Nudelman, C. J., and Bottalico, P., "Virtual reality for performance preparation," in Proc. *Forum Acusticum Euronoise 2025*, Málaga, Spain, 2025.

[9] Park, M. and Kittimathaveenan, K., "Exploring the effects of room acoustics on soprano singers' vocal performance in three virtual venues," in Proc. *Audio Engineering Society 156th Convention*, Madrid, Spain, 2024.

[10] Luizard, P., Bernardoni, N. H., and Böhm, C., "Using virtual acoustics and electroglottography to study the adaptation of singing voice production," presented at the *Forum Acusticum 2020*, Lyon (virtual), France, Dec. 2020.

[11] Palenda, P., Aspöck, L., Morent, S., and Vorländer, M., "Setup for choir recordings in virtual churches." *2023 Immersive and 3D Audio: from Architecture to Automotive (I3DA)*, 1-6, 2023.

[12] Mullins, S. S. and Katz, B. F. G., "Immersive auralisations for choral ensembles," in Proc. *11th Int. Conf. on Auditorium Acoustics*, Institute of Acoustics, Athens, Greece, 2023.

[13] Kittimathaveenan, K. and Ternström, S., "Localisation in virtual choirs: outcomes of simplified binaural rendering," in Proc. *Audio Engineering Society Int. Conf. on Spatial & Immersive Audio*, Huddersfield, UK, 2023.

[14] Daffern, H., Camlin, D. A., Egermann, H., Gully, A. J., Kearney, G., Neale, C., and Rees-Jones, J., "Exploring the potential of virtual reality technology to investigate the health and well being benefits of group singing," *International Journal of Performance Arts and Digital Media*, 15:1, pp. 1–22, 2019.

[15] Fischinger, T., Frieler, K., and Louhivuori, J., "Influence of virtual room acoustics on choir singing." *Psychomusicology: Music, Mind and Brain,* 25(3)*,* pp. 208–218, 2015.

[16] Brereton, J. S., Murphy, D. T., and Howard, D. M., *Singing in Space(s): Singing performance in real and virtual acoustic environments —Singers' evaluation, performance analysis and listeners' perception*, Ph.D. dissertation, University of York, UK, 2014.

[17] Gilliam, T. M., "Effects of Three Common Choral Configurations on Acoustic and Perceptual Measures of a Soprano Section's Sound," *Update: Applications of Research in Music Education*, 39(2), pp. 54–66, 2020.

[18] Daugherty, J. F., "Choir Spacing and Formation: Choral Sound Preferences in Random, Synergistic, and Gender-Specific Chamber Choir Placements," *Int. Journal of Research in Choral Singing*, 1, pp. 48–59, 2003.

[19] Schröder, D., *Physically Based Real-Time Auralization of Interactive Virtual Environments*, Ph.D. dissertation, Institute of Technical Acoustics, RWTH Aachen University, Aachen, Germany, 2011.

[20] Institute for Hearing Technology and Acoustics, RWTH Aachen University. *Room Acoustics for Virtual Environments (RAVEN) – a GA-based room acoustic simulation environment*, Available at: https://www.virtualacoustics.org/RAVEN/ (accessed 31 July 2025).

[21] Hanson, L., Sperling, L., Gard, G., Ipsen, S., and Vergara, O. C., "Swedish anthropometrics for product and workplace design," *Applied Ergonomics*, 40(4), pp. 797–806, 2009.

[22] Vorländer, M., *Auralization: Fundamentals of Acoustics, Modelling, Simulation, Algorithms and Acoustic Virtual Reality*, 1st ed., RWTHedition, Berlin: Springer, 2008.

[23] Bartlette, C., Headlam, D., Bocko, M., and Velikic, G., "Effect of network latency on interactive musical performance," *Music Perception*, 24(1), pp. 49-62, 2006.

[24] Ternström, S., "Hearing myself with others: Sound levels in choral performance measured with separation of one's own voice from the rest of the choir," *Journal of Voice*, 8(4), 1994.

[25] Jers, H. and Ternström, S., "Vocal Ensembles," in *The Oxford Handbook of Music Performance*, vol. 2, G. E. McPherson, Ed., Oxford University Press, pp. 399–417, 2022.

[26] Ternström, S., "Preferred self-to-other ratios in choir singing," *Journal of the Acoustical Society of America*, 105(6), pp. 3563–3574, 1999.

[27] Howard, D. M., *Choral Singing and Healthy Voice Production*, Willow Leaf Pub., 2015.

[28] Kittimathaveenan, K. and Park, M. "The influence of stage acoustics on the singers' performance and perception: a pilot study," in Proc. *Audio Engineering Society 151st* Convention, Online, 2021.

[29] Park, M., Ontakhrai, S., Kittimathaveenan, K., Alfredsson, J., and Ternström, S., "How to make closed-back headphones transparent for a vocalist's own direct sound," in Proc. *Audio Engineering Society 159th Convention*, Long Beach, CA, USA, 2025.