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THE IMPACT OF INTEGRATING ACOUSTIC SURFACE MATERIAL DESIGN INTO INTERIOR SPACE PLANNING FOR HYBRID LEARNING ENVIRONMENTS

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Abstract

The adoption of hybrid teaching and learning has transformed the planning and design of higher education learning environments, requiring classroom interiors to support both face-to-face and remote instruction. However, inadequate acoustic conditions remain a major challenge, reducing speech intelligibility and limiting effective communication. This study investigates the role of interior surface material design in integrating acoustic considerations into the space planning of hybrid classrooms that accommodate conventional and collaborative learning. A combination of field measurements and acoustic simulations was conducted to evaluate the effects of wall and ceiling treatments on reverberation time (RT), speech transmission index (STI), and speech clarity (C_{50}). The findings demonstrate that strategically designed surface materials significantly improve acoustic performance and speech intelligibility. The study provides evidence-based design strategies for interior space planning to create hybrid learning environments that enhance communication and teaching and learning experiences.

Keywords: Hybrid Classroom, Classroom Acoustic, Space Planning

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INTRODUCTION

The design of higher education learning environments has evolved considerably in response to advances in educational technology and changing pedagogical practices. Contemporary learning spaces are no longer viewed merely as physical settings for knowledge delivery but as active environments that influence teaching effectiveness, student engagement, and learning outcomes (Cheung et al., 2021). These environments may be physical or virtual (Zhong et al., 2023), and are increasingly expected to accommodate diverse instructional approaches, ranging from teacher-centred lectures to student-centred collaborative learning (Murphy et al., 2021). Consequently, learning space design has become a multidisciplinary endeavour that integrates principles from architecture, interior design, learning sciences, and environmental psychology to create environments that support evolving educational needs (Ellis & Goodyear, 2016).

The transformation of pedagogical practices has challenged the suitability of conventional classroom layouts, where rows of desks facing a lecturer primarily support one-way knowledge transmission. Such configurations are increasingly inadequate for interactive, collaborative, and technology-enabled learning activities (Cheung et al., 2021). However, despite significant advances in learning space design, there remains limited consensus regarding interior planning strategies capable of supporting the wide range of pedagogical activities expected in future learning environments (Rands & Gansemer-Topf, 2017). This challenge highlights the need for evidence-based design approaches that integrate spatial planning with environmental quality, including lighting, ventilation, and acoustic performance (Suraini & Aziz, 2023).

The rapid adoption of hybrid teaching has further accelerated the transformation of higher education learning spaces. Hybrid classrooms enable face-to-face and remote students to participate simultaneously, offering greater flexibility while extending educational access beyond the physical classroom (Li et al., 2023). Numerous studies have reported positive educational outcomes associated with hybrid learning, including improved student autonomy, flexibility, and overall satisfaction (Monk et al., 2020; Wei et al., 2023).

Although advances in educational technology have enhanced hybrid teaching delivery, maintaining equivalent learning experiences for both face-to-face and remote participants remains a significant challenge. Previous studies have reported that remote learners frequently experience reduced engagement due to technological limitations, ambiguous group membership, and diminished interaction with instructors and peers (Olt, 2018; Zydney et al., 2019). Audio quality has consistently been identified as one of the most critical determinants of successful hybrid learning. Remote participants rely almost exclusively on microphone-captured audio to understand classroom discussions, making speech intelligibility essential for effective participation (Cunningham, 2014).

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Consequently, inadequate classroom acoustics can substantially reduce communication quality, impair student engagement, and negatively affect learning performance (Otčenášek et al., 2022).

Classroom acoustic performance is fundamentally influenced by the interior environment. Excessive reverberation and poor speech transmission reduce speech intelligibility, increase listening effort, and negatively influence students' concentration, cognitive performance, and learning outcomes (Dockrell & Shield, 2012; Mogas et al., 2021). While considerable research has focused on improving classroom acoustics for conventional teaching environments, relatively limited attention has been given to how interior surface material design can support the dual instructional requirements of hybrid classrooms. Furthermore, existing studies primarily emphasise technological solutions, such as microphones and audiovisual systems, while comparatively few have investigated the contribution of interior space planning through strategic surface material design.

Therefore, this study investigates the role of interior surface material design in supporting acoustically favourable space planning for hybrid classrooms. Specifically, the study evaluates the effects of highly absorptive ceiling and wall surface treatments on three key acoustic performance indicators namely reverberation time (RT), speech transmission index (STI), and speech clarity (C_{50}) under two instructional settings: conventional lecture-based teaching and collaborative learning, across two different classroom sizes. The findings contribute evidence-based design strategies that integrate acoustic considerations into interior space planning to support effective communication and enhance learning experiences in hybrid higher education environments.

LITERATURE REVIEW

Classroom Space Design

The design of learning environments extends beyond functional and aesthetic considerations, as spatial architecture influences how users think, feel, and behave within a space (Warburton & Mor, 2022). Consequently, effective learning spaces should be designed based on a comprehensive understanding of users' needs while integrating principles from architecture, learning sciences, and environmental psychology (Ellis & Goodyear, 2016). Barrett et al. (2013) proposed the Stimulation–Individualisation–Naturalness (SIN) model, which identifies three spatial design dimensions that contribute to improved learning outcomes. Among these, naturalness encompasses environmental quality attributes such as lighting, thermal comfort, indoor air quality, and acoustics, highlighting the importance of integrating these elements into the planning and design of contemporary learning environments.

Teaching and Learning Approaches

Instructional approaches are closely linked to the spatial and functional requirements of learning environments. Face-to-face (F2F) learning, the conventional mode of instruction, involves direct interaction between instructors and students within the same physical space and time (Eidenberger & Nowotny, 2022; Ramnarine, 2018). In higher education, the physical learning environment complements pedagogical practices by influencing teaching effectiveness, student engagement, and learning experiences (Anggrawan et al., 2019). As pedagogical approaches continue to evolve from teacher-centred to student-centred and collaborative learning, classroom design has similarly shifted towards more flexible learning environments that support active participation, interaction, and technology-enhanced teaching and learning (Pearlman, 2010).

Classroom Acoustic

Architectural acoustics examines the behaviour of sound within enclosed spaces and its influence on human communication, comfort, and performance (Rossing, 2007). In educational environments, acoustic quality is essential for supporting effective speech communication and facilitating teaching and learning processes. Recognising its importance, several countries have established classroom acoustic standards and guidelines, including American National Standards Institute (2010), Building bulletin 93 (2015), and AS/NZS 2107:2000 (2000). These guidelines specify recommended criteria for key acoustic parameters, such as background noise, reverberation time, and speech intelligibility. Razali et al. (2024) proposed a comprehensive conceptual framework comprising six key design enablers that govern acoustic comfort in classroom environments.

RESEARCH METHODOLOGY

Two classrooms at a public university in Malaysia were purposively selected to represent different spatial scales while retaining common characteristics of university teaching spaces, including rectangular room geometry, lecturer-oriented teaching areas, and student seating zones. Although originally designed for conventional face-to-face teaching, these classrooms reflect the practical adaptation of existing teaching spaces for technology-assisted and hybrid learning. Therefore, they serve as relevant case-study representations rather than statistically representative samples of all Malaysian hybrid learning spaces. The measurements were conducted under unoccupied conditions to evaluate the acoustic characteristics of the rooms. Three key acoustic parameters were assessed: background noise (BN), reverberation time (RT), and speech transmission index (STI). The physical characteristics of the selected classrooms are summarised in Table 1.

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Table 1: Classroom geometrical characteristics

Classroom	Width (m)	Length (m)	Height (m)	Floor Area (m^2)	Volume (m^3)
C1	8.6	6	2.5	51.6	129
C2	8.2	8.7	2.8	71.3	200

Field Measurement

Background noise level (BNL) was measured by recording the equivalent continuous A-weighted sound pressure level (LAeq) in unoccupied classrooms with the heating, ventilation, and air conditioning (HVAC) system operating under normal conditions. The receiver positions were located at representative student seating positions and at each measurement location, the background noise level was recorded continuously for two minutes with a sampling interval of one second. Measurements were conducted using a Cirrus CR:171B sound level meter (SLM) positioned 1.2 m above the finished floor level, corresponding to the average ear height of seated students.

Reverberation time (RT) was measured using an omnidirectional dodecahedron loudspeaker as the sound source. The loudspeaker was driven by a Crown XLS1000 power amplifier to generate the test signal. The acoustic response was captured using a GRAS 46AE ½-inch measurement microphone positioned 1.2 m above the finished floor level and connected to a Scarlett 2i4 audio interface, and the recorded impulse responses were analysed using ODEON Room Acoustics Software (Version 17) to determine the RT values. The receiver positions were identical to those used for the background noise measurements to ensure consistency throughout the acoustic assessment.

Speech transmission index (STI) measurements were conducted using a BOSE M101 loudspeaker positioned 1.5 m above the finished floor level within the designated lecturer teaching zone to represent the instructor's position. A sweep signal generated by a Minirator MR2 signal generator was used to simulate an amplified speech source. The signals received were measured using a Blue Solo 01dB sound level meter integrated with dBBati acoustic measurement software for STI analysis.

Acoustic Simulation

Three-dimensional (3D) models of the selected classrooms were developed using SketchUp Pro® based on the measured room dimensions. Accurate representation of the room geometry and surface areas is essential to minimise modelling errors and ensure reliable acoustic simulations. Previous studies have reported that model verification generally permits a maximum surface area deviation of 20%, equivalent to a minimum geometric accuracy of 80%, although this may vary depending on modelling techniques, software configurations, and

the accuracy of the assigned material absorption and scattering coefficients (Jalil et al., 2019).

Prior to the simulation, the acoustic models were validated by comparing the simulated RT and STI with the corresponding field measurement results using ODEON Room Acoustics Software (Version 17). During the validation process, the surface material properties, sound source locations, and receiver positions were iteratively refined to achieve similarity between the measured and simulated acoustic parameters. Model validation was considered acceptable when the relative differences in RT and STI satisfied the recommended just noticeable difference (JND) criteria. Due to limitations of the existing measurement equipment, C50 could not be measured during the field investigation and was therefore excluded from the validation process. The close agreement between the measured and simulated RT and STI values indicates that the developed models adequately represent the actual acoustic conditions of the classrooms. Although C50 was not independently validated through field measurements, the successful validation of RT and STI provides confidence in the overall reliability of the acoustic models. Therefore, the simulated C50 results were considered appropriate for evaluating the effects of the proposed surface treatments on speech clarity, while acknowledging the absence of direct field validation for this parameter.

Acoustic simulations were performed to evaluate the effects of wall and ceiling surface treatments on RT, STI, and C_{50} under different learning settings. The surface treatment simulation focused on two major interior surfaces, namely the ceiling and wall surfaces. Three scenarios were evaluated for each classroom and learning configuration: (i) the existing condition, representing the original interior surface materials; (ii) the ceiling treatment scenario, in which the treatment was applied to the entire ceiling surface area; and (iii) the wall treatment scenario, in which the treatment was applied to the entire wall surface area. The sound absorption coefficients of the selected materials across the relevant frequency bands, together with the total surface area covered by each treatment, are presented in Table 2.

Table 2: Sound absorption coefficient (SAC) of surface materials and treatment area for each element and classroom

Surface Element	**Frequency (Hz)**						**Treatment Area (m^2)**	
	125	**250**	**500**	**1000**	**2000**	**4000**	**C1**	**C2**
Wall	0.15	0.35	0.65	1.00	0.9	1.00	44	74
Ceiling	0.34	0.43	0.54	0.67	0.65	0.64	46	77

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Virtual microphone receivers were positioned 2.0 m above the finished floor level and were arranged in a 1 m × 1 m grid, resulting in 35 and 70 receiver positions in the small and medium classrooms under two instructional configurations. The first represented a conventional arrangement with students seated in rows facing the lecturer, while the second represented a collaborative learning arrangement using modular group seating. For the conventional learning configuration, a single sound source representing the lecturer's natural raised voice was positioned within the designated teaching area. For the collaborative learning configuration, four sound sources representing students' natural raised voices were positioned at the centre of each discussion group. The surface materials assigned to the wall, ceiling, and floor elements were identical for both classroom configurations, with their acoustic properties.

ANALYSIS AND DISCUSSION

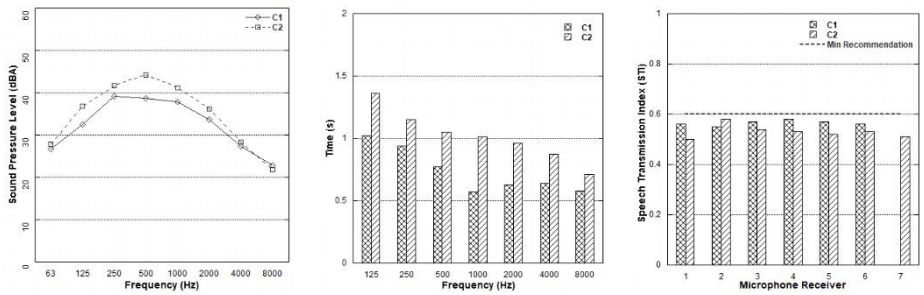
Field Measurement Results

Figure 1(a) presents the measured equivalent continuous A-weighted sound pressure level (LAeq) in the two classrooms under unoccupied conditions with the HVAC system operating. The mean LAeq values were 44.3 dBA for C1 and 47.7 dBA for C2. Both values exceeded the maximum recommended BN level of 35 dBA for unoccupied classrooms specified by American National Standards Institute (2010) and Building bulletin 93 (2015). The elevated background noise levels indicate that the existing acoustic environment may adversely affect speech perception and increase listening effort during classroom activities.

The measured RT values are presented in Figure 1(b). According to American National Standards Institute, (2010) classrooms with a volume of less than 283 m³ should achieve a maximum RT of 0.6 s. The average RT values recorded for C1 and C2 were 0.74 s and 1.01 s, corresponding to room volumes of 129 m³ and 198 m³, respectively. Both classrooms exceeded the recommended RT criterion, indicating inadequate sound absorption within the existing interior environment. Although the measured RT values complied with the maximum limits recommended by Building bulletin 93, (2015), the predominantly reflective surface finishes contributed to prolonged sound decay. Previous studies have demonstrated that improving the sound absorption characteristics of wall and ceiling surfaces is an effective strategy for reducing RT and enhancing classroom acoustic performance (Razali et al., 2023).

Figure 1(c) illustrates the distribution of the STI across the receiver positions in both classrooms. The average STI values were 0.56 for C1 and 0.53 for C2, corresponding to a fair rating according to the IEC 60268-16 classification. These results indicate that the existing acoustic conditions provide only moderate speech intelligibility, which may affect verbal communication during teaching and learning activities. Overall, the measured background noise

level, reverberation time, and speech transmission index indicate that the existing classrooms do not fully satisfy the recommended acoustic performance criteria for educational spaces. These findings establish the baseline acoustic conditions and provide the basis for evaluating the effectiveness of the proposed interior surface material treatments.



(a) (b) (c)

Figure 1: Field measurement findings for (a) BN, (b) RT, and (c) STI

3D Model Verification

The acoustic models were validated by comparing the RT and STI obtained from the simulations with the corresponding on-site measurement results. Model accuracy was evaluated by calculating the relative differences between the measured and simulated acoustic parameters. Previous studies recommend just noticeable difference (JND) of less than 5% for RT and 0.03 for STI to ensure perceptually insignificant differences (Christensen & Koutsouris, 2013). However, Bistafa & Bradley (2000) reported that a maximum relative difference of 10% for RT is generally considered an acceptable level of accuracy for engineering applications.

The validation was performed by comparing the mean RT values over the frequency range of 125–8000 Hz and the STI values at the corresponding receiver locations. As summarised in Table 3, the simulated RT and STI values for both models were in close agreement with the field measurements. The relative differences were below 10% for RT and 0.03 for STI, confirming that both acoustic models adequately represented the measured acoustic conditions and were therefore considered suitable for the subsequent simulation analyses.

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Table 3: Validation results based on the just noticeable difference (JND) for RT and STI

Parameter	Classroom					
	C1			C2		
	Field	Simulation	JND	Field	Simulation	JND
Reverberation time	0.74	0.75	2%	1.01	1.00	2%
STI	0.56	0.56	0	0.53	0.54	0.01

Surface Treatment Simulation

a) Reverberation time (RT)

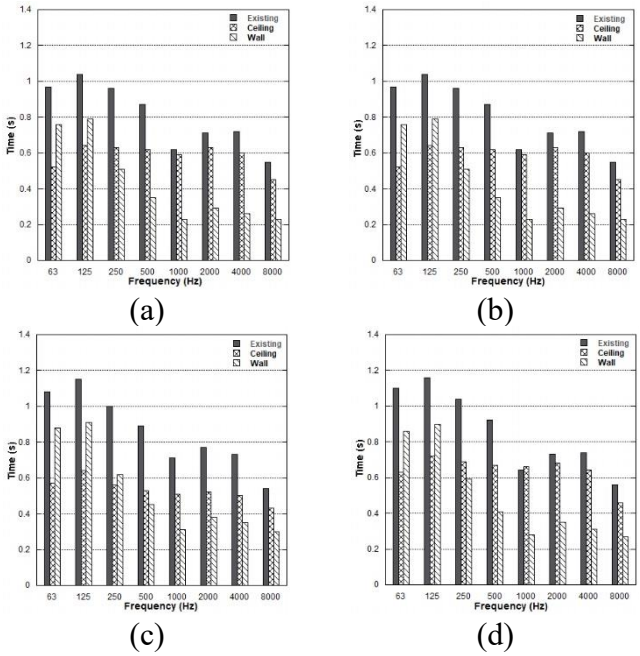

Figure 2: Impact of surface treatments on RT under conventional and collaborative learning settings (a & b) in small classroom, (c & d) medium classroom

According to Building Bulletin 93 (2015), the maximum recommended RT for unoccupied and furnished classrooms is 0.8 s. In comparison, American National Standards Institute (2010) specifies a more stringent RT criterion of 0.6 s for classrooms with a volume of less than 283 m³ and 0.7 s for volumes exceeding 283 m³. Figures 2(a) and 2(b) present the RT results for the small classroom under collaborative and conventional learning configurations, respectively. Under the existing conditions, the average RT values were 0.80 s for collaborative learning and 0.79 s for conventional learning. Although both configurations complied with the BB93 recommendation, they exceeded the RT

limit specified by ANSI/ASA S12.60. Following the application of absorptive ceiling materials, the average RT decreased to 0.59 s and 0.48 s for the collaborative and conventional configurations, respectively. Further reductions were achieved after treating all wall surfaces with absorptive materials, resulting in average RT values of 0.43 s for collaborative learning and 0.44 s for conventional learning. These findings demonstrate that both ceiling and wall treatments substantially improved the acoustic performance of the small classroom.

As illustrated in Figures 2(c) and 2(d), under the existing conditions, the average RT was 0.86 s for both collaborative and conventional learning configurations in medium classroom. The application of absorptive ceiling materials reduced the RT to 0.53 s and 0.64 s for collaborative and conventional learning, respectively. Following wall treatment, the average RT further decreased to 0.51 s and 0.50 s, respectively. The consistent reduction in RT across both room sizes indicates that increasing the acoustic absorption of ceiling and wall surfaces effectively reduced sound reflections and shortened sound decay time.

b) Speech Transmission Index (STI)
Collaborative Learning

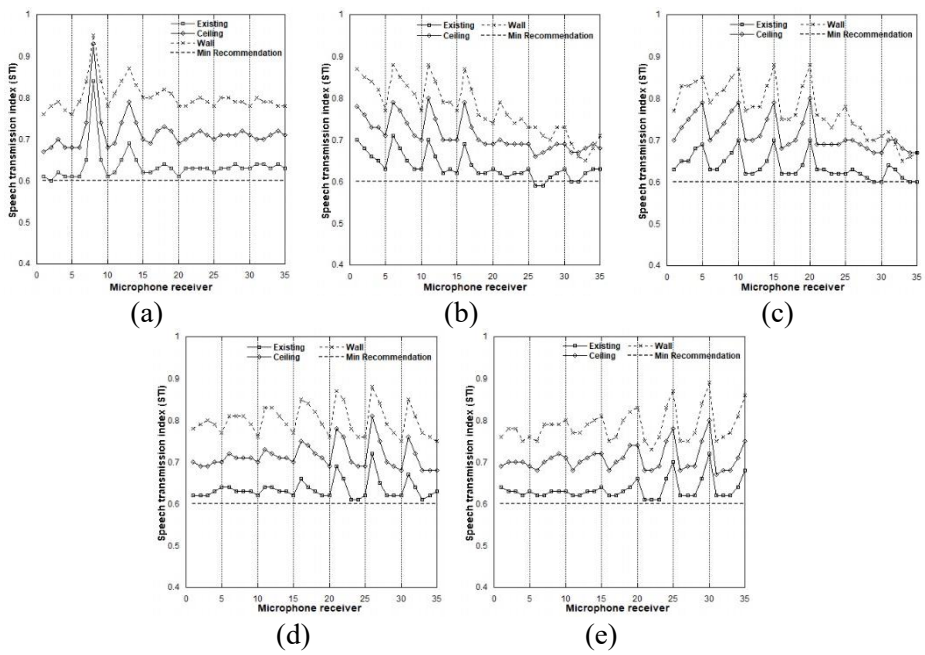

Figure 3: STI distribution in small classroom for different sound source locations: (a) lecturer, (b) S1, (c) S2, (d) S3, and (e) S4

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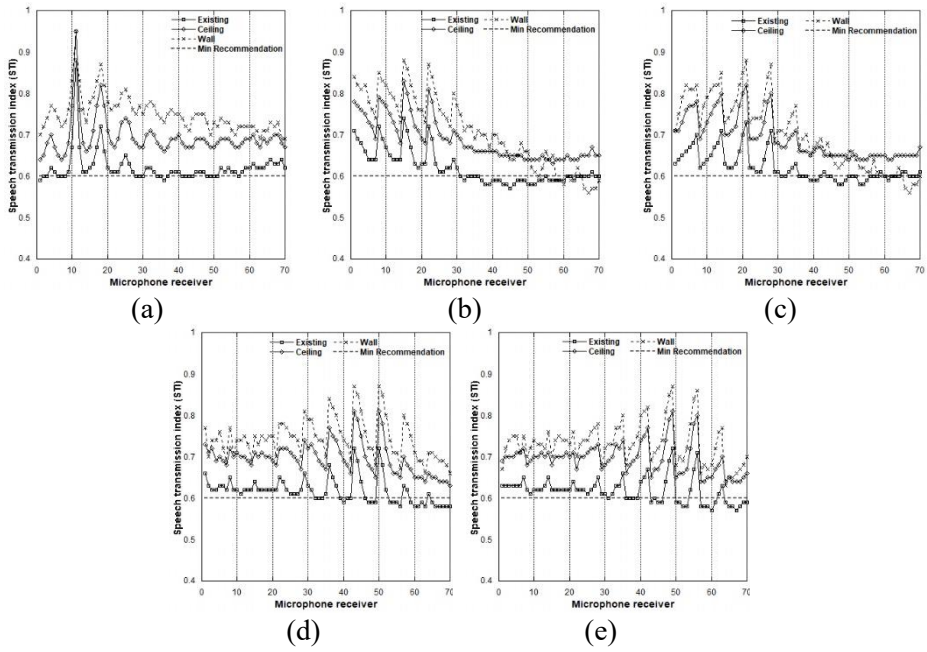


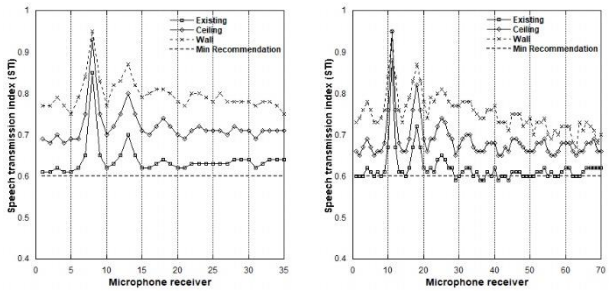
Figure 4: STI distribution in medium classroom for different sound source locations: (a) lecturer, (b) S1, (c) S2, (d) S3, and (e) S4

Figures 3 and 4 present the spatial distribution of STI values for the various surface treatment scenarios in the small and medium classrooms, respectively. Previous studies recommend a minimum STI value of 0.60 to achieve satisfactory speech intelligibility in educational environments. Under the existing room conditions, most receiver locations in the small classroom achieved STI values close to or exceeding this threshold. The application of absorptive ceiling materials increased the STI values across most receiver positions, while further improvements were observed following the treatment of the wall surfaces.

The greatest enhancement occurred at receiver locations within approximately 1.5 m of the active sound source, where the reduction in reverberant sound increased the proportion of direct sound, thereby improving speech intelligibility. A similar trend was observed in the medium classroom, where both ceiling and wall treatments consistently improved STI compared with the existing room condition. However, a slight reduction in STI was observed at several receiver locations associated with S1 and S2. This reduction can be attributed to the orientation of the sound source, which was positioned near the front of the classroom and directed towards the front wall. Consequently, receiver locations situated farther from the source experienced a lower direct-to-reverberant sound ratio, resulting in slightly reduced STI values.

Conventional Learning

Figure 5 presents the spatial distribution of STI values for the existing room condition and the proposed surface treatment scenarios. Under the existing conditions, most receiver locations achieved the minimum recommended STI value of 0.60, indicating satisfactory speech intelligibility for conventional instruction. The application of absorptive ceiling materials resulted in a noticeable increase in STI across most receiver locations, while further improvements were achieved following the installation of absorptive wall panels. At several receiver positions, the STI classification improved from "Good" to "Excellent", demonstrating the effectiveness of increasing the acoustic absorption of the interior surfaces. The enhanced STI performance can be attributed to the reduction in reverberation time, which increased the direct-to-reverberant sound ratio and improved speech transmission throughout the room. These findings indicate a strong relationship between reverberation time and speech intelligibility, whereby lower RT values consistently resulted in higher STI ratings.



(a) (b)

Figure 5: STI distributions for conventional learning in (a) small and (b) medium classrooms

c) Speech Clarity (C_{50})

Collaborative Learning

Under the existing room conditions, only a limited number of receiver locations situated close to the sound source achieved the recommended minimum value of 3 dB as presented in Figures 6 and 7. Following the application of absorptive ceiling materials, C_{50} values increased across most receiver locations, while further improvements were achieved after the wall surfaces were treated with absorptive materials. In both classrooms, the majority of receiver locations exceeded the recommended 3 dB threshold after the surface treatments were applied. The improvement in C_{50} can be attributed to the reduction in reverberation time resulting from the increased acoustic absorption of the ceiling and wall surfaces. The shorter sound decay time reduced the influence of late

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reflections and increased the proportion of early sound energy reaching the receivers, thereby enhancing speech clarity throughout the rooms. These findings are consistent with the STI results, indicating that improvements in reverberation control contribute to enhanced speech intelligibility and overall acoustic performance.

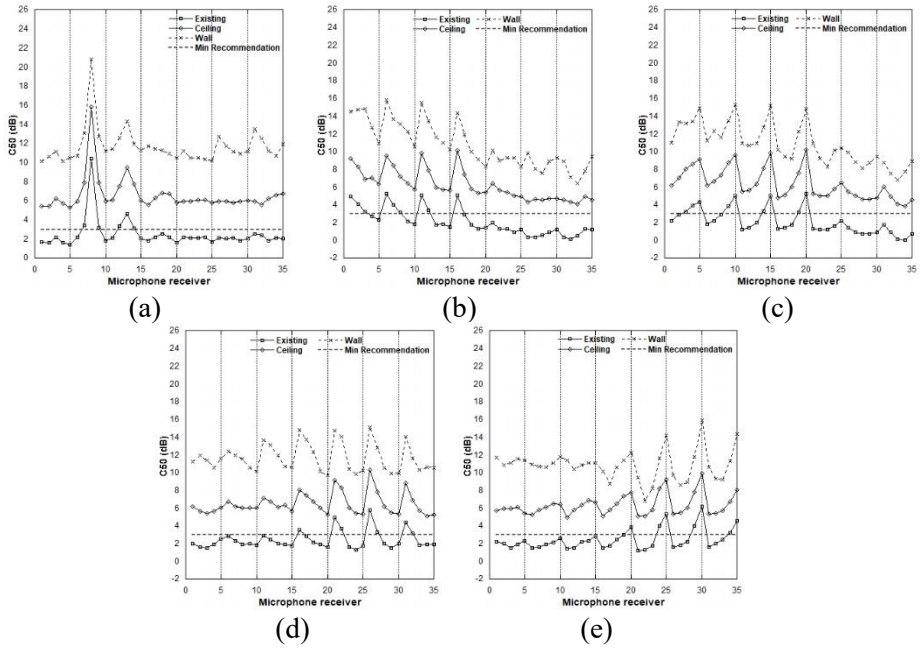
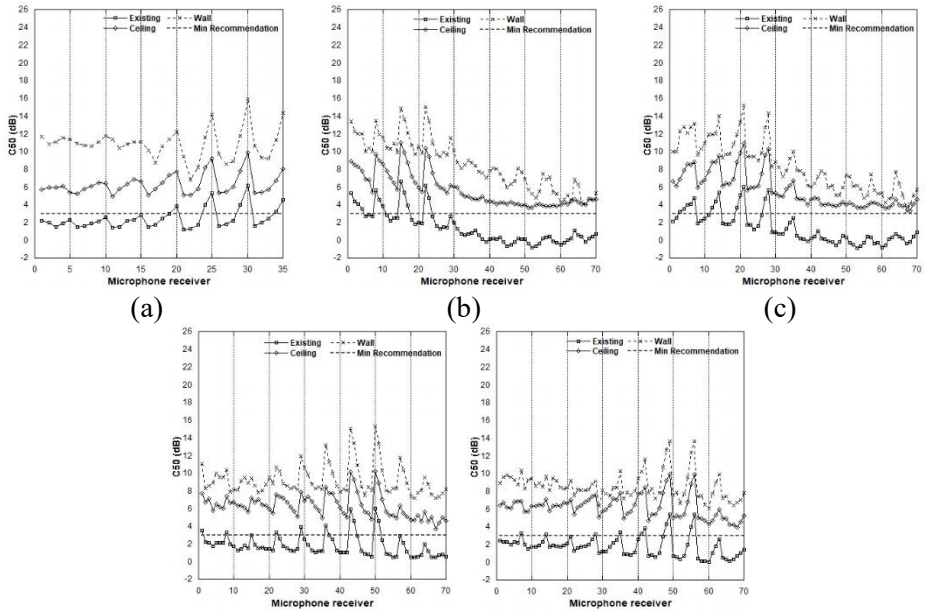


Figure 6: C_{50} performance in small classroom for different sound source locations: (a) lecturer, (b) S1, (c) S2, (d) S3, and (e) S4

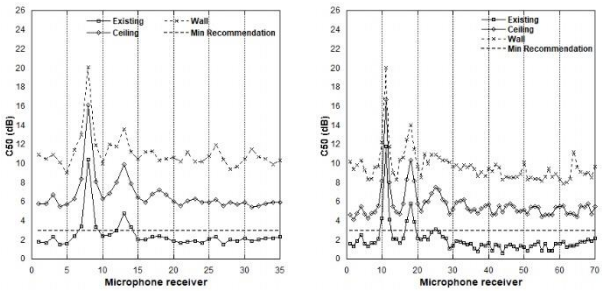


(a) (b) (c)

(d) (e)

Figure 7: C_{50} performance in medium classroom for different sound source locations: (a) lecturer, (b) S1, (c) S2, (d) S3, and (e) S4

Conventional Learning



(a) (b)

Figure 8: C_{50} performance for conventional learning in (a) small and (b) medium classrooms

A similar trend was observed under conventional learning conditions. Figure 8 presents the spatial distribution of C_{50} values for the small and medium classrooms under the existing condition and the proposed surface treatment scenarios. Under the existing room conditions, only a limited number of receiver locations situated close to the sound source achieved the recommended minimum

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C_{50} value of 3 dB. This indicates that speech clarity decreased with increasing distance from the lecturer due to the influence of reflected sound.

The application of absorptive ceiling materials resulted in noticeable improvements in C_{50} across most receiver locations, while further enhancement was achieved following the installation of absorptive wall treatments. After the surface treatments were applied, the majority of receiver locations exceeded the recommended C_{50} threshold of 3 dB, indicating improved speech clarity throughout the room. The improvement in C_{50} was consistent with the reduction in reverberation time observed following the application of the absorptive surface treatments. By reducing sound reflections and increasing the proportion of early arriving sound energy, the surface treatments enhanced speech clarity across the classroom. These findings are consistent with the STI results, demonstrating that improved reverberation control contributes to enhanced speech intelligibility in conventional learning environments.

Comparison between the two learning configurations shows that their influence varies according to the acoustic parameter. For RT, only minor differences were observed between conventional and collaborative configurations. In contrast, STI and C50 showed greater spatial variation due to differences in sound source location, orientation, and source-to-receiver distance. This effect was more evident in the collaborative configuration, where multiple student sound sources were distributed throughout the classroom, compared with the single lecturer source in the conventional configuration. The findings demonstrate that surface absorption primarily controls reverberation, while the spatial arrangement of sound sources and receivers has a greater influence on speech transmission and clarity.

CONCLUSION

The simulation results demonstrated that absorptive wall and ceiling treatments significantly improved the three key acoustic parameters, namely reverberation time (RT), speech transmission index (STI), and speech clarity (C_{50}), in both small and medium classrooms. Similar trends were observed across both instructional configurations, with reductions in reverberation time consistently accompanied by improvements in speech intelligibility and speech clarity. Among the proposed interventions, wall and ceiling treatments effectively enhanced the overall acoustic performance by increasing sound absorption and reducing sound reflections within the rooms. The findings highlight the importance of incorporating acoustic considerations into interior space planning through appropriate surface material selection to support contemporary learning environments. From an operational perspective, university facilities managers should incorporate acoustic performance into classroom refurbishment and maintenance planning, including assessment of background noise, reverberation,

and speech intelligibility before and after major interior modifications. Interior designers and classroom planners should similarly coordinate acoustic material selection with spatial layout at the design stage. Such an integrated approach can reduce the likelihood that acoustics are addressed only after problems in speech communication become apparent during classroom operation. Future studies should investigate the combined influence of other interior design variables, such as room geometry, ceiling height, furniture configuration, and seating layout, on the acoustic performance of learning spaces to establish comprehensive design strategies for hybrid teaching environments.

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