From Concrete Jungle to Learning Sanctuary: A Neuroarchitectural Experiment in Acoustic Materials

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Abstract. This study presents a neuroarchitectural investigation into the acoustic performance of a modern, open-plan primary school classroom in New Zealand. Originally designed with an exposed concrete aesthetic, the space exhibited elevated average noise levels ($L_{Aeq} > 70$ dB) and frequent disruptive peaks ($L_{CPeak} > 105$ dB), posing challenges to cognitive performance and inclusive learning. A ceiling-based intervention using acoustic materials was implemented to reduce reverberation and improve speech clarity. Post-intervention measurements showed a significant reduction in background noise (L_{AFmin}), but minimal change in average levels and an increase in peak events, indicating the limitations of single-surface treatments. Framed within the context of neuroarchitecture, the study highlights how environmental stimuli influence attention, memory, and emotional regulation, particularly for vulnerable learners. The findings support Sustainable Development Goal 4 (Quality Education) and the GDI2025 theme of designing inclusive, resilient learning environments. Recommendations include multi-layered acoustic strategies combining architectural and behavioural interventions to foster cognitively supportive educational spaces.

Keywords: Cognitive Load, Acoustic Materials, Learning Efficiency, SDG 4, Open-Plan Classrooms, Neuroarchitecture.

1. Introduction

Open-plan learning environments, celebrated for their collaborative and flexible pedagogical potential, often present significant acoustic challenges that can undermine the very cognitive functions they aim to support. In educational settings, poor acoustics are known to impair speech intelligibility, increase cognitive load, and reduce learning efficiency—particularly for younger learners and those with sensory or language-based vulnerabilities [1, 2, 3].

This study is situated within the emerging field of **neuroarchitecture**, which explores how architectural design influences human cognition, emotion, and behaviour [4, 5]. Neuroarchitecture integrates insights from neuroscience to inform spatial design, recognising that environmental stimuli—such as light, sound, and spatial configuration—can unconsciously shape attention, memory, and emotional regulation. In educational contexts, these effects are especially pronounced, as children's developing brains are more sensitive to sensory input and environmental stressors [6, 7].

Design elements such as ceiling height, materiality, and spatial zoning have been shown to prime different cognitive responses. For example, higher ceilings may support abstract thinking, while lower ceilings encourage detail-oriented tasks [4]. Acoustics, as a key sensory dimension, play a critical role in this cognitive landscape. Excessive noise and reverberation can disrupt working memory, hinder speech perception, and increase listening effort, particularly in open-plan classrooms where sound travels freely across zones [8, 9].

This paper investigates the acoustic performance of a purpose-built, award-winning open-plan primary school in New Zealand, originally designed with an exposed concrete, industrial aesthetic. Pre-intervention measurements revealed elevated average noise levels ($L_{Aeq} > 70$ dB[1]) and frequent disruptive peaks ($L_{CPeak} > 105$ dB[2]), exceeding recommended thresholds for effective learning environments [10, 11]. These conditions prompted a ceiling-based acoustic intervention using absorptive materials, aiming to reduce reverberation and improve speech clarity.

Framed within a neuroarchitectural lens, this study examines how targeted acoustic treatments influence the sensory and cognitive experience of learners. It also considers the implications for inclusive education, particularly for students with sensory sensitivities or language-based learning needs. By linking architectural design to cognitive outcomes, the research contributes to the broader goals of Sustainable Development Goal

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[1] L_{Ceq} represents the average sound energy over time and is a key indicator of noise exposure in classrooms. According to AS/NZS 2107:2016 Acoustics – Recommended design sound levels and reverberation times for building interiors, and its derivative DQLS-Acoustics, acceptable classroom noise levels should be below 40 dB $L_{Aeq(t)}$, where t is long enough to ensure a stable reading (t = 1 hour). Internationally, the ANSI/ASA S12.60-2010/Part 1 standard recommends a maximum L_{Ceq} of 55 dB to support optimal learning conditions [10].

[2] L_{CPeak} measures the highest instantaneous sound pressure level using C-weighting, which is more sensitive to low-frequency sounds than A-weighting. Unlike time-average metrics, it captures brief, high-intensity sounds such as bangs or claps. It is essential for assessing impulse noise, particularly in environments prone to sudden loud events. To prevent hearing damage, L_{CPeak} should not exceed 140 dB [12].

4 (Quality Education) and aligns with the GDI2025 conference theme of designing for inclusive, resilient, and cognitively supportive environments.

The following sections present the theoretical framework, methodology, and findings from pre- and post-intervention acoustic measurements, offering insights into the role of acoustic design in shaping learning experiences.

2. Literature Review

2.1 Neuroarchitecture: A Cognitive Framework for Design

Neuroarchitecture is an interdisciplinary field that merges neuroscience with architectural design to understand how built environments influence human cognition, emotion, and behaviour [4, 5]. It draws on dual-process theories of cognition—such as Kahneman's System 1 and System 2—to explain how environmental stimuli often act through unconscious, automatic processes (System 1), shaping attention, stress responses, and emotional regulation [4].

One conceptual model of neuroarchitecture, proposed by De Paiva [4], suggests that spatial features such as light, sound, and materiality affect physiological responses (e.g., heart rate, cortisol levels), which in turn influence cognitive performance and well-being. Papale et al. [5] extend this with the concept of "supramodality," where architectural elements evoke multisensory responses that impact cognition even without direct sensory input. These insights highlight the importance of designing learning environments that support both conscious and unconscious cognitive processes.

In educational settings, neuroarchitecture offers a framework for creating spaces that enhance focus, memory, and emotional stability—particularly for young learners whose sensory systems are still developing [6, 7].

2.2 The Role of Acoustics in Neuroarchitectural Design

Acoustics are a critical component of neuroarchitectural design, especially in learning environments. Poor classroom acoustics have been shown to impair speech intelligibility, reduce memory retention, and lower academic performance [1, 2, 3]. Children are particularly vulnerable due to their developing auditory systems and frequent temporary hearing issues [13].

Key acoustic factors include:

- **Sound Pressure Level (L_{Aeq})**: Elevated levels increase cognitive load and reduce speech clarity.
- **Reverberation Time (RT60)**: Longer reverberation times impair comprehension and increase listening effort.
- **Background Speech and Noise (L_{AFmin})**: High background noise disrupts focused tasks and verbal working memory [8, 9].

Prodi and Visentin [9] introduced the concept of "listening efficiency" to quantify the cognitive effort required in noisy environments. Even small increases in reverberation can significantly impair performance, especially for younger students and those with attention or language difficulties.

2.2 Inclusive Learning Environments and Acoustic Equity

Inclusive education requires environments that support diverse sensory and cognitive needs. Acoustically inclusive spaces are designed to reduce auditory distractions and support learners with sensory sensitivities, language-based learning differences, and second-language acquisition challenges [7, 13].

In open-plan classrooms, student-generated noise—such as chatter and movement—can significantly reduce comprehension and increase stress [14]. This is particularly problematic for second-language learners, who experience reduced speech intelligibility under identical acoustic conditions [7]. Children with attention disorders or auditory processing challenges are also disproportionately affected [6].

Mercugliano et al. [2] argues that traditional acoustic metrics may not fully capture the complexity of modern classrooms, calling for child-centred research and updated standards. Tools such as child HATS[3] and psychoacoustic metrics offer more accurate assessments of children's auditory experiences [15].

2.4 Acoustic Materials and Multi-Layered Strategies

Effective acoustic design in classrooms often involves multi-layered strategies, combining ceiling treatments, wall absorbers, soft furnishings, and spatial zoning [16, 17]. Ceiling treatments are particularly effective in reducing reverberation and improving the Speech Transmission Index (STI), which correlates with literacy and cognitive performance [18, 19].

However, excessive absorption can reduce STI and hinder speech clarity, requiring a balanced approach [20]. The use of absorptive and diffusive surfaces has been shown to improve reading speed and reduce listening effort [19, 9].

Recent studies advocate for real-time acoustic assessment tools, such as the SoundOut app, which allow educators to monitor and adjust classroom acoustics dynamically [21]. These tools support the creation of responsive learning environments that align with neuroarchitectural principles and inclusive education goals.

3. Methodology

3.1 Research Approach and Design

This study adopts a quantitative research approach, using empirical acoustic measurements to evaluate the impact of architectural interventions on classroom sound

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[3] Head and Torso Simulator (HATS) used in acoustic measurements to simulate the human head and torso, particularly for testing how sound is perceived by human ears.

environments. The research design is experimental, involving a pre- and post-intervention comparison of acoustic conditions in a real-world educational setting.

The intervention focused on modifying ceiling surfaces to reduce reverberation and improve speech clarity, with measurements taken before and after the installation of acoustic materials. The study aims to assess how these changes influence key acoustic metrics relevant to cognitive performance and inclusive learning.

3.2 Sampling Technique and Participants

A purposive sampling technique was employed, targeting teaching staff in a Year 0–1 open-plan classroom. Three teachers wore calibrated dosimeters during regular classroom hours (09:00–15:00) to capture noise exposure data. This approach prioritised staff well-being and provided insight into the broader acoustic challenges faced in early childhood education environments.

While the focus was on teacher exposure, the classroom served approximately 60 students aged 4–5 years, whose activities and behaviours contributed significantly to the acoustic profile. The dynamic nature of the space—characterised by collaborative and individualised learning—created fluctuating noise levels that were representative of typical open-plan pedagogical structures.

3.3 Classroom Description and Acoustic Context

The study was conducted in a purpose-built, award-winning open-plan primary school classroom in New Zealand. The space measured 8 × 15 metres with a high industrial-style ceiling (3.2 m) and exposed concrete surfaces, resulting in a highly reverberant environment (384 m^3). The combination of hard surfaces, extensive glazing, and minimal soft furnishings contributed to elevated noise levels and poor speech intelligibility.

Distinct acoustic zones were created by contrasting flooring materials—industrial carpet and vinyl—further influencing sound reflection and reverberation. The classroom layout included breakout spaces, reading corners, and wet areas, each with varying acoustic properties.

3.4 Acoustic Measurement Protocol

Acoustic data were collected using DoseBadge™ noise dosimeters (Cirrus Research PLC), worn on the shoulders of teaching staff during regular classroom hours. This method captured real-time exposure to sound pressure levels, focusing on sustained and impulsive noise events.

Three key acoustic metrics were evaluated:

- L_{Aeq} (Equivalent Continuous Sound Level): Represents average sound energy over time. Elevated L_{Aeq} levels are associated with reduced speech intelligibility and increased cognitive load [22].
- L_{CPeak} (Peak Sound Pressure Level): Captures the highest instantaneous sound pressure level, reflecting sudden, disruptive events such as shouting or dropped objects. These peaks are particularly problematic for learners with sensory sensitivities [23].

- L_{AFmin} (Minimum A-weighted Sound Level): Indicates the quietest background conditions. Lower L_{AFmin} values support focused listening and are especially beneficial for second-language learners and students with attention difficulties [16].

These metrics were selected for their relevance to learning outcomes and their ability to reflect both sustained and transient acoustic conditions in educational environments.

3.5 Intervention Description

The initial intervention involved installing Autex acoustic insulation[4] above exposed ceiling services. This material was chosen for its strong mid- to high-frequency absorption, essential for improving speech clarity [18]. The intervention was implemented in stages, beginning with partial coverage and later expanding to full ceiling treatment, including insulation within inverted beams and upper cavities.

The intervention aimed to reduce reverberation time and improve the Speech Transmission Index (STI), thereby enhancing the acoustic environment for both teachers and students. Subsequent modifications—including wall panels and flooring changes—were implemented but not formally measured due to constraints imposed by the COVID-19 pandemic.

4. Results

This section presents the acoustic measurements collected before and after the ceiling-based intervention in the open-plan classroom. The selected metrics—L_{Aeq}, L_{CPeak}, and L_{AFmin}—provide a comprehensive profile of the classroom's sound environment, capturing average exposure, peak disruptions, and background quietness. These metrics are widely recognised in educational acoustics for their relevance to speech intelligibility, cognitive load, and inclusive learning [16, 22, 23].

4.1 Pre-Intervention Acoustic Environment

Prior to the intervention, the classroom exhibited elevated noise levels and frequent impulsive sound events. The mean L_{Aeq} was 71.0 dB (range: 65.0–74.5 dB), exceeding recommended thresholds for primary classrooms (typically <65 dB) [10 ,11]. This persistent ambient noise floor is known to impair speech clarity and increase cognitive effort, particularly for younger learners and those with sensory or language-based needs.

The L_{CPeak} values averaged 101.5 dB, with peaks reaching 110.2 dB, indicating frequent high-intensity sound events such as shouting, dropped objects, or slamming doors. These events are disruptive and can trigger sensory overload, especially in students with auditory sensitivities [7, 13].

The L_{AFmin} averaged 42.6 dB, with a minimum of 36.2 dB, suggesting that even during quiet periods, the baseline noise level remained high. This compromises the clarity

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[4] Acoustic Panels and Solutions for NZ | Autex Acoustics www.autexacoustics.co.nz

of soft speech and hinders focused listening tasks, which are essential for literacy and second-language acquisition [16].

4.2 Post-Intervention Acoustic Environment

Following the installation of Autex insulation above exposed ceiling services, post-intervention measurements revealed mixed outcomes. The mean L_{Aeq} was 70.9 dB (range: 67.0–78.2 dB), representing a negligible reduction of 0.1 dB. This suggests that while reverberation may have been reduced, overall sound energy remained high, likely due to persistent student-generated noise and reflective surfaces.

Unexpectedly, L_{CPeak} values increased to a mean of 105.8 dB, with a maximum of 117.7 dB. This indicates that the intervention did not effectively mitigate impulsive noise events, which continue to pose challenges for learners with sensory sensitivities and for teacher well-being.

In contrast, L_{AFmin} improved significantly, dropping to an average of 32.8 dB, with a minimum of 27.7 dB. This quieter baseline supports clearer speech during low-activity periods and reduces listening effort, particularly for students with attention or language processing difficulties [16, 9].

4.3 Summary of Acoustic Metrics

Table 1 summarises the pre- and post-intervention values for each metric.

Table 1. Summary of Changes in Key Acoustic Metrics Pre- and Post-Intervention (Source: author's own work)

Metric	Pre-Intervention Mean (dB)	Post-Intervention Mean (dB)	Change (dB)
L_{Aeq}	71.0	70.9	−0.1
L_{CPeak}	101.5	105.8	+4.3
L_{AFmin}	42.6	32.8	−9.8

Figures 1 and 2 visually represent these changes, highlighting the substantial reduction in L_{AFmin}, minimal change in L_{Aeq}, and increase in L_{CPeak}.

These results suggest that while the ceiling treatment improved baseline quietness, it did not sufficiently address average or peak sound levels.

The findings reinforce the need for multi-layered acoustic strategies, including wall absorbers, soft furnishings, spatial zoning, and behavioural noise management, to create truly inclusive and cognitively supportive learning environments.

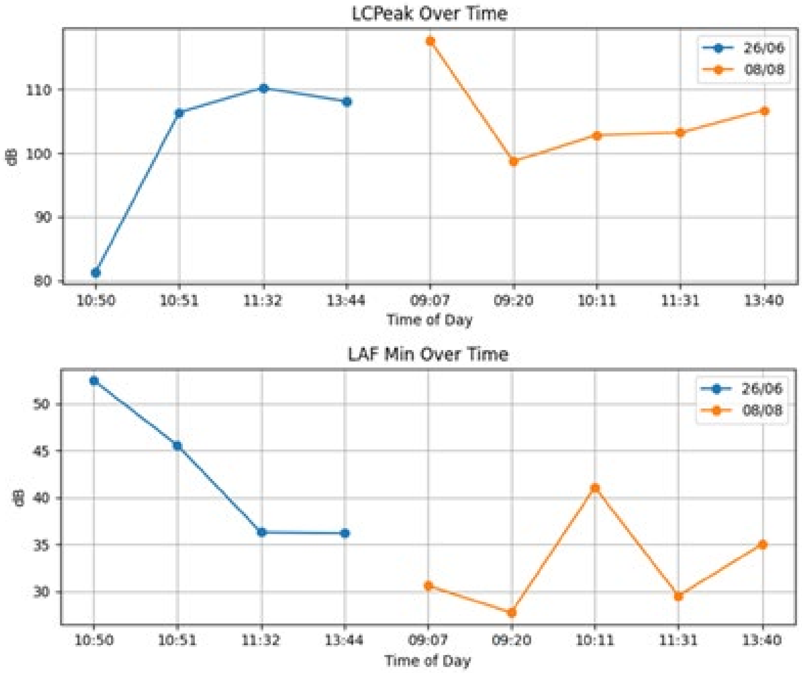

Fig. 1. Time-aligned line graphs of L_{CPeak}, and L_{AFmin} across the school day. (Source: author's own work)

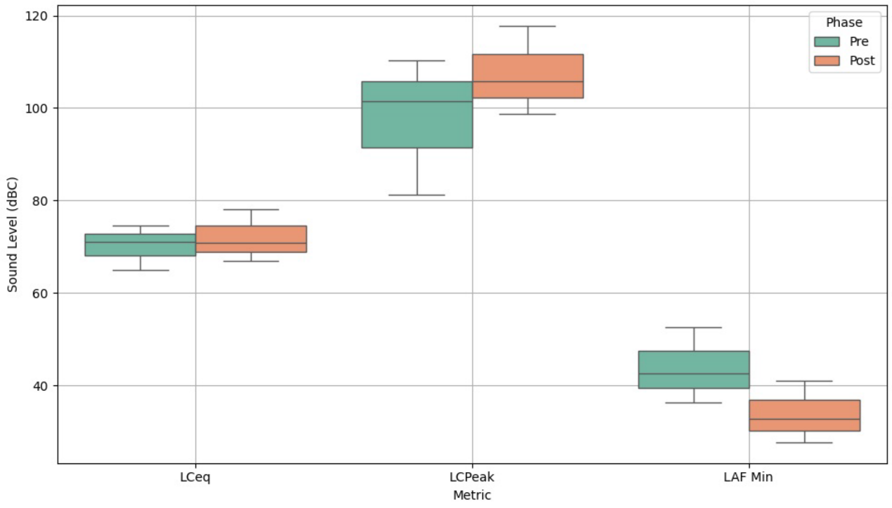

Fig. 2. Distribution of Acoustic Metrics (L_{Aeq}, L_{CPeak}, and L_{AFmin}) Pre- and Post-Intervention. (Source: author's own work)

5. Discussion

The ceiling-based intervention—installing Autex insulation above exposed services—had a measurable but limited impact on the classroom's acoustic profile. While the L_{AFmin} values improved significantly, indicating a quieter baseline during low-activity periods, the L_{Aeq} and L_{CPeak} values remained elevated or worsened. These findings suggest that single-surface treatments are insufficient in addressing the complex acoustic demands of open-plan learning environments.

From a neuroarchitectural perspective, elevated L_{Aeq} and L_{CPeak} values reflect ongoing sensory overstimulation, which can impair attention, memory, and emotional regulation. According to De Paiva's model [4], environmental stimuli such as noise act through unconscious cognitive pathways (System 1), triggering stress responses and reducing cognitive efficiency. Papale et al. [5] further argue that architectural elements evoke multisensory reactions, meaning that sound interacts with other sensory inputs to shape behaviour and learning outcomes.

The modest reduction in L_{AFmin} supports clearer speech and reduced listening effort during quiet periods, aligning with neuroarchitectural principles that advocate for low-stimulation environments to support focused tasks. This is particularly beneficial for second-language learners, students with attention disorders, and those with auditory sensitivities [7, 16, 13].

However, the increase in L_{CPeak} post-intervention highlights the limitations of ceiling-only treatments. Impulsive noise events—such as shouting or dropped objects—remain disruptive and can trigger sensory overload, especially in inclusive classrooms where learners have diverse needs. These findings reinforce the importance of multi-layered acoustic strategies, including wall absorbers, soft furnishings, spatial zoning, and behavioural noise management [24, 9].

The results also support Mercugliano's critique [2] that traditional acoustic metrics may not fully capture the complexity of modern classrooms. Future research should incorporate child-specific psychoacoustic metrics, such as listening effort and speech clarity (C50), to better understand how acoustics affect learning and well-being.

In summary, while the intervention marked a positive step toward acoustic remediation, it was not sufficient on its own. A holistic approach—grounded in neuroarchitectural theory and inclusive design principles—is essential for creating learning environments that support cognition, emotional regulation, and educational equity.

6. Conclusion and Recommendations

This study highlights the complex acoustic challenges inherent in open-plan primary classrooms and evaluates the impact of a ceiling-based intervention within a neuroarchitectural framework. While the intervention successfully reduced background noise (L_{AFmin}), it did not significantly improve average sound levels (L_{Aeq}) or mitigate disruptive peak events (L_{CPeak}). These findings highlight the limitations of single-surface treatments and the need for comprehensive, multi-layered acoustic strategies.

From a neuroarchitectural perspective, the results affirm that environmental stimuli—particularly sound—play a critical role in shaping cognitive performance, emotional regulation, and overall well-being. Elevated noise levels contribute to sensory overstimulation, impairing attention and abstract thinking, while quieter baselines support focused tasks and inclusive learning. These insights align with the goals of Sustainable Development Goal 4 (Quality Education), which advocates for inclusive and effective learning environments for all.

To support inclusive education, future design strategies should integrate:

- Ceiling and wall absorbers to reduce reverberation and improve speech clarity.
- Soft furnishings and spatial zoning to manage sound distribution and reduce cognitive load.
- Behavioural noise management to complement architectural interventions.

These recommendations are particularly relevant for:

- Architects and designers working on educational facilities.
- School administrators and facilities managers responsible for learning environments.
- Policy makers and regulators developing acoustic standards for schools.
- Educators and researchers interested in the intersection of design, cognition, and inclusion.

Future research should explore the cumulative effects of layered interventions and incorporate child-specific psychoacoustic metrics such as listening effort and speech clarity (C50). Mixed-methods approaches—including qualitative feedback from students and teachers—will be essential for capturing the lived experience of acoustics in learning environments.

By embedding acoustic comfort within broader neuroarchitectural strategies, educational spaces can better support diverse learners, reduce cognitive strain, and foster environments conducive to academic success and emotional well-being.

7. Limitations

This study presents several limitations that should be considered when interpreting the findings:

Temporal Gap and Data Integrity: There was a significant delay between the initial data collection (2019) and the analysis phase (2025). During this period, some source files were lost or became inaccessible, limiting the ability to verify all acoustic metrics with full confidence. As a result, the analysis adopts a "state of play" perspective, presenting indicative rather than definitive findings.

Scope of Intervention Evaluation: Only the first phase of the acoustic intervention—ceiling insulation—was formally evaluated. Subsequent modifications, including wall treatments and flooring changes, were implemented without accompanying acoustic measurements due to constraints imposed by the COVID-19 pandemic and the repurposing of the classroom space. This restricts the ability to assess the cumulative impact of multi-layered strategies.

Measurement Focus on Staff Exposure: The study relied solely on quantitative acoustic data collected via teacher-worn dosimeters. While this method provides valuable insights into staff exposure and well-being, it does not capture the full range of student auditory experiences, particularly those of younger learners with sensory sensitivities or language-based learning needs.

Absence of Qualitative Data: The study did not incorporate qualitative feedback from teachers or students, which could have enriched the interpretation of the acoustic environment and its perceived effects. Future research should adopt a mixed-methods approach to better understand the lived experience of acoustics in educational settings.

These limitations highlight the challenges of conducting longitudinal research in real-world environments and highlight the need for more robust, child-centred methodologies in future studies.

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