Intelligent Passive Room Acoustic Technology for Acoustic Comfort in New Zealand Classrooms

A thesis by Megan Burfoot

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Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

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Co-Authored Works and Declaration of Collaboration

Statement from co-authors confirming the authorship contribution of the Ph.D. candidate:

As co-authors of the research “Intelligent passive room acoustic technology for acoustic comfort in New Zealand classrooms” we confirm that Megan Burfoot contributed over 80% of the research. Megan Burfoot is responsible for writing, ideas, and the content of the research.

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Thesis Abstract

Background: Classrooms are dynamic, progressive spaces, uniquely shaped by the very students and educators occupying the space. Just how we can change the lighting, ventilation, temperature, and layout of a classroom, we must too be able to change the acoustic 'state'. To change the acoustic state, we need to alter the total sound absorption in the space, thereby changing the Reverberation Time (RT). RT is the time taken in seconds for the sound level to decay by 60dB, similar to the amount of echo in a space. For example, during group discussions or loud activities, we want more absorption (lower RT). During teacher lectures, we want to project and echo the sound, so we want less absorption (higher RT). Our options for changing RT are to alter the sound-absorbing properties of existing surfaces. Technology with this quality is referred to as Passive Variable Acoustic Technology (PVAT), whose properties you can vary to change the RT in the space. Conveniently, intelligent advancements can be made to PVAT to achieve a desired RT more precisely.

Originality: The solution presented in this work will finally recognise classrooms as dynamic, changing spaces which require dynamic, changing RTs. The solution contains two critical components: the PVAT, and the intelligent capability. The PVAT component is achieved by overlaying reflective, rotating louvers over a sound absorbing panel. If the louvers rotate open, they allow sound through to be absorbed by the panel behind, decreasing the RT. If they rotate closed, they block and prevent sound from being absorbed, thus echoing the sound, and increasing the rooms RT. The second component aims to give the technology an intelligent mind of its own. Microphones set-up around the room detect the sound waves in the space. These waves are then transformed into an output that can be interpreted by a machine learning classifier. The classifier is trained with algorithms to recognise and define from the transformed sound waves, which acoustic 'scene' is happening in the room. Once the scene has been determined, a pre-programmed algorithm calculates the perfect RT for that acoustic scene. There are diverse negative effects that commonly result from inappropriate RT, which could therefore be alleviated with IPRAT. IPRAT could improve occupant health and safety, increase communication clarity, and improve occupant wellbeing.

Aim: With the novel IPRAT, classrooms can finally achieve optimised RTs, for any activity happening in the space. The concept of optimising RT in real-time is new, so it was not known which RTs would optimise each classroom activity. The research question for this work thus followed; what is the effect of IPRAT on classroom acoustic comfort? The aim of this work was to quantify the effects of IPRAT on classroom acoustic comfort. This aim is satisfied by comparing the acoustic comfort of several classrooms using IPRAT, with the same classrooms not using IPRAT. An efficient and economical way this comparison was realised was to firstly use software to simulate the behaviour and results of 5 classrooms using IPRAT, and secondly, conduct a case study using an IPRAT prototype in a real classroom. Finally, the two sets of data were statistically analysed to determine the final effect of

IPRAT on classroom acoustic comfort. Additionally, this data was compared with professional industry standards (for New Zealand namely, AS/NZS Recommended Design Acoustic Standards).

Methodology: This thesis is submitted as Format Two: Submission by four manuscript publications. The first manuscript aimed to determine the rationale for IPRAT. A best-evidence synthesis and prior art search were conducted to determine the highest level of intelligence for passive variable acoustic technology. It was discovered that dynamic spaces should be designed with varying RT's however, a literature gap exists for intelligently adjusting RT to suit changing space uses. The unique IPRAT solution was conceptualised, which integrates PVAT and Acoustic Scene Classification. Thus, IPRAT was proclaimed, developed, and analysed, and a use case example for IPRAT was provided. The findings from manuscript one strongly suggested the need to test or prototype IPRAT. The second manuscript aimed to establish a simulation method for testing IPRAT. Using secondary data, 20 classroom environments 'typical' to New Zealand were detailed and developed. Additionally, a software method was established which could be used to simulate acoustic technology. The 20 classroom profiles were detailed and demonstrated using I-Simpa, a pre/post-processor for acoustic codes, and Autodesk software. With these virtual environments, it was suggested that IPRAT should now be simulated, to demonstrate its potential to improve acoustic comfort. The third manuscript aimed to determine the effect of IPRAT on acoustic comfort using simulation. IPRAT was thus simulated in the 20 environments established in manuscript two, statistically analysing the effect of IPRAT on RT, sound strength and clarity. The output of this manuscript firstly included an acoustic simulation method in I-Simpa software presented for initial technology validation. Secondly, the quantified improvements of IPRAT on acoustic parameters RT, sound strength and clarity were determined. Last, a database of RTs which improve acoustic quality for four aural situations typical to classrooms was derived. In this simulation, the benefits of IPRAT were found to be statistically significant, and it was recommended that future research physically prototype the technology. The fourth and final manuscript aimed to determine the effect of IPRAT on acoustic comfort using a case study. An IPRAT prototype was deployed in a tertiary classroom by constructing and testing only the PVAT component. The IPRAT was tested by adjusting the prototype's sound absorption.

Results: Despite the simulation study achieving a more significant RT reduction and RT range, when we compare it with the ASNZS recommendations, the case study data was much more significant. At a room volume of 170m^3, NZS Acoustic Standards recommends a mid-frequency RT of 0.55 for 'Rooms for Speech', and 0.7 for 'Rooms for 'Speech/Lecture'. Using the equation relating IPRAT coverage and RT from manuscript 4, the researchers could propose that at 20.5% coverage, the RT can be varied between 0.58 and 0.70s. This comes a mere 0.03 and 0.00s away from matching the industry standards for both room types. Thus, it is concluded that by using IPRAT in the case study classroom, the conditions of both room types can be satisfied – increasing the acoustic comfort in both classroom learning and classroom lecture. Existing studies in literature test single RT values, and usually aim to improve the singular RT for the classroom with some form of acoustic treatment. The thesis results can be generalised to New Zealand but may also offer benefits on a global scale. Additionally, by optimising classroom acoustics the most benefits are realized by vulnerable students. This includes children with sensory disabilities, hearing difficulties and those speaking a second language. It is probable that the adoption of this technology in industry will involve a slower progression of intelligence toward IPRAT, beginning with manual and then automated control. This is also a wise way to save development costs whilst slowly introducing the technology into opportune spaces. Trade-offs will need to be made in any spaces using IPRAT as a significant proportion of free wall space will be taken up by the technology. Future studies should compare different methods of achieving PVAT and find the most effective design. After which, the quantitative and qualitative improvements to acoustics should be researched from a human comfort perspective.

Findings: The key takeaways from this thesis for industry professionals, academics and policy makers are as follows: First, acoustic comfort is largely neglected within IEQ. Acoustic optimisation is perceived as a complicated design aspect and thus is often avoided as a core topic in architecture curriculum. Thus, acoustic comfort should be taught in all architectural courses as having equal importance to other IEQ's. The discomfort associated with poor acoustics for varying space uses should be understood by students. Second, the acoustic design of spaces is often neglected by designers, as it is set as a low priority. Clients wont intuitively budget for acoustic design. Acoustic optimisation is often an afterthought. When designed for, the acoustics of a space is considered, a trade-off is made for varying space uses. Thus, the acoustics for varying space uses should be optimised. Acoustic engineers should be employed on project teams to advise the most appropriate technology to achieve the varying acoustics. Third, the development of variable acoustic technology is slow, and the current technology in development is unaffordable. No technology is in development which could provide intelligent optimisation. Thus, engineers should continue to test and develop variable acoustic technology, with the goal being to create affordable variable acoustic options. Last, acoustic standards recommended singular acoustic states for flexible and dynamic spaces, including classrooms. Therefore, acoustic standards should reflect the changing acoustic needs for flexible and dynamic spaces, beginning with recommended classrooms acoustics. This responsibility lies with policy makers.

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List of Acronyms

Table 0.1. List of Acronyms

IPRAT	Intelligent Passive Room Acoustic Technology	A novel concept developed by the authors, is the use of ASC in combination with PVAT to constantly maintain an optimised RT **(Burfoot, Ghaffarianhoseini, Naismith, & Ghaffarianhoseini, 2021)**.
PVAT	Passive Variable Acoustic Technology	Technology which suppresses sound by modifying the environment close to the sound source, with a variable component to alter its modification effect (Schira, 2016).
AI	Artificial Intelligence	A system's ability to correctly interpret external data, to learn from such data, and to use those learnings to achieve specific goals and tasks through flexible adaptation (Kaplan & Haenlein, 2019).
ML	Machine Learning	A branch of computational algorithms that are designed to emulate human intelligence by learning from the surrounding environment (El Naqa & Murphy, 2015).
ASC	Acoustic Scene Classification	The task of classifying environments from the sounds they produce (Barchiesi, Giannoulis, Stowell, & Plumbley, 2015).
RT	Reverberation Time	The time (in seconds) required for the sound energy density to decrease by 60 dB after the source emission has stopped (Prato, Casassa, & Schiavi, 2016).

Chapter 1. Introduction

1.1 The Research Problem

It is widely understood that today, our society is facing increasingly persistent sensory issues; spaces overflowing with distractions, stress levels interfering with cognitive efficiency and higher-than-ever rates of mental ill-health (Jens & Gregg, 2021) (Sousa & Neves, 2021). People are spending up to 90% of their time indoors, spaces are over-crowded due to a growing population, and general sensitivity to stimuli is increasing (Pessotti, 2021) (Yang & Moon, 2019). When we attempt to measure the effects of stimuli in a space, the Indoor Environmental Quality (IEQ) can be used (Larsen et al., 2020). This accounts for the overall comfort level building occupants experience; thermal comfort, air quality, light comfort and acoustic comfort. The architectural engineering industry has made considerable advancements to thermal, air quality and light control. With economic, sustainable, intelligent and responsive solutions, successful examples of such architecture are giving building occupants an indoor experience like never before (Ferdous, Bai, Ngo, Manalo, & Mendis, 2019). The technological advancements seen in the past decade, combined with a highly valued and progressive architectural industry, mean our buildings today are something of a marvel (Appio, Lima, & Paroutis, 2019).

However, acoustic comfort has been left behind, deemed less important than its competing qualities (Chapter 2) (Clements-Croome, 2015), (Vardaxis, Bard, & Persson Waye, 2018). Building users, however, experience first-hand the effects of these spaces and thus prioritise acoustic comfort for IEQ (J. Chen & Ma, 2019) (Sezer & Erbil, 2015). This neglect by both industry and academia is causing unacceptable symptoms experienced by building users across the globe (E. Lee (2019). When the acoustics of the room is not optimized, adverse effects arise (Lupășteanu, Chingălată, and Lupășteanu (2018) **(**Selamat and Zulkifli (2016) (Loupa, Katikaridis, Karali, & Rapsomanikis, 2019) (Asadi, Mahyuddin, and Shafigh (2017) (Morales and Manocha (2018) (Abbasi, Motamedzade, Aliabadi, Golmohammadi, and Tapak (2018). Additionally, complexities within the subject area make acoustic excellence difficult to measure and obtain (Taghipour, Sievers & Eggenschwiler, 2019) (Yang, Moon & Kim, 2018) (Bluyssen, Zhang, Kim, Eijkelenboom, & Ortiz-Sanchez, 2019). Intelligent or responsive acoustic solutions in architecture are very limited. Interestingly, when looking at spaces intended for cognitive functions, noise is one of the most studied IEQ factors in relation to effects on occupants (C. Wang et al., 2021). Studies reveal acoustics as the major factor for IEQ acceptance in university classrooms (M. C. Lee et al., 2012) and primary school classrooms (D. Zhang, Ortiz, & Bluyssen, 2019) (Bluyssen, Kim, Eijkelenboom, & Ortiz-Sanchez, 2020). Nevertheless, although great strides have been made in recent literature to improve the IEQ elements of indoor air quality, thermal and light comfort (Berquist, Ouf, & O'Brien, 2019) (Kallio et al., 2020) (Korsavi & Montazami, 2019) (Korsavi, Montazami, & Mumovic, 2020) (Z. Zhang, Geng, Wu, Zhou, & Lin, 2022), acoustic comfort research is trailing behind. One space receiving detrimental effects from acoustic neglect is the classroom. The classroom is where our youth spend most of their time growing and developing. Classrooms also contribute towards forming who they become, the knowledge they acquire, the habits they develop and the attitudes they carry with them for the rest of their lives. Our current classroom acoustic solutions belong in the 20th century. They are contributing to impaired communication, lack of concentration, impaired mental cognition, ill-motivation to engage, failure in school and teacher vocal dis-ease (Kraus & Juhásová Šenitkov, 2017) (Kitapci & Galbrun, 2019). It should be mentioned that these symptoms affect ten-fold those with sensory disabilities, autism spectrum disorder or those learning in a second language.

One reason for these acoustic issues is related to professional standards. Classrooms have been recognised as single-use spaces, meaning there is only one key activity carried out in the space. The problem with this, is that designers of educational buildings therefore design the classroom to have one acoustic 'state.' For old classrooms, this 'state' is a loud, echoing space. For new or renovated classrooms, this 'state' is an attempt to absorb as much sound as possible, leaving a dull, dampened space. The assumption that classrooms are single-use spaces is a damaging compromise between the numerous activities requiring different acoustics. Classrooms are dynamic, progressive spaces, uniquely shaped by the very students and educators occupying the space. Just how we can change the lighting, ventilation, temperature and layout of a classroom, we must too be able to change the acoustic 'state' (Scannell, Hodgson, García Moreno Villarreal, & Gifford, 2016). To change the acoustic state, we need to alter the total sound absorption in the space, thereby changing the Reverberation Time (RT) [the time taken in seconds for the sound level to decay by 60dB] (Prato et al., 2016). For example, during group discussions or loud activities, we want more absorption (lower RT). During teacher lectures, we want to project and echo the sound, so we want less absorption (higher RT). Our options for changing RT are to alter the number of sound-absorbing surfaces or alter the sound-absorbing properties of existing surfaces. Ideally, we want to be able to achieve any state between the lower RT and the higher RT. Technology with this quality is referred to as Passive Variable Acoustic Technology (PVAT), whose properties you can vary to change the RT in the space (Schira, 2016).

1.1.1 Research Gap

Literature addressing the acoustic comfort of spaces has been improved and refined since the first address of this quality in 1949, where Leo Beranek studied acoustics' role in comfort and safety in dwellings by conducting surveys and measuring Sound Pressure Level (SPL) (Beranek, 1949). Ever since the number of articles published per year is increasing (Figure 1.1). The steady increase of PVAT papers is also evident, following similar trends to that of acoustic comfort papers.

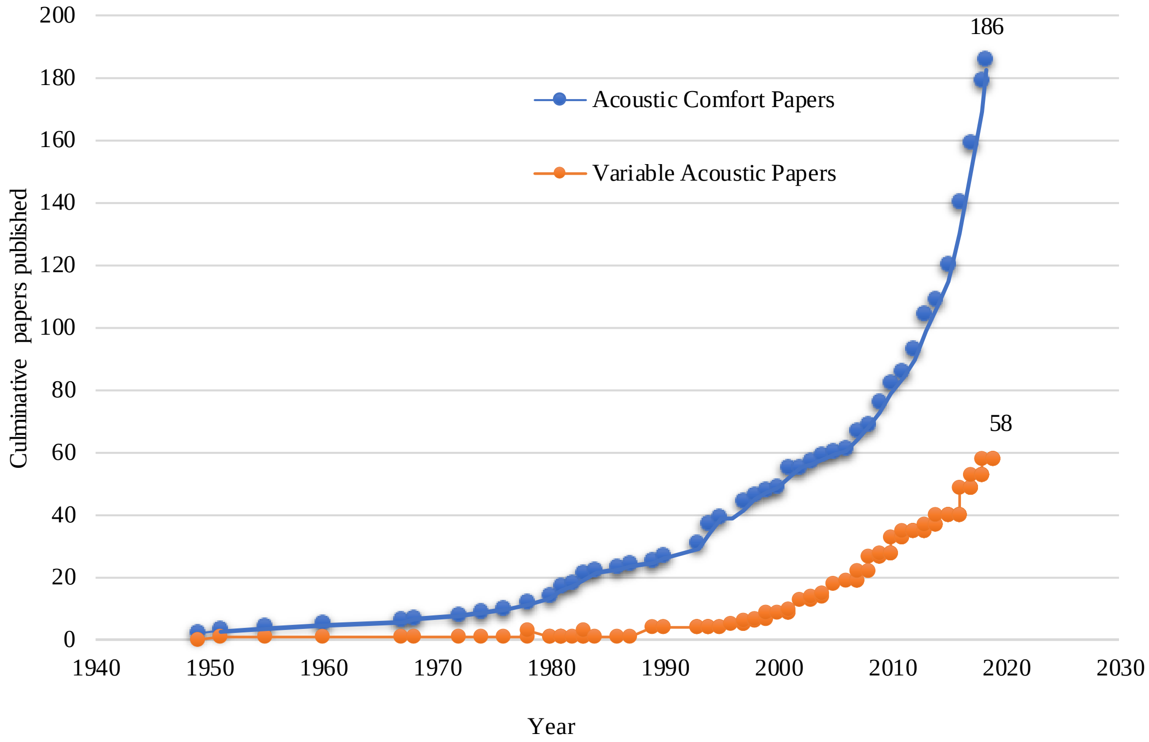


Figure 1.1. 'Acoustics comfort' papers published per date range and the relationship between cumulative: 'acoustic comfort' vs. 'PVAT.'

The study of 'acoustic comfort' is not straightforward or easy to define (Taghipour, Sievers & Eggenschwiler, 2019), and cannot be determined purely from physical measurements. Human perception of sound depends not only on the sound itself, but additionally the emotional or sensory effect the brain processes from the other existing sensory conditions of the space (Yang, Moon & Kim, 2018), and their interaction (Bluyssen et al., 2019).

Published articles in the 1900's generally attempted to define and measure acoustic comfort, and more recent articles discuss specifics related to various acoustic topic areas. These articles were manually sorted into common topic areas by deciphering the main themes explained in abstracts (Figure 1.2). The trend of these topic areas sees the recent growth of papers addressing acoustic classification, backing the evolution toward ASC.

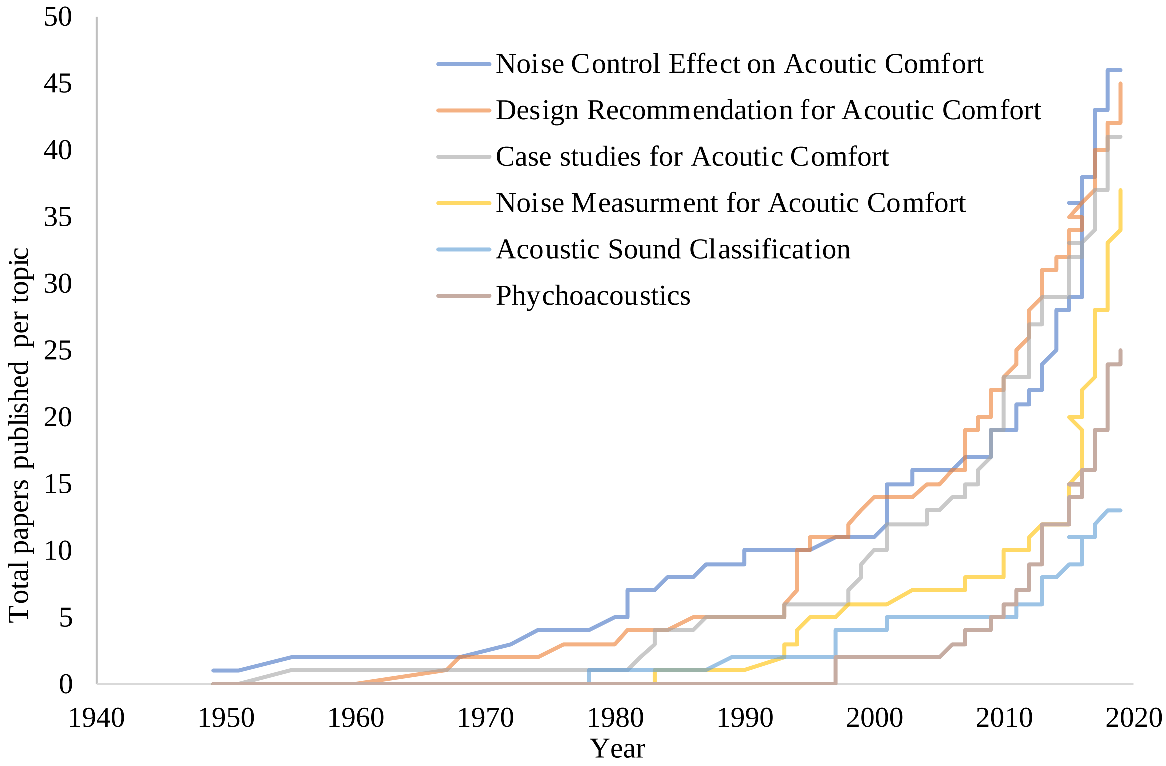


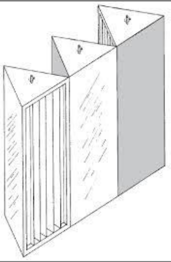
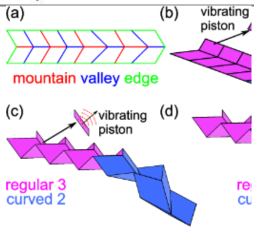
Figure 1.2. Main topic areas discovered within acoustic comfort papers, and cumulative papers published per year for each acoustic topic area

A range of PVAT exist which manually vary RT, including; shortening RT by adding a reverberation absorptive chamber, lowering a ceiling to decrease volume, increasing absorption with rotating acoustic panels, rolling curtains, or hinged flaps (Kozlowski (2018) (Hough, 2016). As an advancement to manual PVAT, automated systems have been created to achieve a significantly higher level of acoustic comfort, as they provide more adaptability and efficiency in varying acoustics. Each acoustic system presented below strives to vary the RT in a space as simply and efficiently as possible. Acoustic Enhancement Systems (AES) use electronics to repeat sounds from other speakers, thereby extending the RT (Schmidt, Löllmann, & Kellermann, 2018). An intelligent AES system was initially proposed in 2010 and further developed where the RT is measured in-situ, compared with the desired RT and the discrepancy added as artificial RT (F. F. Li, 2010). This system does not act to vary RT, however.

Demonstrating the highest level of intelligence PVAT has reached will help understand the development and progress toward intelligent acoustics in academia and industry (Table 1.1 and Figure 1.3). Certain solutions have been focused toward select architectural spaces (Figure 1.4), and the identification of these research directions aid us in understanding which spaces require immediate attention.

Table 1.1. PVAT solutions and the spaces they have been applied in

Level of Intelligence	PVAT	Illustration	Source(s)	Space of Focus

None	Manual Portable		Howarth and Robinson (2017) Inácio (2018) Holzman, Nevola, and Lukanic (2010)	Industrial workplaces, Classroom, Boardroom, Large Hall, Open-plan Offices
	Manual Fixed		Cairoli (2018)	Large Hall
Programmable, Motorized, controlled remotely	Triffusor		D'antonio (2002)	Large Hall
	Acoustic Origami Tessellations		Zou and Harne (2017) X. Yang (2017)	Boardroom
	Evoke		Adelman-Larsen (2018).	Large Hall

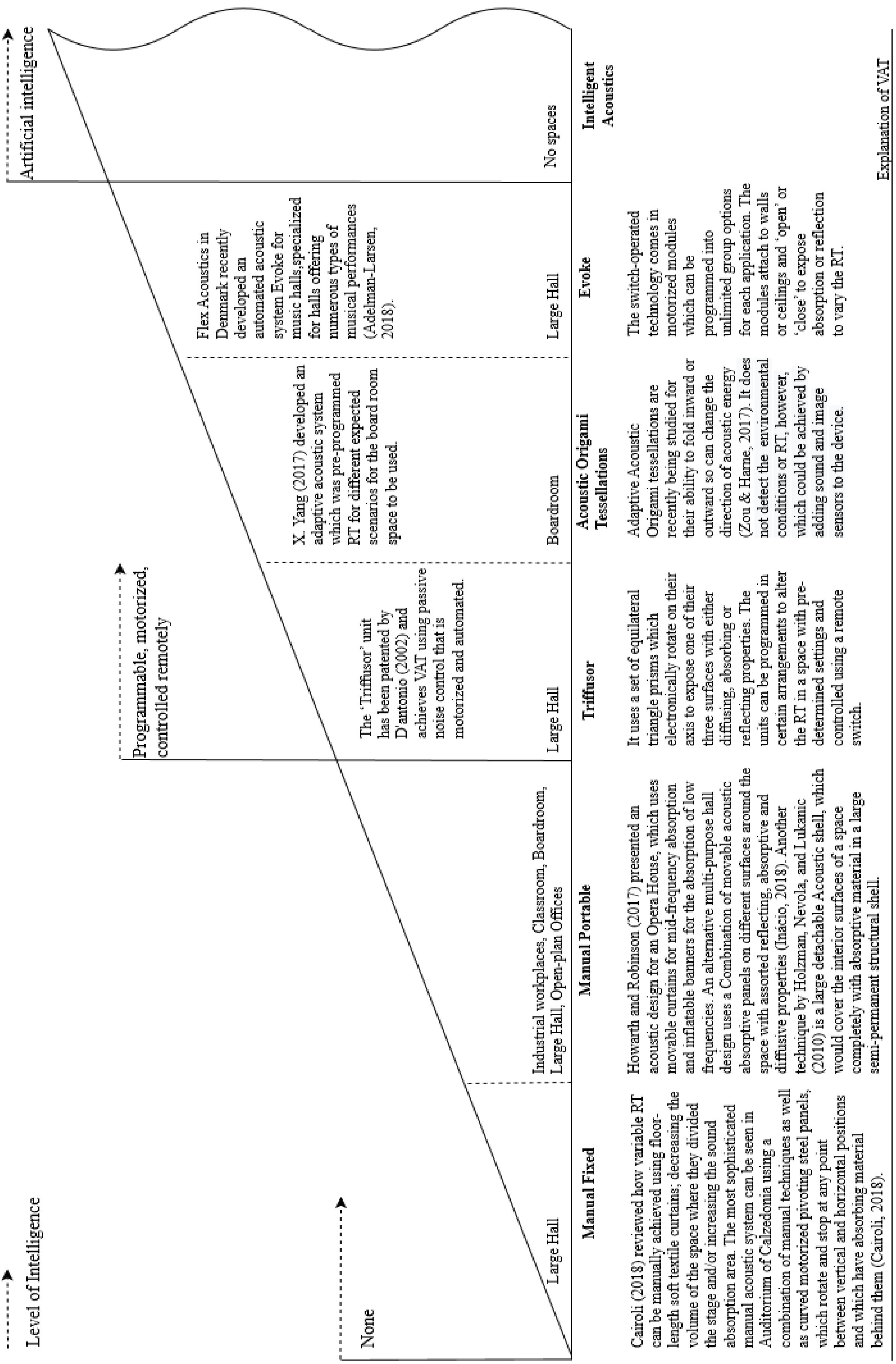


Figure 1.3. Historical development of PVAT

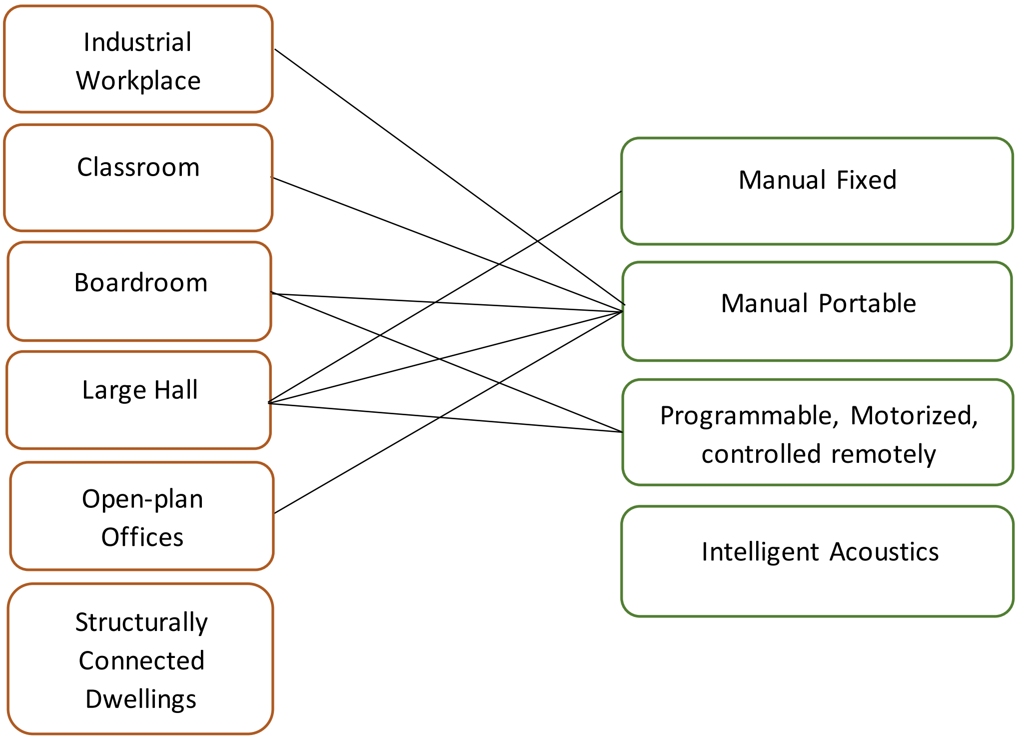


Figure 1.4. Architectural spaces and their PVAT solutions

PVAT exists and is already present in our built environment, in adjustable sound curtains, portable acoustic screens and more advanced remote-controlled and automated acoustic panels. The main-streamed PVAT solutions often require manual labour for adjustment, and occupy a lot of space in a building interior. A research gap exists whereby no architectural acoustic technology has been given intelligent capabilities. This means our quick-advancing smart building industry has also left acoustic solutions behind. The highest level of intelligence architectural PVAT has reached in automated and programmable; exhibition no machine learning or artificial intelligence capabilities. The purpose of this study is to close this research gap, so a solution is tested in classrooms.

1.1.2 Solution Concept

Conveniently, intelligent advancements can be made to PVAT to more precisely achieve a desired RT. Intelligence within our built environment is experienced as buildings optimally responding to occupants' needs, thus achieving significant improvements to user wellbeing, sustainability and adaptability of architecture (Clements-Croome, 2011) (Ghaffarianhoseini et al., 2016).

The solution presented in this work will finally recognise classrooms as dynamic, changing spaces which require dynamic, changing RT's. The solution contains two critical components; the PVAT, and the intelligent capability (Burfoot, Ghaffarianhoseini, et al., 2021). The PVAT component is achieved by overlaying reflective, rotating louvers over a sound absorbing panel. If the louvers rotate open, they allow sound through to be absorbed by the panel behind, decreasing the RT. If they rotate closed, they block and prevent sound from being absorbed, thus echoing the sound and increasing the rooms RT. The louvers can also rotate to any state between 'open' and 'closed', to achieve a wide range of RT's for the space. The second component aims to give the technology an intelligent mind of it's own. Microphones set-up around the room detect the sound waves in the space. These waves are then transformed into an output that can be interpreted by a machine learning classifier. The classifier is trained with algorithms to recognise and define from the transformed sound waves, which acoustic 'scene' is happening in the room. This type of machine learning is called Acoustic Scene Classification (ASC) (Barchiesi et al., 2015). Once the scene has been determined, a pre-programmed algorithm calculates the perfect RT for that acoustic scene. The desired RT value is then expressed as a value for the 'required rotation' (0-90degres). This command is then communicated through Wi-Fi to a mechanical actuator, which rotates the louvers as specified to achieve the perfect RT for the space. This intelligent classification from microphone to louver is happening in real-time, without the need of user command or interface. The integration of this intelligent component with the PVAT creates a novel solution, never seen before in academia or industry. The researchers have named this solution Intelligent Passive Room Acoustic Technology (IPRAT).

The emergence of ASC has explicitly seen improvements for a variety of systems, due to its intelligent audio classification capabilities (Phan et al., 2019). Moreover, it has been gaining attention in recent years due to its vast variety of applications and gradual performance improvements (Lagrange, Lafay, Rossignol, Benetos, & Roebel, 2015). The need for incorporating smart technologies into our built environment to maximize IEQ has been demonstrated in past literature (Ghaffarianhoseini, Ghaffarianhoseini, Boarin, Haarhoff, & Walker, 2019) (GhaffarianHoseini, 2013). This is due to occupants having changing preferences and needs over time (Bluyssen, 2019). IPRAT has been designed with the intention to remove such adversities around room acoustics, as artificial intelligence used in flexible spaces can significantly enhance all areas of IEQ (Panchalingam & Chan, 2019).

1.1.3 IPRAT Benefits

There are diverse negative effects that commonly result from inappropriate RT, which would therefore be alleviated with IPRAT. Through understanding these diverse discomforts, it is possible to formulate a hypothesis on how IPRAT would solve these issues. Firstly, IPRAT would improve occupant health and safety. Exposure to workplace noise is disruptive and, in long durations damaging to occupants' hearing (Rabiyanti, Rahmaniar, & Putra, 2017). Without IA, disruptive ambient noise in a residential building can lead to decreased wellbeing (Kraus & Juhásová Šenitkov, 2017), poor sleep/insomnia, distress to people with sensory disabilities (such as Asperger's Syndrome), and induced exhaustion (Motlagh, Golmohammadi, Aliabadi, Faradmal, & Ranjbar, 2018). Office workers in a disruptive environment experience stresses that negatively impact cognitive performance, memory, heart rate and eye activity. Additionally, teachers experience greater exerting effort to recognize how long they should attenuate vowels for and what volume they should speak at, with increases of lung pressure and vocal fatigue arising (Bottalico (2017).

Secondly, IPRAT would increase communication clarity. Where important information is being communicated, the appropriate acoustic quality of the space is paramount for an accurate understanding between parties. When students find it challenging to comprehend their lessons, they experienced tiredness, restlessness, ill motivation and the inability to concentrate effectively, especially for the mentally impaired (Madbouly, Noaman, Ragab, Khedra, & Fayoumi, 2016). Kitapci and Galbrun (2019) similarly discovered a relationship between the acoustic conditions of a space, and the performance of students speaking or listening in multilingual environments. Furthermore, Amlani and Russo (2016) found an increase in mental effort and an even higher mental effort for listeners seated further back from the speaker beyond a determined 'critical distance.' Theatre performances also rely on having appropriate acoustics for the audience to understand the work and enjoy the music without it sounding blurred (Luizard, Brauer, & Weinzierl, 2019).

Lastly, IPRAT would improve occupant wellbeing. Decreased occupant health and communication clarity, both addressed above, subsequently result in decreased wellbeing. Creating a comfortable acoustic environment that enhances wellbeing is necessary in spaces where occupants spend large portions of their time. Although PVAT is continually being optimized to eliminate RT discomforts, many more of these discomforts would be alleviated by IPRAT as an extended benefit, for its ability to match the acoustic condition of a space to its specific application. We can see that different architectural spaces experience different acoustic discomforts and have received focus from select PVAT solutions. Figure 1.5 provides a way to accurately expose the imbalances between issues and solutions for each architectural space. Although each ill effect and PVAT carry different levels of contribution and significance, finding appropriate weightings for each phenomenon is not within the scope of this review, and would be subject to many different external environmental parameters.

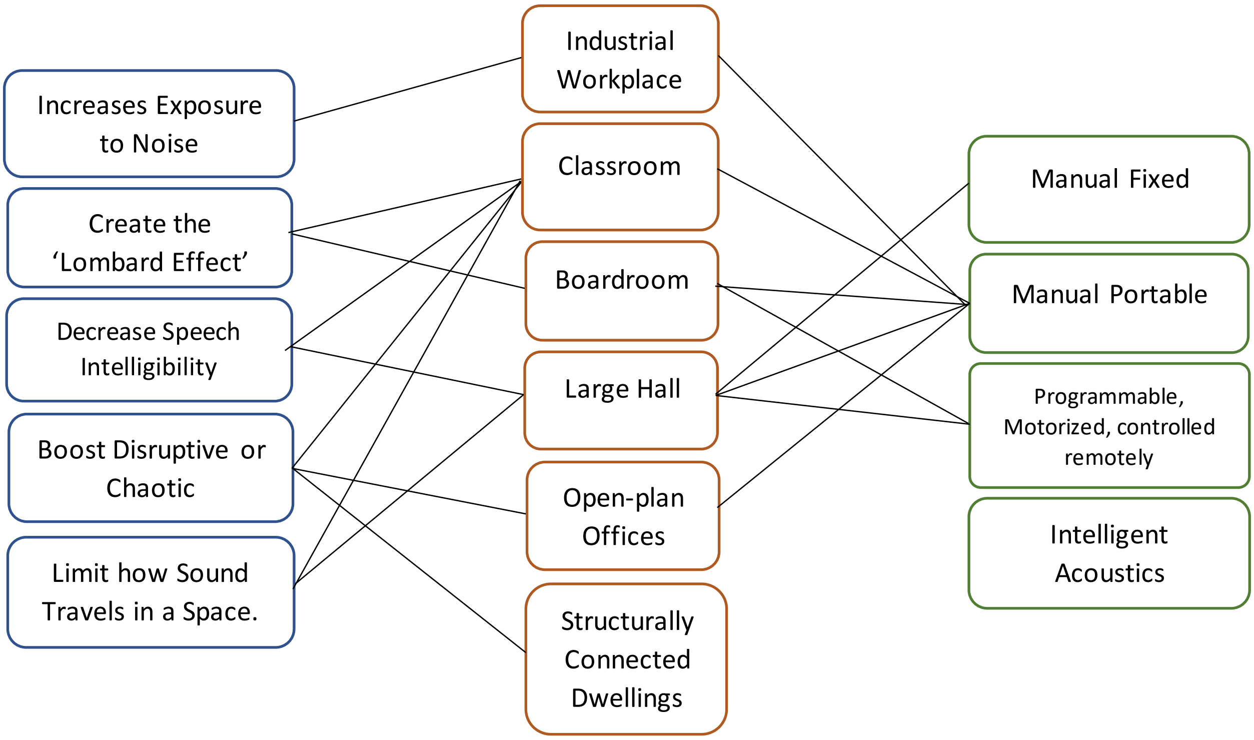


Figure 1.5. Acoustic discomforts and associated PVAT solutions for architectural spaces

Large halls have received the most attention from PVAT, even though classrooms suffer the most acoustic discomfort. All except one discomfort was experienced in classrooms of which being 'loud signal noises causing hearing loss' which was predictable only experienced in industrial workplaces.

Generally, large halls are privately owned and rented to performance groups (Bonet & Schargorodsky, 2018), whereby IEQ holds utmost importance to the design of the space (Tan, Fang, Zhou, Wang, & Cheng, 2017). PVAT for large halls have thus been reviewed, studied, designed, improved and optimized, as theatre companies have both the capital and motivation to invest in enhanced stage performances for profit maximization (The Theatres Trust, 2017). On the contrary, most schools and educational institutions in NZ are government-owned (Ministry of Education, 2019). The public nature of these buildings means there is limited funding from taxpayers for each project, where funds fail to create the optimum acoustic environments. The goals for schools are not to make a profit, but to educate the youth of NZ as efficiently and effectively as possible. Although there are numerous private-owned education institutions in NZ, academia and industry have underestimated the importance of the acoustic environment (Vardaxis et al., 2018). The validity of this claim is questionable, however, as there has been no distinction in literature between acoustic differences of private and public NZ schools, although their funding situations are very different.

D. Zhang and Bluyssen (2019) conducted a survey of various IEQ's in classrooms and children's perception of them. Noise was discovered as the leading cause of annoyance for the children, above all other IEQ's. There is a prevailing need for better acoustic solutions in classrooms, rather than in large halls, questioning the incoherent nature of this imbalance. In a more specific context, the population of NZ affected by acoustic discomfort in large halls is significantly less than those affected in classrooms: At any given time, approximately 17% of the NZ population is attending school full time (The Ministry of Education, 2019b); (Worldometers, 2019), which is considered as 30 hours per schooling week (The Ministry of Education, 2019a), excluding higher education institutions. Additionally, it can be calculated from an NZ General Social Survey in 2016 that New Zealanders spend on average at least 9 times more hours in classrooms than they do in large halls (Statistics NZ, 2018). This further raises the question of why acoustic solutions for classrooms have been so neglected.

1.1.4 Research Question

With the novel IPRAT, classrooms can finally achieve optimised RT's, for any activity happening in the space. But which exact RT would be considered 'optimised' for each activity? The concept of optimising RT in real-time is new, so there is no current answer to this question, it is not known which RT's would optimise each classroom activity. Thus, a way to calculate these optimised RT values was determined. In any moment, the acoustic comfort in an educational or highly cognitive space can be determined by how clearly the occupants understand speech. The clarity of speech can be quantified as speech Clarity (C50). For this quantity, the higher the value = the higher the clarity = better understanding and cognition = better acoustic comfort. Therefore, whichever RT maximises C50, acoustic comfort is maximised and thus is the optimal RT for that space and activity. The research question for this work follows; *what is the effect of IPRAT on classroom acoustic comfort?* In the same way that we determine optimised RT values, we can quantify the effects of this changing RT on acoustic comfort.

1.1.5 Research Methodology

The methodology for this study will follow a positivism research philosophy. This philosophy is often associated with quantitative research methods and is free from bias due to the beliefs or values of the researcher (Ryan, 2018). Positivism is the most appropriate philosophy for this research as it relies upon proving physical results and facts using tangible measurements. Further, the initial research process will follow a quantitative experimental method for structured and ridged validity (Cypress, 2017). Again, this is appropriate because the nature of the research is based upon modelling and testing a tangible device to measure tangible improvements of appropriate acoustic parameters in NZ classrooms. The theoretical framework for the study follows an experimental and causal design. A mixed field experiment of 'true experiment' and 'one group pre-test post-test' will be used to prove and demonstrate the causal relationship between IPRAT use and acoustic comfort, discovered through RT , C50 and G parameters. This analysis will reveal the effect of IPRAT in NZ classrooms.

The aim of this work is to quantify the effects of IPRAT on classroom acoustic comfort. This aim can be satisfied by comparing the acoustic comfort of a number of classrooms using IPRAT, with the same classrooms not using IPRAT. An efficient and economical way to realize this comparison is to firstly use software to simulate the behaviour and results of 5 classrooms using IPRAT, and secondly, conduct a case study using an IPRAT prototype in a real classroom. The less resource-consuming simulations with a larger sample size will provide large quantities of data, whilst the more resource-consuming case study will provide some realistic data and act to verify the accuracy of the simulation results (Jin, Zhong, Ma, Hashemi, & Ding, 2019). Finally, the two sets of data can be statistically analysed to determine the final effect of IPRAT on classroom acoustic comfort. Additionally, this data can be compared with professional industry standards (for New Zealand namely; AS/NZS Recommended Design Acoustic Standards).

Experimentally, this work will thus compare 6 classrooms (5 virtual classrooms and 1 physical classroom) not using IPRAT (pre-condition) with the same 6 classrooms using IPRAT (post-condition). The simulations will measure RT and C50, while the case study will measure RT. The Null-hypotheses (which the researchers stand to disprove) thereby states that IPRAT has no effect on RT and thus no improvement for acoustic comfort. Figure 1.1 demonstrates the statistical analysis used to prove or disprove the null hypothesis.

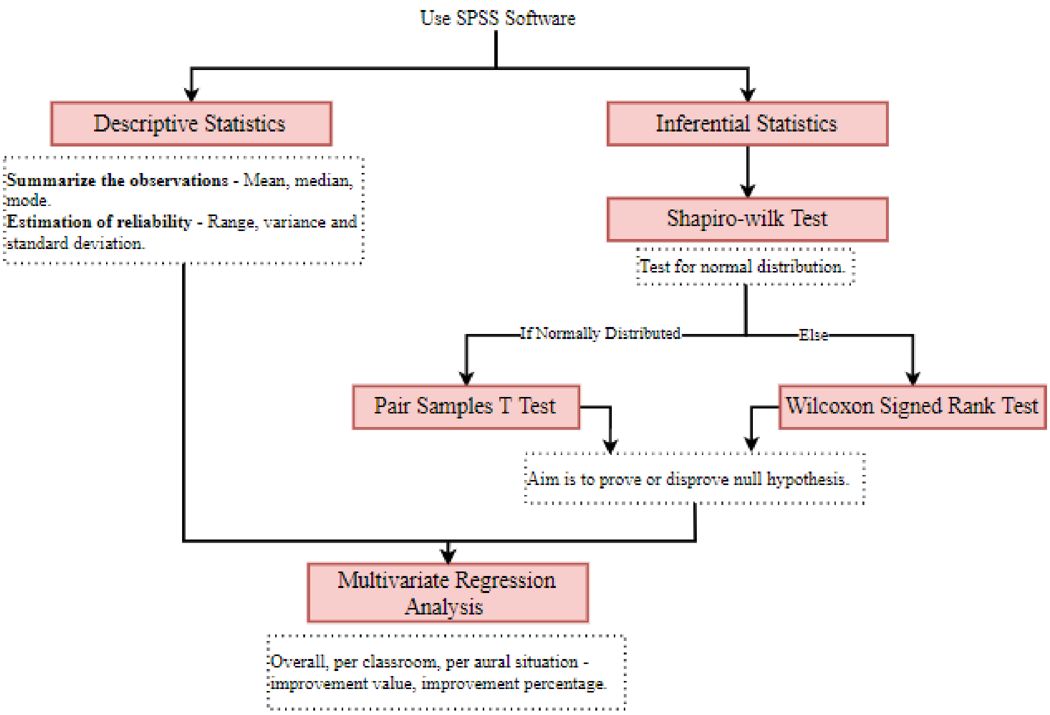


Figure 1.6. Statistical analysis to prove or disprove null-hypothesis

It follows that our independent (manipulated) variable is the absence or use of IPRAT, and our dependant (measured) variables are RT and C50. The absence of IPRAT variable is realized when we take measurements of the classrooms in their current, existing state. The use of IPRAT variable is realized when the RT is optimised in each space for classroom activity, as the behavioural success of the IPRAT depends solely on its' achievement of such optimised RT values. To quantify this success, the classroom activities must thus be defined and controlled. This can be done by categorizing all classroom activities into four distinct 'aural situations.' This finalises the controlled (managed) variables as; classroom number (1-6) and aural situation (1-4). Manuscripts 1 and 2 produce novel contributions through the use of secondary data. Manuscripts 3 and 4, however, generate their own primary data, and statistical analysis of this data is conducted. The null hypothesis is thus disproved using the data from manuscripts 3 and 4. In chapter 6 of this thesis, the data from these 2 manuscripts is compared and analysed against each other, to produce more significant results.

1.2 Aims, objectives and contributions

By challenging acoustic standards and their pitfalls, we can propose that acoustic optimization should account for the current activities in the space to determine the appropriate acoustic condition. This is because dynamic spaces should be designed with varying Reverberation Times. A literature gap exists for intelligently adjusting RT to suit changing space uses. Thus, paper 1 presented the novel IPRAT that solves this advocation for real-time RT optimisation through the integration of PVAT and ASC. Literature on IPRAT was understood by recounting the evolution of PVAT intelligence. Inevitably, this revealed a literature gap related to PVAT automatically and intelligently adapting to changing occupant needs. By synthesizing existing literature on PVAT and ASC, IPRAT was defined, and by evaluating the integration of PVAT and ASC, the design, development and use of state-of-the-art IPRAT was predicted. From these indications, it was inferred that IPRAT is able to increase IEQ in architectural spaces. Finally, challenges and implications of IPRAT were considered, and conclusions about the technology and how it can be used in the built environment were drawn.

There have been 20 virtual New Zealand classroom environments developed (5 classroom types multiplied across 4 aural situations) in paper 2. There are two inputs necessary when simulating acoustics; software and a virtual environment. The virtual environment constitutes a variety of physical and acoustic attributes. The literature on virtual NZ classrooms, including such attributes is, lacking a holistic description. The purpose of this paper was to create virtual classroom environments by collating secondary data from existing studies. Initially, classroom types common to New Zealand were examined and explored. Various types of physical classroom documentation were analyzed to show five typical classroom profiles. Secondly, four typical aural situations encountered in classrooms were defined based on existing research. Interpolation and mode analysis were used on the quantitative physical and aural data which was exposed in these investigations. Through these methods, the characteristics used in the final profiles were derived. The final classroom profiles are demonstrated using I-Simpa, a pre/post-processor for acoustic codes, Autodesk Revit and 3DSMax. Using 3DSMax, you can create and export 3D-scene environments that can be imported into I-Simpa to create 3D aural environments. The profiles are designed for industry professionals and academics requiring 'typical' or 'normal' virtual classroom profiles. The use of these virtual classrooms is imagined to save preparation and simulation time for these professionals.

It is important to continuously analyze and re-define the effect of the built environment on occupant wellbeing, and acoustic quality shouldn't be overlooked. The new technology, IPRAT, has the potential to revolutionize room acoustics. Thus, it is necessary to analyze and quantify its effect. This paper aimed to discover the potential for IPRAT. Paper 3 examined the effect of IPRAT using acoustic simulation, where 20 virtual environments were simulated by combining 5 classrooms with varying characteristics and 4 acoustic scenes. RT, C50, and G were the acoustic parameters considered in this study. These parameters can be used to determine the effects of improved acoustics for both teacher vocal relief and student comprehension. The IPRAT was assumed to vary RT and was represented in the simulation by 6 different absorption coefficient spectrums. The simulation was conducted in I-Simpa and the method for this simulation was detailed to provide a novel research output. In this simulation, sound reflecting louvers were rotated in front of porous sound absorption panels to control RT. Therefore, the 6 absorption coefficients were expressed as louver rotations from 0-100% open. The optimised acoustic parameters were derived from relationships between C50, RT and G. These relationships and optimal RT's contribute a unique database to literature. IPRAT's advantages were discerned – for the first time - from a comparison of "current," "attainable," and "optimized" acoustic parameters. In this way, the effects of IPRAT are quantified, providing a valuable contribution to academia.

In this paper, an existing tertiary classroom at Auckland University of Technology was used to evaluate the acoustic impact of using IPRAT. In this pilot study, IPRAT's benefits were quantified for the first time. If only the PVAT component of IPRAT is installed and manually adjusted rather than using an intelligent system, it is still possible to determine the potential acoustic improvements from IPRAT. Therefore, such a simplified methodology was employed in this case study to understand the potential significance of IPRAT without adopting a time and cost-intensive strategy. For this study, reflective, rotating louvers were overlayed over panels that absorb sound to make up the PVAT. This prototype was built, and RTs were measured according to international standards before and after installing PVAT in the classroom. The results were then analyzed to quantify the potential improvements to classroom acoustic comfort, where IPRAT be used. The manuscript contributes a unique prototyped technology, as well as results of tests conducted in the classroom.

Table 1.2 and figure 8 presents the aims and objectives of each manuscript and the corresponding outputs. The overall aim is to answer the research question: *what is the effect of IPRAT on classroom acoustic comfort?* This is answered through 4 sub-aims and 8 objectives, which compliment one another and answer the research question.

Table 1.2. Manuscript aims and objectives

Manuscript title	Aim	Objective(s)	Output(s) or novel contributions
(Manuscript 1) The Birth of Intelligent Passive Room Acoustic Technology: A Qualitative Review	Determine the rationale for intelligent passive room acoustic technology	Conduct a best-evidence synthesis and prior art search to determine the highest level of intelligence for passive variable acoustic technology	Dynamic spaces should be designed with varying Reverberation Times; however, a literature gap exists for intelligently adjusting RT to suit changing space uses

Published in SASBE		Conceptualise the unique solution: IPRAT, which integrates Passive Variable Acoustic Technology and Acoustic Scene Classification	IPRAT is proclaimed, developed and analysed, and a use case example is provided
(Manuscript 2) Developing virtual classroom environments for intelligent acoustic simulations Published in ASA conference	Establish a simulation method for testing IPRAT	Using secondary data, develop and detail 20 classroom environments ‘typical’ to New Zealand	20 classroom profiles are detailed and demonstrated using I-Simpa, a pre/post-processor for acoustic codes, and Autodesk software
		Establish a software method that can be used to simulate acoustic technology	
(Manuscript 3) The potential for intelligent passive room acoustic technology in classrooms: A BIM-based simulation Published in CONVR conference	Determine the effect of IPRAT on acoustic comfort using simulation	Simulate IPRAT in 20 aural environments, statistically analysing the effect of IPRAT on RT, C50 and G	An acoustic simulation method in I-Simpa software is presented for initial technology validation
			The quantified improvements of IPRAT on acoustic parameters RT, C50 and G is presented
			A database of RTs which improve acoustic quality for 4 aural situations typical to classrooms is provided
(Manuscript 4) Intelligent Passive Room Acoustic Technology in Classrooms: A Pilot Case Study Submitted to SASBE	Determine the effect of IPRAT on acoustic comfort using a case study	Deploy a IPRAT prototype in a tertiary classroom by constructing and testing only the PVAT component	The prototype development is outlined, as well as an acoustic measurement method with uses Android applications
		Use IPRAT in a case study classroom by adjusting the prototypes sound absorption, and quantify the benefits	The key benefits of IPRAT are realized in its ability to vary RT, and are statistically significant. Additionally, benefits are realized in an overall RT reduction.
		Analyse the performance of IPRAT against industry standard guidelines, and optimise the improvements achieved with IPRAT	Design optimisation for using IPRAT in classrooms is provided, and by using IPRAT in a single space, the recommended RTs for two room types outlined in the NZ Acoustic Standards can be satisfied

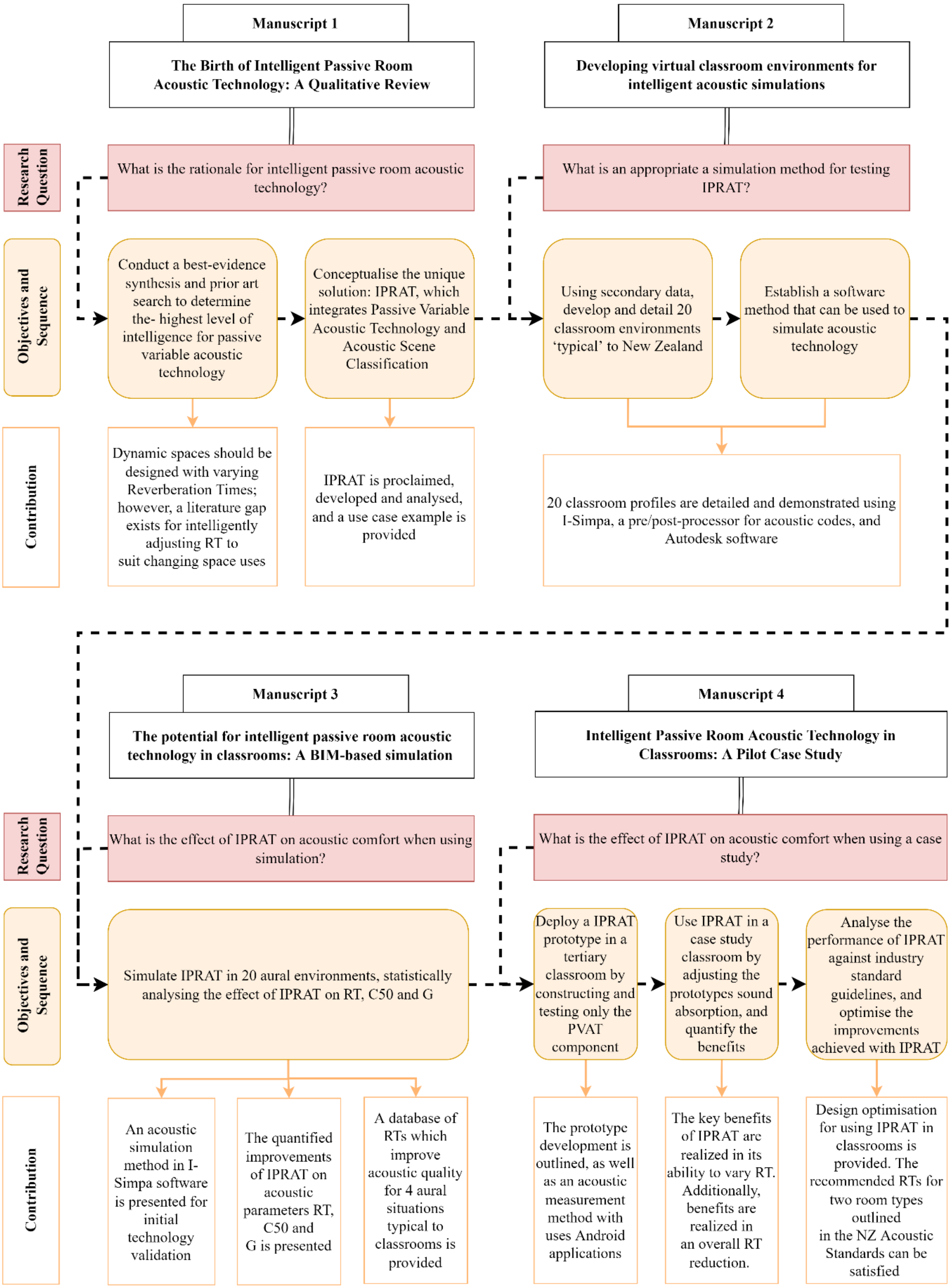


Figure 1.7. Reseach questions, processes and outputs

1.3 Thesis structure

This thesis is submitted as Format 2: Submission by manuscript publication. Chapter one has provided critical information about the research problem, research gap, research significance and research questions. Following, 4 manuscripts comprise chapters 2-5, and are detailed below.

1.3.1 Manuscript 1 'The Birth of Intelligent Passive Room Acoustic Technology: A Qualitative Review'

The first manuscript, 'The Birth of Intelligent Passive Room Acoustic Technology: A Qualitative Review' aimed to determine the rationale for IPRAT. A best-evidence synthesis and prior art search were conducted to determine the highest level of intelligence for passive variable acoustic technology. It was discovered that dynamic spaces should be designed with varying RT's however, a literature gap exists for intelligently adjusting RT to suit changing space uses. The unique IPRAT solution was conceptualised, which integrates PVAT and Acoustic Scene Classification. Thus, IPRAT was proclaimed, developed, and analysed, and a use case example for IPRAT was provided. The findings from manuscript 1 strongly suggested the need to test or prototype IPRAT.

1.3.2 Manuscript 2 'Developing virtual classroom environments for intelligent acoustic simulations'

The second manuscript, 'Developing virtual classroom environments for intelligent acoustic simulations' aimed to establish a simulation method for testing IPRAT. Using secondary data, 20 classroom environments 'typical' to New Zealand were detailed and developed. Additionally, a software method was established which could be used to simulate acoustic technology. The 20 classroom profiles were detailed and demonstrated using I-Simpa, a pre/post-processor for acoustic codes, and Autodesk software. With these virtual environments, it was suggested that IPRAT should now be simulated, to demonstrate its potential to improve acoustic comfort.

1.3.3 Manuscript 3 'The potential for intelligent passive room acoustic technology in classrooms: A BIM-based simulation'

The third manuscript, 'The potential for intelligent passive room acoustic technology in classrooms: A BIM-based simulation' aimed to determine the effect of IPRAT on acoustic comfort using simulation. IPRAT was thus simulated in the 20 environments established in manuscript 2, statistically analysing the effect of IPRAT on RT, C50 and G. The output of this manuscript firstly included an acoustic simulation method in I-Simpa software presented for initial technology validation. Secondly, the quantified improvements of IPRAT on acoustic parameters RT, C50 and G were determined. Last, a database of RTs which improve acoustic quality for four aural situations typical to classrooms was derived. In this simulation, the benefits of IPRAT were found to be statistically significant, and it was recommended that future research physically prototype the technology. As the first original research attempting to quantify the effect of IPRAT, this paper makes significant contributions to acoustic technology advancement, acoustic quality improvement, and smart acoustic control in buildings

1.3.4 Manuscript 4 'Intelligent Passive Room Acoustic Technology in Classrooms: A Pilot Case Study'

The fourth and final manuscript, 'Intelligent Passive Room Acoustic Technology in Classrooms: A Pilot Case Study' aimed to determine the effect of IPRAT on acoustic comfort using a case study. An IPRAT prototype was deployed in a tertiary classroom by constructing and testing only the PVAT component. The IPRAT was tested by adjusting the prototype's sound absorption. The benefits to acoustic comfort were quantified, and the performance of IPRAT was analysed against industry standard guidelines. The PVAT is prototyped, and the RTs are measured according to international standards before and after classroom installation. The prototype development was outlined, as well as an acoustic measurement method that uses Android applications. The key benefits of IPRAT were realized in its ability to vary RT, and were statistically significant. Additional benefits were realized in an overall RT reduction. Lastly, design optimisation for using IPRAT in classrooms was provided. Using IPRAT in a single space, the recommended RTs for two room types outlined in the NZ Acoustic Standards were satisfied.

The collation of these four manuscripts sufficiently answers the research question *what is the effect of IPRAT on classroom acoustic comfort?* In chapter 6, the statistical outputs from the manuscripts are summarised and compared against each other, to further strengthen the thesis and explain the benefits of IPRAT. Figure 9 illustrates the thesis structure.

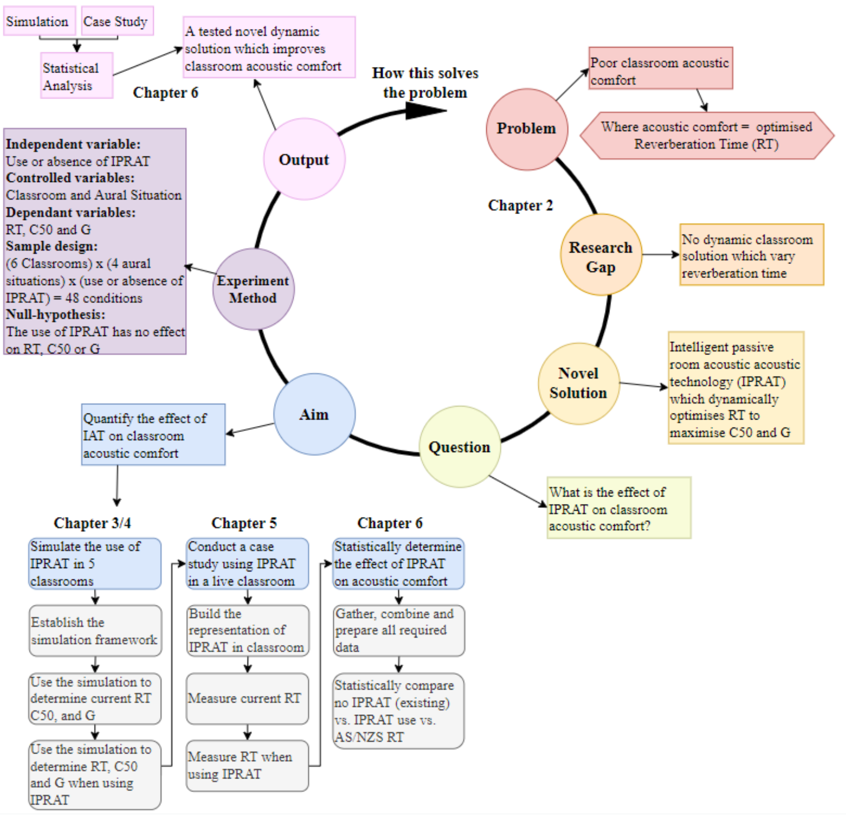


Figure 1.8. The thesis structure

1.4 Classroom acoustic comfort concerns, limitations and future research directions

In the field of architectural acoustics, it has been widely recognised that classrooms are a space requiring highly considered acoustic conditions. It has even been suggested that careful acoustic design of learning environments can help to satisfy sustainable development goals (SDG), especially goal 3 (health and wellbeing), goal 4 (quality education) and goal 9 (sustainable infrastructures) (Montiel, Mayoral, Navarro Pedreño, & Maiques, 2019). Additionally, ISO 28,802 guidelines recommend the consideration of both material and subjective acoustic measurements to improve acoustic comfort (ISO, 2012). Therefore, acoustic consideration is always required, especially to positively influence student attention (Aliabadi, Mahdavi, Farhadian, & Shafie Motlagh, 2013). There have also been strong connections found between health symptoms and noise pollutions, suggesting that continuous real-time monitoring of acoustic comfort measures is beneficial (Marques & Pitarma, 2020). For example, both students and teachers find the greatest source of annoyance inside the classroom is the noise generated by neighboring classrooms and the neighboring teacher's voice (Zannin & Marcon, 2007). In this case, it was recommended in simulations to reduce the RT. The approach to reducing RT is beneficial, as a strong correlation has been found between RT and background noise level (Puglisi et al., 2015). Another study found that teachers' working conditions were unsatisfactory for ensuring their health during workdays (Levandoski & Zannin, 2020). The main cause of these discomforts arises inside classrooms, with teachers constantly exceeding vocal intensity tolerable limits, even in ‘acoustically comfortable’ classrooms. Concerningly, a recent study confirmed that the quality of acoustically-designed vernacular architectural buildings still requires improvements to their acoustics, and modern classrooms are preferred (John, Thampuran, & Premlet, 2016).

Very recent literature (2022) still also reveals the existence of poor acoustic conditions in our built environment. For example, one study found background noise levels exceeding 50dB, thus, in need of acoustic improvement (Al-Isawi, Idan, & Hassan, 2022). It has been found that when noise levels are higher than 65dB, the stress response in humans is likely triggered, and above 55dB, cognitive performance is disrupted (Golmohammadi et al., 2022). Furthermore, one study exposes that a university building from 1950 in Mexico did not have to consider its acoustic comfort because it was located in a rural area (Kuri, 2022). Nevertheless, much effort has been made to improve the acoustic customization of a space in the past years (Segura Alcaraz, Bonet-Aracil, Julia Sanchis, Segura Alcaraz, & Seguí, 2022).

To design an acoustically comfortable building, two tasks must be considered (Medved, 2022). First, room acoustic design which considers sound in a space and the quality of sound perceived by the listeners. This can be improved by adequately designing the architectural forms of the spaces, and the sound-absorption of room surfaces to control RT. Second, building acoustics considers minimising the transmission of noise from the surroundings and neighbouring rooms. This must consider sound insulation for impact and airbourne sound. A solution has been presented which improves the room acoustic conditions of a space, and the building acoustics simultaneously (Rodríguez, Alba, & del Rey, 2022). As a more innovative approach, living walls have been considered for their acoustic treatment of spaces, and to reduce RT by increasing sound absorption area (Scamoni, Scrosati, Depalma, & Barozzi, 2022). The walls also increased sound insulation, improving the acoustics in both ways recommended by Medved (2022).

Another innovative acoustic approach is to embed solar energy technology in noise barriers (Hasmaden, Zorer Gedik, & Yüğrük Akdağ, 2022). There has been a surge of awareness around the effect of our built environment on our health and quality of life, which is promising (Amatkasmin, Berawi, & Sari, 2022). Lou and Ou (2019) discovered that occupants in spaces who required high concentration levels due to their complex mental work are more sensitive to noise. Classrooms require much higher concentration levels, as significantly more complex mental work is performed in these spaces than others (Kool & Botvinick, 2018). For example, occupants with autism spectrum disorder are particularly sensitive to their external environments, and of the four IEQ's they place the most significant consideration to acoustic comfort (Caniato, Zaniboni, Marzi, & Gasparella, 2022). Consequently, they require a better acoustic environment and a reduction of distractions, achieved by ensuring an appropriately varied RT for each classroom activity or learning technique executed in a classroom. These advances in acoustic comfort litertature are a promising sign of the research trends and breakthroughs that we could see in coming years.

1.4.1 Research limitations and future directions

There are a few limitations present in this research. Firstly, Manuscript 1 which acted as the literature review for the thesis had limitations when researching past literature. An 'English language' delimiter was used in conjunction with 'publication type' delimiters, limiting the search to peer-reviewed journals and conference articles except for sources relating to the PVAT's, as patents and prior art searches were required. A future study could explore prior art and recent literature in different languages. In the second Manuscript, classroom types common to NZ were investigated and explored, to set up for the simulation study. Documentation exposing the physicality of various classroom types were collated to detail 5 typical classroom profiles and 4 typical aural situations, based on existing studies. Limiting the sample size to 20 possible combinations was necessary as there was not an extensive range of past literature to base these profiles on. Thus, for the simulation study, the results are limited to primary schools in NZ, and aural situations that occur in typical primary schools. Specifically, older classrooms either permanent or relocatable were analysed. The physics of acoustic manipulation is not largely affected by the demographic of building occupants however, so this data could be transferred to other classroom types and countries if similar building materials are used. Also, even if different building materials are used, that fact that IPRAT provides varying absorption coefficients, the RT is the space will be altered regardless of other factor. Other acoustic factors such as clarity and strength may be altered in different ratios though. Additionally, although the study considers classroom environments typical to New Zealand, the contributions can be helpful for professionals in other parts of the world, also looking to improve classroom acoustics using smart technology. The BIM method explained in Manuscript 2 can also be followed regardless of geographical considerations. This stands true as long as the appropriate alterations have been made to the classroom characteristics and aural situations, as the effect of IPRAT is unique for each classroom geometry and aural situation.

When selecting PVAT to review, strict eligibility criteria was adopted. All Variable Acoustic Technologies (VAT's) were reviewed, not exclusive to passive technology. Alternative acoustic technologies can be variable by nature due to their noise control objectives including; metamaterials (Kadic, Milton, van Hecke, & Wegener, 2019), active acoustics (Lam, Elliott, Cheer, & Gan, 2018) silencers (Moradpour, Farhadi, Mohsenabadi, Jalali, & Hesam, 2018) and mufflers. However, they do not primarily vary the RT of a space (K. Yu, Fang, Huang, & Wang, 2018), so were excluded from the review. Acoustic Enhancement Systems (AES) use electronics to repeat sounds from other speakers, thereby artificially extending RT (Schmidt et al., 2018). Unfortunately, like active acoustics these systems produce unnatural impressions, causing an artificial sound experience. Their abilities are limited as they can add energy (adding SPL and RT), but they cannot remove energy. In this sense, it could be argued that acoustics are not optimised when using artificial or electronic solutions, so AES's are also excluded from the review. Likewise, voice amplification systems fall outside of the scope of this study, as they are also not a passive system. Many modern learning environments are designed in a way which rely heavily on voice enhancement systems, so these would not be the opportune spaces to deploy IPRAT.

Another limitation to the study for both the simulation and case study is that the technology is tested in classrooms. Research for this novel technology should not be limited to classroom spaces. Benefits will be realised in any flexible, dynamic or multi-use architectural space in the built environment, especially in smart environments where human comfort is prioritized (Amirhosein Ghaffarianhoseini et al., 2017). Thus, other room types such as meeting rooms and function spaces could largely benefit from the technology. However, these spaces present slightly different physical characteristics and functions so could not be directly transferable. Nevertheless, the classroom data could be used to propose how the technology would perform in other building spaces, as an initial hypothesis before new studies test these spaces. Another space worth mentioning are architectural design studios. These spaces are used in increasingly flexible ways, and present the perfect variation of acoustic needs for this technology to be useful in.

In the fourth Manuscript, the data gathered is limited by the percentage of classroom surface area covered by PVAT, based on resources and installation access. For the study, 7x panels were constructed measuring 2.88m2 each, covering 20.16m2 of (approximately) 120m2 wall, floor and ceiling surface area. This covered 16.8% of the total surface area in the space, and since the achievable

RT alteration depends upon the surface area covered by the panels, this created strict boundaries for the possible results. Nevertheless, the data was extrapolated to explore various other surface area cover percentages to hypothesis different results. Future studies should quantify the effect of different surface area coverages of the technology. Further limitations exist in the room conditions where the case study took place, namely, by the absence of furniture and people. Both furniture and people act to absorb sound in a space, thereby reducing the RT. Without people and furniture, the RT will measure longer than it would in a typical classroom setting. Fortunately, the nature of the simulation programming allowed the presence of people and furniture to be factored into the acoustic measurements. This was not achievable with the case study, so the results show relatively high RTs. Nevertheless, this knowledge is in fact favourable, as in reality we would be able to achieve desired RTs in the classroom with much less IPRAT coverage, as shown in section 5.4.3.

Chapter 2. The Birth of Intelligent Passive Room Acoustic Technology: A Qualitative Review

2.1 Prelude to Manuscript 1

Informed by acoustic design standards, our built environments are designed with single Reverberation Times (RT's), a trade-off between long and short RT's needed for different space functions. A range of RT's should be achievable in spaces, to optimise the acoustic comfort in different situations. The following manuscript proclaims a novel concept: Intelligent Passive Room Acoustic Technology (IPRAT), which achieves real-time room acoustic optimisation through the integration of Passive Variable Acoustic Technology (PVAT) and Acoustic Scene Classification (ASC). ASC can intelligently identify changing aural situations, and the PVAT can physically vary the RT. This manuscript acts as the literature review for the Ph.D. within the thesis. A best-evidence synthesis method is used to review the available literature on PVAT and ASC. The review exposes a gap of integrating PVAT and ASC, thus IPRAT is considered a novel and appropriate continuation of the literature. The development, functionality, benefits, and challenges of IPRAT offer a holistic understanding of the state-of-the-art IPRAT, significantly contributing to the research aim. This paper also provides a theoretical case study example. Going forward, it is concluded that IPRAT should be prototyped and its impact on acoustic comfort quantified.

2.2 Introduction

Sensory discomfort in our built environment is persisting relentlessly. People are spending more time indoors, in over-crowded spaces, abundant with distractions. Exposure to indoor stimuli is increasing, leading to higher stress levels, cognitive inefficiencies, and mental ill-health. We attempt to measure the effects of stimuli in a space by using the Indoor Environmental Quality (IEQ). This accounts for the overall comfort level building occupants experience; thermal comfort, air quality, light comfort and acoustic comfort. The art of *thermal, air quality* and *light control* have been mastered by the architectural engineering industry. The technological advancements seen in the past decade, combined with a highly valued and progressive architectural industry, mean our buildings today are a marvel. But where does this leave *acoustic comfort*? Unfortunately, acoustic comfort has been left behind, deemed less important than its competing qualities (Vardaxis et al., 2018). This neglect is causing unwarranted complications to building occupants across the globe.

Firstly, complexities within the subject area make acoustic excellence difficult to measure and obtain (Taghipour, Sievers & Eggenschwiler, 2019) (Yang, Moon & Kim, 2018) (Bluyssen et al., 2019). And secondly, acoustic quality in the residential sector is considered to be a low priority factor for determining IEQ (E. Lee, 2019). Building users, however, experience first-hand the effects of these spaces and thus prioritise acoustic comfort for IEQ (Huang, Zhu, Ouyang, & Cao, 2012) (J. Chen & Ma, 2019) (Sezer & Erbil, 2015). A study by D. Yang and Mak (2020) revealed the acoustic environment as the second most essential factor affecting university classroom students, after thermal quality. Furthermore, acoustic comfort levels play a crucial role in reducing the symptoms of Sick Building Syndrome (SBS) (Ghaffarianhoseini, AlWaer, Omrany, et al., 2018). In addition to academic review, worldwide Google search trends dating back to 2004 confirm this topic area neglect (Figure 2.1). Google search engine was prescribed as it encompasses both academic and industry search focus. The 4 key IEQ's are plotted relative to each other, authentically revealing a favoured search focus of indoor air quality, light and thermal comfort over acoustic comfort.

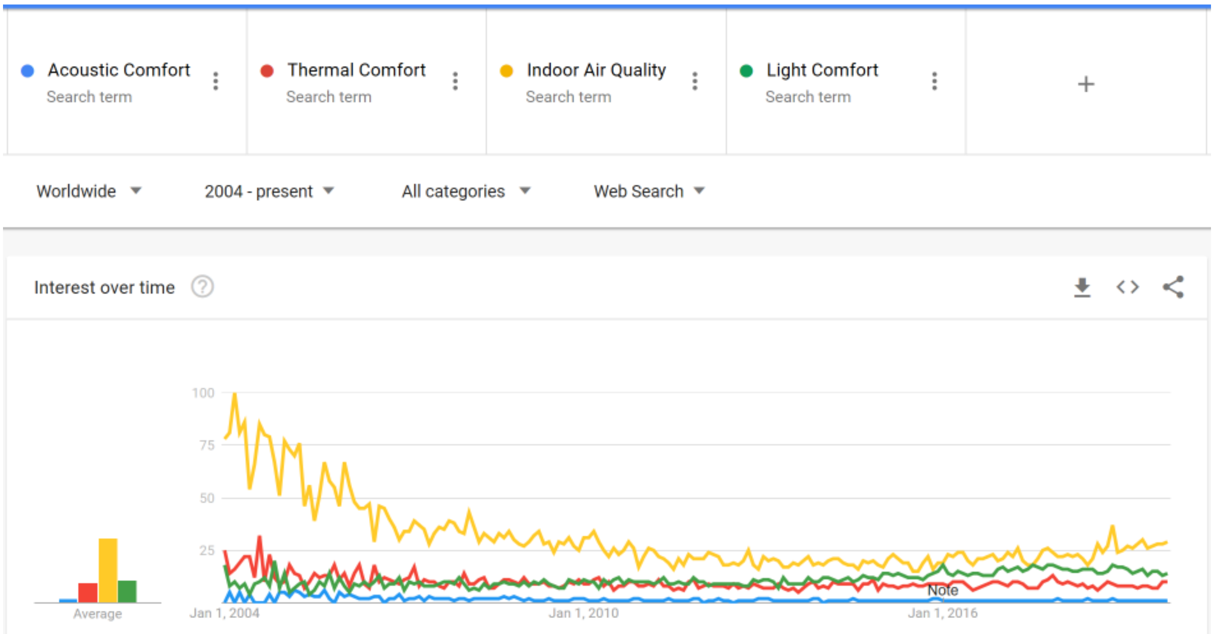


Figure 2.1. Trend of Google searches for IEQ's

Alongside this acoustic neglect, we have abundant discomfort due to misinformed acoustic parameter specification. Internationally recognised acoustic standards provide values which would provide a comfortable aural environment, for Sound Pressure Level (SPL) and Reverberation Time (RT). SPL describes the sound energy (or loudness) in a room, in decibels [dB]. RT describes the time taken for sound in a room to dissipate, (the amount of *echo* or *sound absorption)* in seconds. As a designer, it is difficult to manipulate the SPL in a space, as this depends largely on the sound sources (e.g. human voices). Similarly, Signal-to-Noise Ratio (SNR) and is hard to alter with room design, as it depends on the ratio between sound source level and ambient noise in a space. RT, however, can easily be altered through the design of the room, and is often used to inform the overall 'acoustic condition' of a space.

Changing the RT will affect many other acoustic parameters such as Clarity, Strength, Speech Transmission Index (STI) and Speech Intelligibility (SI) (Figure 2.2). In combination, these parameters can describe the acoustic condition of a room, and if RT principally informs the value of these parameters, it is appropriate to use RT to measure acoustic comfort.

A long RT will increase the echo and reverberation in a space, increasing Strength, causing sound to stay longer in a space, decreasing Clarity. Long RT's can be useful for aural situations with lecture or presentation.

A short RT will cause sound to dissipate quickly, increasing Clarity but decreasing Strength and making it hard for voices to carry in a space. Short RT's can be useful for aural situations with silent work, high concentration levels or in spaces with multiple people speaking.

STI is used to quantify the objective intelligibility of a room; how well a listener can understand a speaker. The subjective measure of STI is Speech Intelligibility (SI). RT has a significant effect on STI (as does SPL), enough that STI can be estimated by using RT (Nowoświat & Olechowska, 2016).

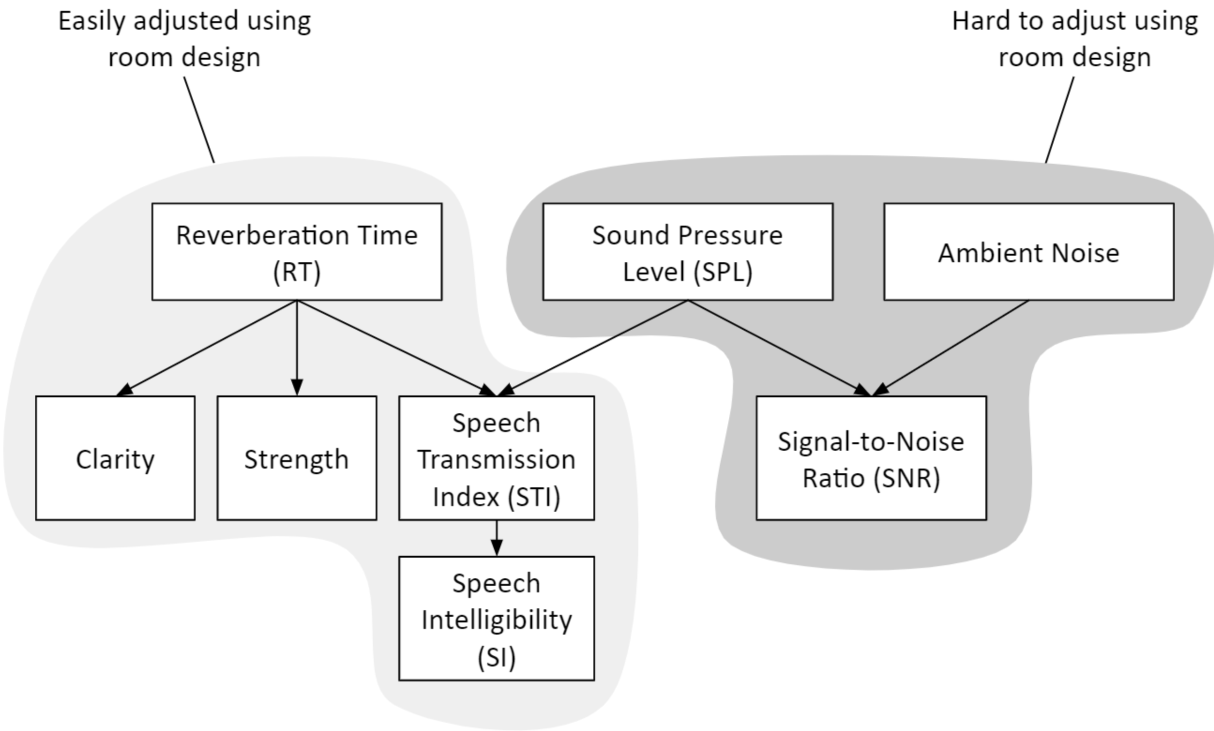


Figure 2.2. The interaction between room acoustic parameters from a room design perspective (illustration by the authors)

The concept underlying international design standards is that spaces should be designed with one static acoustic state. This recommendation enforces a trade-off between long and short RT's required in different aural situations. This 'compromise' has normalised RT's that are either too long or too short, causing harmful acoustic discomforts in our built environment. Fundamentally, these standards fail to recognise buildings as flexible, multi-use spaces. It is disappointing that thermal, air quality and lighting professionals have managed to identify these flexible building needs, but acoustics have largely been left behind. Building occupants are using spaces in increasingly dynamic ways (Søiland & Hansen, 2019), and without reflecting this trend into our design thinking, this dynamic use will become ever more detrimental to acoustic comfort.

Consequently, an alternative theory for acoustic design thinking is required: designing for varying RT. If a space were given a range of RT's to achieve, acoustic conditions could be adapted to the changing functions and needs of a space, consistent with the aural situation. This RT consistency would improve the acoustic condition and thus comfort of a space, by providing suitable Clarity, Strength and STI values for differing space uses. For example, it is detrimental to apply single RT's to classrooms, as activities executed in a typical learning environment are dynamic and varied in nature. The aural situation, based on sound level and number of people speaking, should determine which RT is optimal for a space (Francis F Li, 2010). This acoustic flexibility should reduce the occupant discomfort originating from compromised specifications of RT.

2.2.1 Background

RT can be altered by adjusting the physical variables of a space; volume, geometry, diffusion coefficient, or sound absorption coefficient (McAsule, Amah, Ahemen, & Gesa, 2018). Technology which has this capability is called Passive Variable Acoustic Technology (PVAT). PVAT manipulates sound propagation by changing the acoustic treatment of a space (Esmebasi, Tanyer, & Çaliskan, 2017), using passive means to change the sound absorption coefficient. Here, passive simply means without the use of electronics or artificial sound, discussed further in Section 2.1. PVAT is primarily used to improve acoustic comfort by achieving a desired RT for changing aural situations (Schira, 2016). Consistency can be created between RT and a spaces' unique aural situation, and room acoustics can be adjusted and optimised (Scannell et al., 2016).

So, if the optimal RT changes as a function of the space use, and PVAT can achieve changing RT's, intelligent advancements can be made to PVAT to optimise RT automatically. The integrated intelligent system must be able to identify the aural situation in a space and calculate an optimised RT based on pre-programmed instructions. Acoustic Scene Classification (ASC), a Machine Learning (ML) method, does just that. Microphones detect the sound in a space and the ASC interprets and 'classifies' the aural environment into specified categories (Phan et al., 2019). Artificial intelligence (AI) used in flexible spaces can significantly enhance all areas of IEQ (Panchalingam & Chan, 2019). In this case, ASC is integrated with PVAT to achieve the novel Intelligent Passive Room Acoustic Technology (IPRAT). IPRAT achieves room acoustic comfort by intelligently classifying the aural situation using ASC, and varying the RT accordingly using PVAT (Figure 2.3).

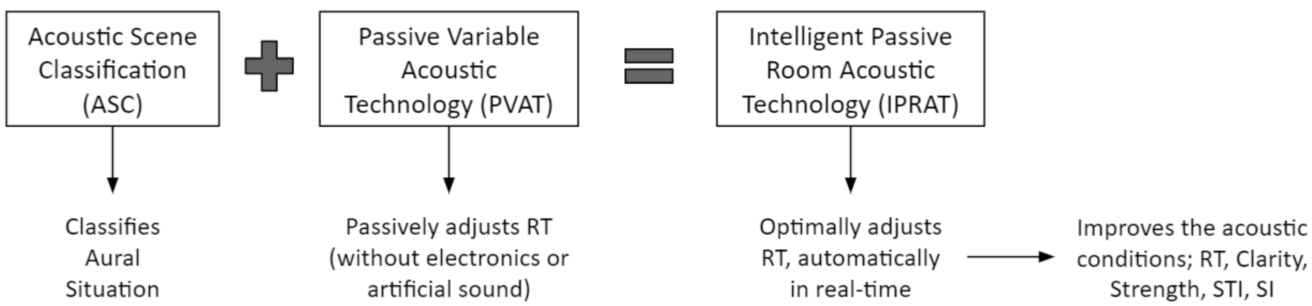


Figure 2.3. The function of ASC and PVAT for IPRAT, and the affected acoustic parameters (illustration by the authors)

2.2.2 Objective

By questioning acoustic standards and the adversities they cause, we can advocate that for acoustic optimization, the present-time activity in the space should determine the required acoustic condition. Through the integration of PVAT and ASC, IPRAT satisfies this advocation for real-time RT optimisation. The novel IPRAT is proclaimed in this paper with a narrative review. The literature progression toward IPRAT is demonstrated by firstly recounting the advancing levels of intelligence of PVAT. Inevitably, this exposes a literature gap of *PVAT intelligently adjusting RT according to changing occupant needs*. To fill this gap, the available literature on PVAT and ASC is synthesised and IPRAT is denoted. By evaluating the integration of ASC and PVAT, the design, development and use of state-of-the-art IPRAT is theorized. From this indication, it is derived how IPRAT would improve the IEQ of architectural spaces. Finally, challenges and implications of IPRAT are discussed, and conclusions are drawn about the technology and its future residence in the built environment.

2.3 Methods

A best-evidence synthesis method was used to achieve the paper objectives, executing a comprehensive narrative review of previously published information. This method combines the systematic literature search methods of meta-analysis with the traditional detailed analysis of key studies (Slavin, 1995). Each research subfield PVAT, ASC and IPRAT exhibited varying quantities of associated prior studies, thus personalized inclusion criteria were required. Best-evidence synthesis appropriately facilitated the assessment of past literature, thoroughly synthesizing the subfield research in a useful and unbiased way. The specific criteria outlined below was derived from a preliminary search of the literature.

Firstly, a preliminary literature search was conducted to refine the objective of the narrative review and determine the inclusion criteria for each subfield. The search exposed a clear research gap: zero papers mentioned IPRAT or suggested the integration of AI and PVAT thus establishing the need for this paper. Secondly, a comprehensive search was performed to identify specific technological advancements within PVAT and ASC. The Auckland University of Technology (AUT) Library search function was used, which incorporates 200+ databases including IEE Explore, ScienceDirect, Web of Science, Google Scholar and Scopus. Figure 2.4 outlines the methodological approach used for the synthesis, and sections 2.1-2.2 provide additional detail on eligibility criteria, search strings and inclusion/exclusion criteria for each search.

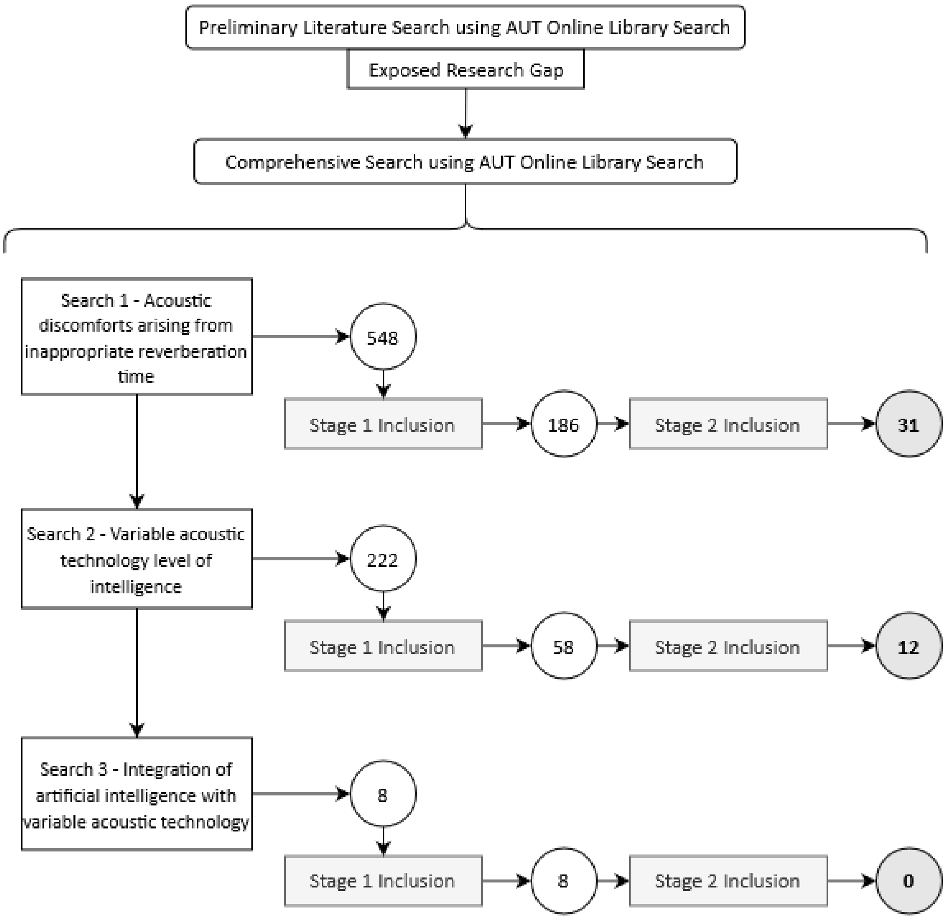


Figure 2.4. Methodological approach used for the synthesis (illustration by the authors)

2.3.1 Eligibility Criteria

Best-evidence synthesis requires reviewers to apply consistent, well justified, and clearly stated inclusion criteria (Slavin, 1995). Firstly, PVAT fundamentally works by changing the RT of a space, therefore it was necessary to review discomforts that arise from inappropriate RT. RT has been identified as a key parameter in the determination of room acoustic comfort, due to its' integration with other room acoustic parameters (Figure 2.2). When the RT is not optimised, other room acoustic parameters function inappropriately, and acoustic discomfort is realized. Fortunately, RT is also a variable we can easily change in a space, making it an opportune focus for this review to reduce acoustic discomfort.

When selecting PVAT to review, strict eligibility criteria was adopted. All Variable Acoustic Technologies (VAT's) were reviewed, not exclusive to passive technology. Alternative acoustic technologies can be variable by nature due to their noise control objectives including; metamaterials (Kadic et al., 2019), active acoustics (Lam et al., 2018) silencers (Moradpour et al., 2018) and mufflers. However, they do not primarily vary the RT of a space (K. Yu et al., 2018), so were excluded from the review. Acoustic Enhancement Systems (AES) use electronics to repeat sounds from other speakers, thereby artificially extending RT (Schmidt et al., 2018). Unfortunately, like active acoustics these systems produce unnatural impressions, causing an artificial sound experience.

Their abilities are limited as they can add energy (adding SPL and RT), but they cannot remove energy. In this sense, It could be argued that acoustics are not optimised when using artificial or electronic solutions, so AES's are also excluded from the review. Lastly, voice amplification systems fall outside of the scope of this study, as there are also not a passive system.

'Any time' and 'English language' delimiters were used in conjunction with 'publication type' delimiters, limiting the search to peer-reviewed journals and conference articles except for sources relating to the PVAT's, as patents and prior art searches were required. Based on the required inclusion and exclusion criteria (further elaborated below), search strings were designed for the review (Table 2.1) to be uniquely combined together for different searches.

Table 2.1. Purpose of search strings to encompass a specific scope

Purpose	String
To encompass acoustics as a whole	('acoustic comfort' OR 'acoustic discomfort' OR 'architectural acoustics' OR 'room acoustics')
To encompass any form of variable acoustic technology	('variable acoustic*' OR 'adjust* acoustic*' OR 'adapt* acoustic*' OR 'intelligent* acoustic*')
To encompass AI within acoustic applications	('artificial intelligence' OR 'machine learning' OR 'acoustic scene classification')
To narrow search for focus on RT parameter	('reverberation')
To narrow search to architectural spaces	(architect* OR building)

2.3.2 Paper Search

The study explored literature using the strings denoted above, to identify relevant studies within searches 1, 2 and 3 (Table 2.2).

Table 2.2. Development of search strings and results

Search No.	Search String Combinations Used	AUT Library
Search 1 - Acoustic discomforts arising from inappropriate reverberation time	('acoustic comfort' OR 'acoustic discomfort') AND ('reverberation') AND (architect* OR building) AND ('acoustic solution*')	548
186 papers selected and further reduced to 31		31
Search 2 – Variable acoustic technology level of intelligence	('variable acoustic*' OR 'adjust* acoustic*' OR 'adapt* acoustic*' OR 'intelligent* acoustic*') AND (architect* OR building) AND 'reverberation'	222
58 papers selected (including a prior-art search) and further reduced to 12		12
Search 3 – Integration of artificial intelligence with variable acoustic technology	('acoustic comfort' OR 'acoustic discomfort' OR 'architectural acoustics' OR 'room acoustics') AND ('artificial intelligence' OR 'machine learning' OR 'acoustic scene classification') AND 'reverberation' AND ('variable acoustic*' OR 'adjust* acoustic*' OR 'adapt* acoustic*' OR 'intelligent* acoustic*')	8
8 papers reduced to 0		0

Search 1 was conducted to gain a broad understanding of acoustic discomforts arising from inappropriate RT. Secondly, search 2 was conducted to establish the current forms of PVAT. It was necessary here to expose the highest level of intelligence that state-of-the-art PVAT has reached. The exclusion criteria defined in Section 2.1 was used to identify which technologies were using passive means to vary RT. Within this search, AI technology with the capacity to integrate with PVAT, namely ASC, was also reviewed. Lastly, search 3 was conducted to reveal literature addressing AI PVAT, and the concept of IPRAT for RT manipulation. Titles and abstracts were screened, and duplicates removed. Studies were then independently assessed, and full-text articles were categorized and further assessed in 2 stages against the inclusion criteria in Figure 2.5.

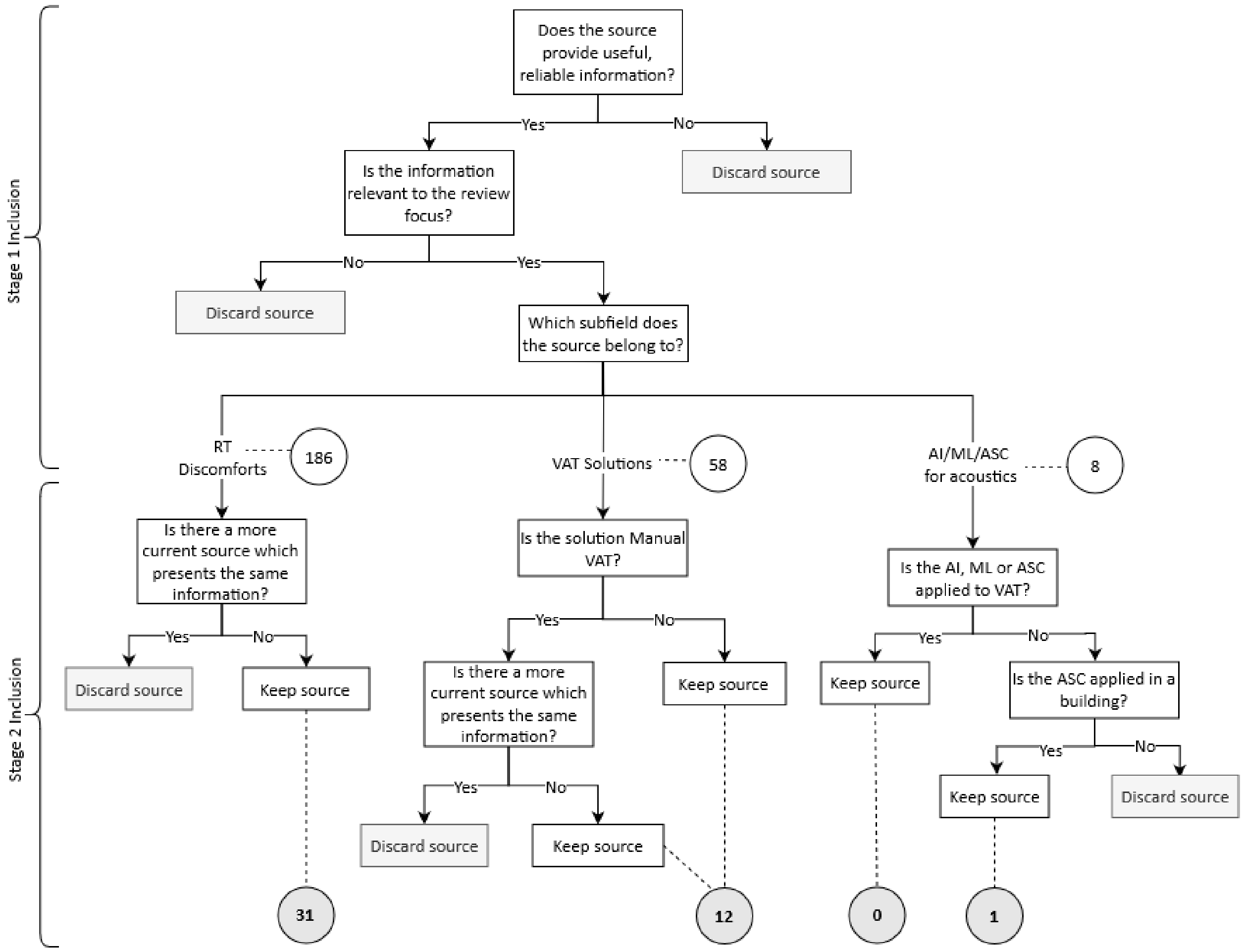


Figure 2.5. Paper search inclusion criteria (illustration by the authors)

2.4 Literature Synthesis

This section synthesizes information retrieved from the literature searches into the following discussion fields: passive variable acoustic technology, intelligent passive room acoustic technology, and intelligent passive room acoustic technology for indoor environmental quality.

2.4.1 Passive Variable Acoustic Technology

After many successful advancements in industry and academia, programmable automated systems achieve the highest level of intelligence for PVAT. A range of PVAT's exist which manually vary RT, including; shortening RT by adding a reverberation absorption chamber, lowering a ceiling to decrease volume, increasing absorption with rotating acoustic panels, rolling curtains, or hinged flaps (Kozlowski (2018) (Hough, 2016). As an advancement to manual solutions, automation has been integrated with PVAT to dramatically improve acoustic comfort, providing more adaptability and efficiency in varying acoustics. Although excluded from the review (see Section 2.1), it should be mentioned out of interest that an intelligent AES has been proposed in 2010 where RT measurements are estimated in-situ, and the discrepancy between measured and desired RT is added using the AES (F. F. Li, 2010). Again, AES's provide inferior room acoustic quality and thus do not meet the criteria to be considered as RT optimising technology. For the study, the historical development of intelligent PVAT systems has been ordered and illustrated by the authors in Figure 2.6.

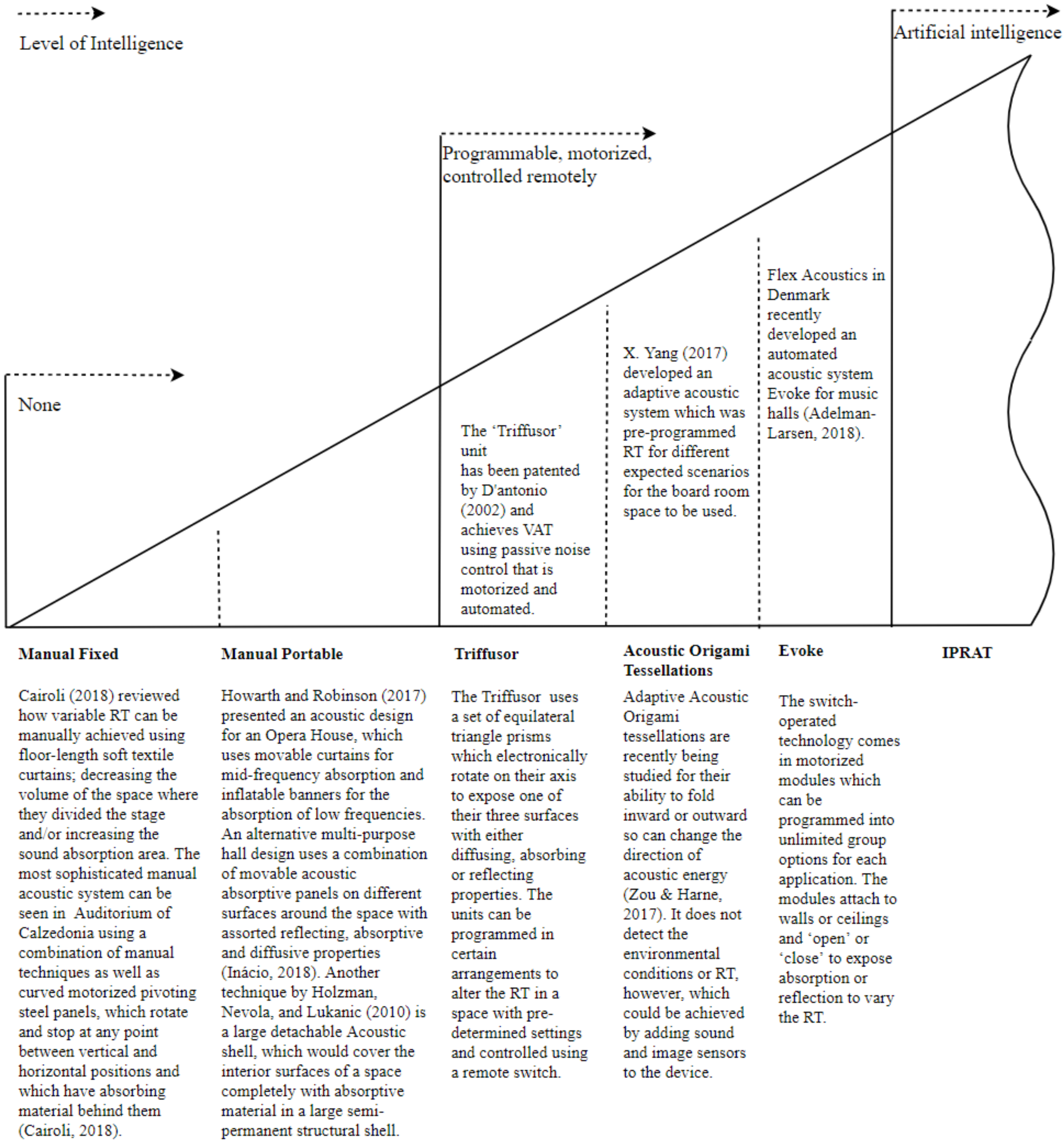


Figure 2.6. Development of PVAT level of intelligence (illustration by the authors)

By demonstrating the highest level of intelligence that PVAT has reached, we can understand the development toward IPRAT in academia and industry. It is worth noting that professional acoustic works could not have been published yet for confidentiality reasons. Nevertheless, it can be confidently stated that to the best of our knowledge, motorized automation is the height of intelligent passive room acoustic development.

2.4.2 State-of-the-art - Intelligent Passive Room Acoustic Technology

Intelligent Passive Room Acoustic Technology (IPRAT) achieves real-time RT optimisation by integrating PVAT and ASC. Intelligent systems characteristically contain unique embedded algorithms, which inform commands based on environmental inputs they receive (Russell & Norvig, 2016). AI can be used to help PVAT determine a desired RT, by classifying the acoustic event in the space. ASC is examined in this review for its suitability as a ML process, which recognizes aural situations by detecting and analysing audio signals (Phan et al., 2019). Various other components and embedded software are also required to develop state-of-the-art IPRAT, discussed in Section 4.1. This section will firstly outline existing work relating ASC, and subsequently, compare the behaviour of IPRAT against other PVAT.

2.4.2.1 Acoustic Scene Classification

ASC is a ML process where a machine attempts to recognize an event or environment by detecting and analysing audio signals from that scene (Phan et al., 2019). This is a widespread single-label ML classifier, which assign inputs into singular class labels (Stowell, Giannoulis, Benetos, Lagrange, & Plumbley, 2015). The emergence of ASC has explicitly seen improvements for a variety of systems, due to its intelligent audio classification capabilities (Phan et al., 2019). Moreover, it has been gaining attention in recent years due to its vast variety of applications and gradual improvements of performance (Lagrange et al., 2015). ASC models extract various features from audio signal data sets, and train a classifier to be able to successfully categorize a new piece of audio data into a specific class (Xie & Zhu, 2019). The extracted features will determine the accuracy of the classifier and can be made up of audio, visual, or a combination of both (Xie & Zhu, 2019). To help determine the feature engineering required for different audio inputs, hierarchical taxonomy is used (Xu, Huang, Wang, & Plumbley, 2016).

Uses for ASC currently include sensing, analysis, surveillance and machine listening. For example, Shapsough and Zualkernan (2018) designed an ASC model to use in classrooms. The goal was to successfully classify different teaching methods, so that teachers could record their unique distribution of daily teaching methods. The HTLM5 and JavaScript application was designed for use on teachers' smartphones, as it was aimed at providing a cost-effective solution for developing countries. The classified teaching methods were demonstration/lecture, questions and answers, classroom management, practice/drill, assignment/classwork and reading aloud. Tree-based methods did not perform well (JRip and J48). However, their model achieved 67.4% success for K-Nearest Neighbour and 68.9% for Random Forest model training techniques. These techniques thus present favourable qualities for ASC used in IPRAT.

2.4.2.2 Intelligent Passive Room Acoustic Technology

ASC is used to help PVAT achieve a desired RT, by using real-time sensors to classify the acoustic event in a space. Figure 2.7 illustrates the proposed behaviour of IPRAT compared with the existing

PVAT detailed in Figure 2.6. Although IPRAT is a novel concept developed by the author, its unique behaviour is detailed here to highlight its differences and similarities with existing technology. Current trends in literature affirm a rising level of intelligence for PVAT, and the development of IPRAT is a novel and appropriate continuity of such literature. Further details on the proposed IPRAT functionality are found in Section 4.

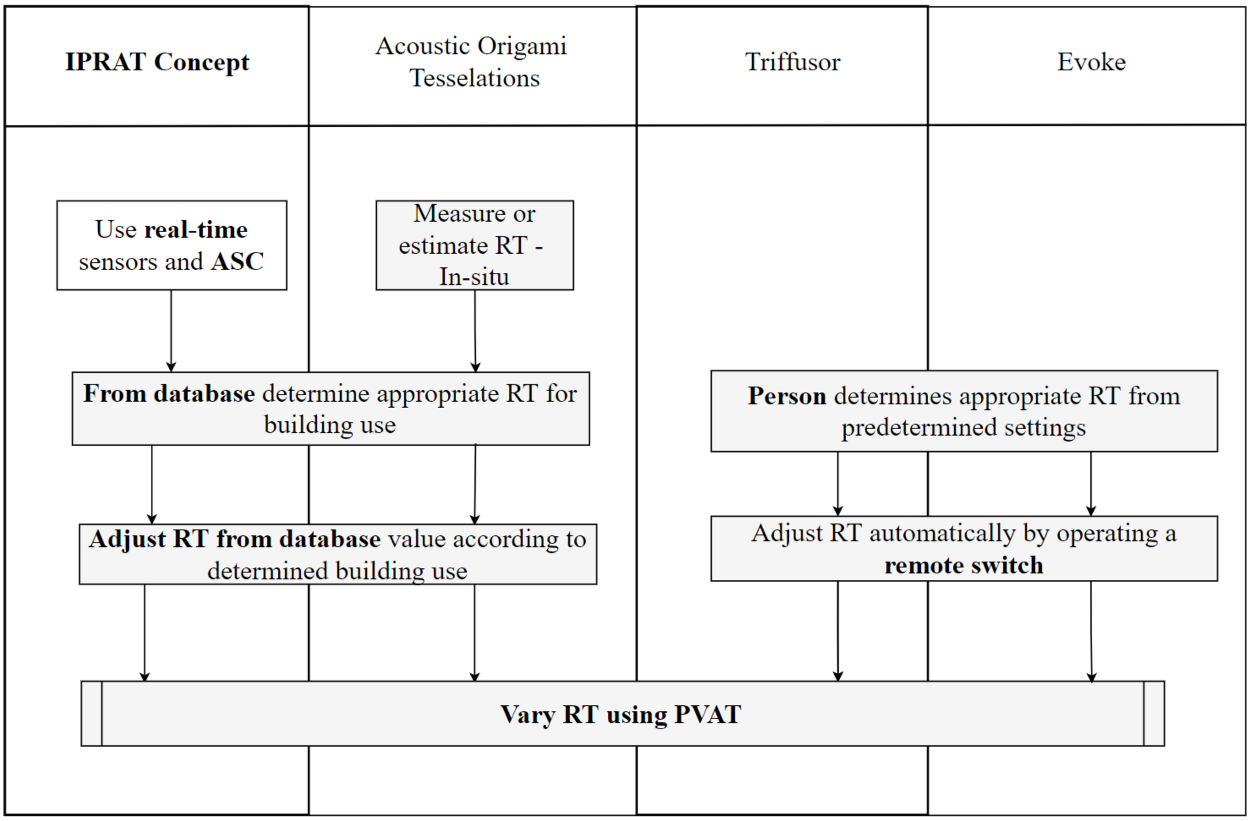


Figure 2.7. Behaviour of IPRAT compared with existing PVAT (illustration by the authors)

2.4.3 Intelligent Passive Room Acoustic Technology and Indoor Environmental Quality

To maximize IEQ , smart technology should be incorporated into our built environment (Ghaffarianhoseini et al., 2019) (GhaffarianHoseini, 2013). This intelligence is characterised as buildings optimally responding to occupants' needs. Occupants have changing preferences and needs over time (Bluyssen, 2019), and their pleasure and comfort are closely linked to their perceived control of an environment (Cole & Brown, 2009). This implies that flexible, adaptive spaces will achieve improvements to user comfort and IEQ, and that operable and automated technology should be encouraged in these adaptive environments.

Fortunately, IPRAT can adapt to the aural situation in a flexible or dynamic space, and automatically adjust RT to improve acoustic comfort. Giving the technology intelligence reduces manual interference or human error, and ensures real-time acoustic optimization. Additionally, IPRAT has the capacity to transform formerly single-purpose spaces into multi-use spaces, by adjusting the acoustic properties intelligently to suit. Mainstreaming acoustically functional multi-use spaces will reduce the size requirement of building footprints, benefiting economic and environmental considerations. And finally, by optimising RT, concentration, communitive clarity, productivity and mental wellbeing will be improved as unwanted noise is attenuated (Kraus & Juhásová Šenitkov, 2017) (Kitapci & Galbrun, 2019).

IPRAT achieves acoustic comfort by maintaining an optimal RT in any space, for any unique situation. When the RT of the room is not optimized, adverse effects arise which would be alleviated with IPRAT (Lupăşteanu et al. (2018) (Selamat and Zulkifli (2016) (Loupa et al., 2019) (Asadi et al. (2017) (Morales and Manocha (2018) (Abbasi et al. (2018). Figure 2.8 illustrates various acoustic discomforts stemming from RT's that are too long or too short.

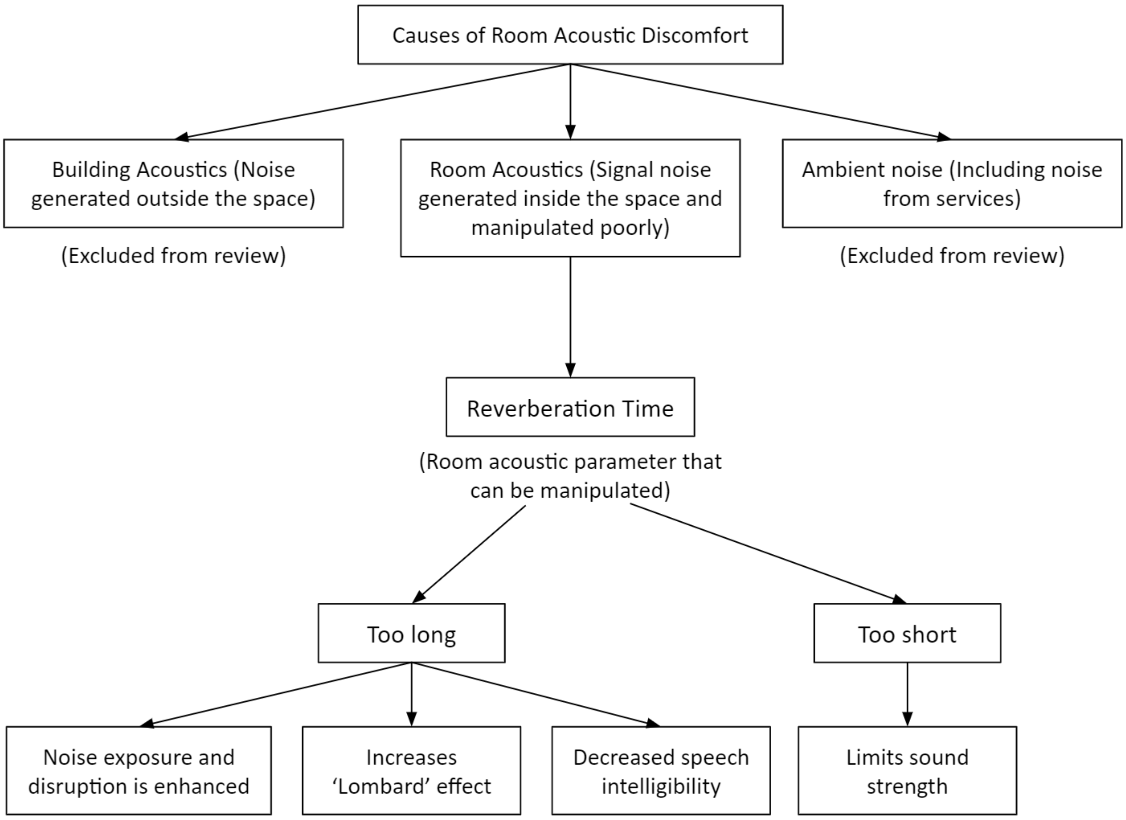


Figure 2.8. Discomforts stemming from inappropriate RT (illustration by the authors)

When RT is too long, unwanted or disruptive noise is heightened and intensified, as it lingers in a space for longer. In this sense, IPRAT could improve occupant health and safety. Exposure to workplace noise is disruptive and in long durations damaging to occupants' hearing (Rabiyanti et al., 2017). Disruptive ambient noise in a residential building can lead to decreased wellbeing (Kraus & Juhásová Šenitkov, 2017). It can also lead to poor sleep/insomnia, distress to people with sensory disabilities (such as Asperger's Syndrome), and induced exhaustion (Motlagh et al., 2018). Office workers in disruptive environments become stressed, negatively impacting cognitive performance, memory, heart rate and eye activity. Additionally, teachers experience great exerting effort to recognize how long they should attenuate vowels for and what volume they should speak at, causing increases of lung pressure and vocal fatigue (Rabelo, Santos, Souza, Gama, and de Castro Magalhães

(2019) (Rollins, Leishman, Whiting, Hunter, and Eggett, 2019) (Bottalico (2017). Additionally, in any noisy situation, the 'Lombard' effect can worsen the noise. This is where people continually speak louder to be heard over a group of people and in turn, those people speak louder as well.

Secondly, when RT is too long, speech clarity is reduced as sound can become incoherent. Thus, IPRAT could increase communication clarity (Gramez & Boubenider, 2017) (Mahmud, Mahmud, & Jahan, 2018) (Samaras and Ferreira (2019) (Vlahou, Seitz, & Kopčo, 2019) (Klatte, Hellbrück, Seidel, & Leistner, 2017). Where vital information is being communicated, the appropriate acoustic quality of the space is paramount for an accurate understanding between parties. When students are challenged to understand their lessons, they loose the ability to concentrate, becoming tired, restless and ill motivated, especially for the mentally impaired (Golmohammadi, Aliabadi, & Nezami, 2017) (Madbouly et al., 2016). Kitapci and Galbrun (2019), (D. Yang & Mak, 2018) and (Munro, 2016) similarly discovered a relationship between a classrooms' acoustic condition, and the achievement of students learning in a second language. Furthermore, Amlani and Russo (2016) discovered increased mental strain for students seated beyond a determined 'critical distance' from the teacher. The most significant noise generated inside the classroom is due to student interaction (D. Yang & Mak, 2017), and fortunately this source of noise can be controlled and manipulated by IPRAT. Theatre performances also rely on having appropriate acoustics (Luizard et al., 2019) for the audience to understand and enjoy the music without it sounding blurred (Panton, Holloway, Cabrera, & Miranda, 2017) (Suyatno, Alfianti, Basworo, Prajitno, & Indrawati, 2019) (Cairoli, 2018).

Decreased occupant health and communication clarity, both addressed above, subsequently result in decreased wellbeing (Renz, Leistner, & Liebl, 2018) (Park & Lee, 2019) (Gao, Hong, Yuan, and Kong (2018). Creating a calm acoustic environment is absolutely necessary in spaces where occupants spend large portions of their time (Setunge & Gamage, 2016). Although PVAT is continually being optimized to eliminate RT discomforts (see Section 3.1), many of these discomforts would be easily alleviated with IPRAT, for its ability to match the RT to any specific application. An extended benefit of IPRAT is that intelligent systems do not need command prompts from a user, so any user interface interaction or training which vulnerable individuals struggle with will be eliminated. Additionally, IPRAT would not have to be integrated within building design, it could be retrofitted into existing buildings efficiently.

2.5 Proposed IPRAT Concept, Development and Use Case

2.5.1 IPRAT Concept

IPRAT contains two components: the PVAT, and the integrated intelligent system. The PVAT component can be achieved by overlaying sound-reflective, rotating louvers over sound absorbing panels. If the louvers rotate open, they allow sound through to be absorbed by the panel behind, decreasing the RT. If they rotate closed, they block and prevent sound from being absorbed, reflecting sound off the louvers and thus increasing the rooms echo and RT. The louvers can also rotate to any state between ‘open’ and ‘closed’ (0-90 degrees), to achieve a wide range of RT’s. The material selection for these components should place emphasis on material sustainability. The material’s specific acoustic requirements can be satisfied easily, however stainability considerations require purposeful consideration and intention (C.-J. Yu & Kang, 2009). For example, the louvers could be made of timber, and the absorber panels made of recycled fibres.

The second component provides the PVAT with intelligent capabilities. Microphones set-up around the room are required to detect the sound waves in the space, specifically, the real-time SPL. The SPL is then transformed into an output that can be interpreted by the ASC. The ASC is trained with algorithms to recognise which acoustic ‘scene’ is occurring, based on the SPL recordings. Once the scene has been determined, a pre-programmed algorithm calculates the optimised RT for that acoustic scene. This RT value is then expressed as an output value for the ‘required rotation’ (0-90 degrees). The rotation is finally communicated through Wi-Fi to a mechanical actuator, which rotates the louvers as specified to achieve the perfect RT. This intelligent classification from microphone to louver is happening in real-time, without the need for a user command or interface. The integration of this intelligent system with PVAT creates our novel solution, illustrated in Figure 2.9.

Figure 2.9. IPRAT functionality (illustration by the authors)

The RT’s achieved by IPRAT cannot account for multiple individual preferences, but rather attempt to satisfy the acoustic state for *most* individuals. Unlike lighting or temperature, sound in a room behaves as a single entity and cannot be significantly varied within a space to suit individual needs. If required, this should be achieved through internal room layout.

2.5.2 ASC Training and Validation

In order for the ASC to accurately identify the acoustic ‘scene’, it must be trained with data sets containing SPL recordings of each of the proposed acoustic scenes. This training can be implemented by adapting a Support Vector Machine (SVM) and using trial-and-error. SVM’s extract and engineer selected audio features from SPL recording datasets. The SPL recordings should be 3 seconds long to ensure successful detection in dynamic spaces where aural situations can change quickly. The number of recordings required to maximize the SVM will depend on the successful results of each evaluation (Weiss & Provost, 2001).

The audio features to extract for this SVM application are: *zero-crossing rate, energy, the entropy of energy, spectral centroid, spectral spread, spectral entropy, spectral flux, spectral roll-off, mel frequency cepstral coefficients, chroma vector and chroma deviation*. The features should be trialled and an appropriate combination found to maximize the model's success. For transferability, the pitch should not be chosen as a feature, as it varies for different aged building occupants. Speech intelligibility differs for different age groups (D. Yang & Mak, 2021). Additionally, acoustic comfort perspectives have been found to differ due to country of origin (Frontczak & Wargocki, 2011) so the ASC should be tailored accordingly.

Computer simulations should be used for preliminary system validation. By testing and refining various inputs and outputs, the simulation results can be compared with expected theoretical results. After which, to test the functionality of the system-on-chip, a block model simulator on PyCharm could be used. The outputs should be consistent with the expected results from the validated results above. The technology can thus be refined to its optimum state. Intelligent aspects of buildings require the achievement of three Key Performance Indicators (KPIs), being *Smart Technology Awareness, Economic Efficiency and Personal/Social Sensitivity* (Ghaffarianhoseini et al., 2016). IPRAT should be analysed against all three KPI's, by explaining and interpreting the implications of the technology against each indicator.

2.5.3 IPRAT Use Case

IPRAT optimises reverberation of noise generated within a space (e.g. human voice). Thus, IPRAT would be suitable for use in classrooms, boardrooms, large halls, or any space where voices are used in varying ways. Of these spaces, classrooms are the most crucial environments where optimum RT should be achieved. Classrooms ensure the successful growth and knowledge development of children in a critical time of their lives. Occupants who require high concentration levels due to complex mental work are *more sensitive to noise (Lou & Ou, 2019).* These higher concentration levels are required in classrooms as there is more complex mental work performed in these spaces compared with others (Kool & Botvinick, 2018). Consequently, classrooms require a better acoustic environment and a reduction of distractions, achieved by ensuring an appropriately varied RT for each classroom situation.

Let us consider a hypothetical classroom which has IPRAT installed. When a teacher lectures, they require a long RT (high sound strength) for their voice to travel without inducing vocal strain. IPRAT would detect and classify the sound in the space as a situation needing a long RT. The reflective louvers would rotate closed, not allowing any sound to be absorbed. The teachers voice would be effortlessly projected to the students at the front and back of the class. In turn, this would reduce teacher vocal disease whilst increasing student comprehension and connection. Alternatively, when the students are working individually or executing group tasks, the RT should be minimised to increase clarity and absorb disruptive noise. IPRAT would detect these acoustic states and rotate the louvers open, to allow sound through to be absorbed by the panels behind. The shortened RT will create the conditions for enhanced clarity, concentration and focus. It will also decrease noise-induced anxiety or stress for vulnerable students. Rather than designing the classroom with a RT trade-off (as is current practise), the use of IPRAT will optimise the acoustic condition for many situations.

2.6 Discussion

Achieving an optimal acoustic condition can be more complex than simply changing sound absorption (Alibaba & Ozdeniz, 2019). Many contributing factors are at play and quantifying acoustic comfort can be subjective. The success of IPRAT relies on its ability to a) correctly interpret and calculate an optimized RT and b) precisely adjust PVAT to achieve this optimized RT. For both of these functions, challenges will arise, specifically regarding building physics interactions and sound frequencies. Furthermore, the need for such technology may also be questioned due to acoustic design standards.

2.6.1 Building Physics

Heat energy in a room has a minor effect on the way sound waves travel in a space, as it changes the sound absorption ability of the air. Fortunately, temperature and relative humidity have a negligible effect on the RT in a space (Baruch, Majchrzak, Przysucha, Szeląg, & Kamisiński, 2018). Additionally, although a correlation does exist, there is no significant effect on sound absorption coefficient due to water content (D'Alessandro, Baldinelli, Bianchi, Sambuco, & Rufini, 2018). The psychoacoustical effects of temperature, relative humidity and illumination must however be considered when defining the optimum RT for a space. For example, in bright spaces, a decrease of noise level increases overall comfort, and at thermoneutrality, perceived acoustic comfort is greater (W. Yang & Moon, 2019) (Guan et al., 2020). This explains how humans feel uncomfortable when they are overstimulated. If noise levels are a controlled variable; when temperature or illumination is greater noise levels should be decreased (by decreasing RT) to maintain a satisfactory IEQ. It is always strongly encouraged to consider all IEQ's holistically when creating a comfortable environment (Krüger & Zannin, 2004).

2.6.2 Sound Frequencies

At high (5,000-20,000Hz) and low (20-250Hz) sound frequencies, predicted and measured RT's can become inaccurate (Vasov, Cvetković, Bogdanović & Bjelić, 2018). For example, RT's are perceived as longer in low frequency sound (Adelman-Larsen, Jeong & Støfringsdal, 2018), and if the RT in mid-high frequencies is long, this reverberation can be concealed by low frequency sound. Additionally, high and low frequency sound negatively affect the Speech Transmittion Index (STI) in a space (Brixen, 2016). Luckily, RT discrepancy from frequencies between 1000 and 4000 Hz (human speech) is negligible at +/- 0.05 seconds (Vardaxis & Bard, 2018) (McKinlay, 2018). Thus, IPRAT will achieve acoustic comfort with accuracy in spaces where high and low frequency sounds do not occur often (e.g. a classroom).

2.6.3 Acoustic Design Standards

Acoustic design standards, prepared by technical committees, are in place to ensure that new buildings adhere to satisfactory levels of acoustic comfort. Hence, physical acoustic values of different parameters within standards have historically defined acoustic comfort (Radziejowska & Rubacha, 2018). Because the standards specify single fixed values, there is little motivation for designers to optimise this within a range of values for different situations. For example, New Zealand uses AS/NZS2107:2016 to recommend single RT levels to achieve in classrooms (dependant of classroom size) (Standards New Zealand, 2016). We know now that it is inappropriate to apply single RT values to classrooms, as the activities executed in learning environments are varied. Although AS/NZS2107:2016 recommends singular design RT's, this is simply a trade-off between the long and short RT's needed. These standards make it difficult for designers to truly optimise acoustic comfort in these spaces, or to recognize the need for IPRAT.

2.7 Conclusion

The concept underlying international design standards is that spaces should be designed with one static acoustic state. This recommendation enforces a trade-off between long and short RT's required in different aural situations, causing harmful acoustic discomforts in our built environment. Instead, we must begin to design for varying RT's. If a space were given a range of RT's to achieve, acoustic conditions could be adapted to the changing functions and needs of a space. Current trends in literature evidence a rising level of intelligence for PVAT. However, no systems utilize AI to classify building use and adjust the RT optimally. The development of IPRAT is found to be a novel and appropriate continuity of the literature.

IPRAT integrates ASC with PVAT to identify the specific building use in real-time, and adjust the RT accordingly to optimise acoustic comfort. With this real-time optimization, dynamic building activities can receive the perfect acoustic treatment, whether it be sound projection or noise absorption. In our built environments, many RT adversities exist causing a wide range of acoustic discomforts. Through understanding these discomforts, it is formulated that IPRAT could improve communication clarity, occupant health and safety and occupant wellbeing. The use of IPRAT in classrooms will reduce teacher vocal disease and improve student comprehension, concentration, and achievement.

With recent developments in automation, it is becoming easier to incorporate advanced motorized and computerized mechanisms and embedded software into architectural components (Puri & Nayyar, 2016). A high level of position accuracy can be achieved from automated actuators, significantly improving unique space personalization (Gunge & Yalagi, 2016). Technological challenges for IPRAT to overcome will be defining optimum acoustic conditions and achieving these with precision. Such challenges have not hindered other buildings services, however. Heating, ventilation and lighting have found ways to utilize intelligent systems and optimise occupant conditions. Acoustic solutions are trailing behind, and it is recommended that acoustic comfort is given more attention within IEQ (Clements-Croome, 2015).

Our built environment creates strong and lasting effects on occupant wellbeing, and these effects should continually be explored and redefined (Ghaffarianhoseini, AlWaer, Ghaffarianhoseini, et al., 2018). In this paper, the proclamation, design, and analysis of IPRAT lays a solid foundation for subsequent research studies. Going forward, IPRAT should be prototyped, and its impact on acoustic comfort quantified. In combination with this paper, it would significantly contribute to architectural acoustic and intelligent building professionals.

2.8 Conclusion to chapter

2.8.1 Original contribution and realization of aims and objectives

By challenging acoustic standards and their pitfalls, it is proposed that acoustic optimization should account for the current activities in the space to determine the appropriate acoustic condition. This is because dynamic spaces should be designed with varying Reverberation Times. A literature gap exists for intelligently adjusting RT to suit changing space uses. Thus, this paper presented the novel IPRAT that solves this advocation for real-time RT optimisation through the integration of PVAT and ASC. Literature on IPRAT was understood by recounting the evolution of PVAT intelligence. Inevitably, this revealed a literature gap related to PVAT automatically and intelligently adapting to changing occupant needs. By synthesizing existing literature on PVAT and ASC, IPRAT was defined, and by evaluating the integration of PVAT and ASC, the design, development and use of state-of-the-art IPRAT was predicted. From these indications, it was inferred that IPRAT is able to increase IEQ in architectural spaces. Finally, challenges and implications of IPRAT were considered, and conclusions about the technology and how it can be used in the built environment were drawn (Table 5).

Table 2.3. Manuscript 1 title, aim, objective and output(s)

Manuscript title	Manuscript aim	Objective	Output(s) or novel findings
(Manuscript 1) The Birth of Intelligent Passive Room Acoustic Technology: A Qualitative Review Published in SASBE	Determine the rationale for intelligent passive room acoustic technology	Conduct a best-evidence synthesis and prior art search to determine the highest level of intelligence for passive variable acoustic technology	Dynamic spaces should be designed with varying Reverberation Times; however, a literature gap exists for intelligently adjusting RT to suit changing space uses
		Conceptualise the unique solution: IPRAT, which integrates Passive Variable Acoustic Technology and Acoustic Scene Classification	IPRAT is proclaimed, developed and analysed, and a use case example is provided

2.8.2 Differentiation of contribution from existing literature

PVAT is currently able to achieve a high level of intelligence through programmable automated systems thanks to various successes in industry and academia. A range of PVATs can reduce RT manually; for example, by adding reverberation absorption chambers, by lowering a ceiling or by increasing acoustic absorption with rotating panels, rolling curtains, or hinged flaps. Compared to manual solutions, automation has improved acoustic comfort, providing greater adaptability and efficiency in varying acoustic environments. In comparison, IPRAT includes an integrated intelligent system.

The PVAT component which exists in literature is not novel when standing on its own. However, this component can be achieved by overlaying sound-reflective, rotating louvers over sound absorbing panels. Rotating the louvers open allows sound to be absorbed by the panel behind, reducing the RT. If they rotate closed, they block and prevent sound from being absorbed, reflecting sound off the louvers and thus increasing the rooms echo and RT. A wide range of RT's can be achieved by allowing the louvers to rotate between open and closed (0-90 degrees). Materials for these components can be selected according to their ability to absorb and reflect sound and their sustainability. The material's specific acoustic requirements can easily be met, but stainability requires more careful consideration. Timber louvers and recycled fibre absorber panels, for instance, could be used.

The second component provides the PVAT with intelligent capabilities, making IPRAT a novel concept. A set of microphones around the room is required to detect sound waves in the space in real-time, specifically the SPL. The SPL is then transformed into an output, interpreted by the ASC. Based on the SPL recordings, the ASC is trained to recognize which acoustic 'scene' is taking place. Based on the acoustic scene, a pre-programmed algorithm calculates the optimised RT for that acoustic scene. This RT value is expressed as the ‘required rotation’ (0-90 degrees). Ultimately, the rotation is communicated via Wi-Fi to a mechanical actuator, which rotates the louvers as specified to reach the perfect RT. Opportunely, a user command or interface is not required to make this intelligent classification from the microphone to the louver. Incorporating this intelligent system with PVAT creates the unique IPRAT solution.

The use-case described in this paper is also a novel contribution, as it is proposed for the first time how the benefits of IPRAT could be realised in a classroom. With regards to the ASC, the methods used to develop and train the model would not be novel. It is a fact of using an ASC in a classroom for room acoustic optimisation, which is a novel concept. In this sense, using an ASC for a RT application would be the first of its kind, and planting this seed in the built environment literature is a small, unique contribution.

2.8.3 Final Considerations

Technical committees prepare acoustic design standards to ensure that new buildings adhere to satisfactory levels of acoustic comfort. Consequently, acoustic comfort has historically been defined by physical acoustic values within a standard. The standards specify single fixed values, so designers have little incentive to optimize this across a range of values. New Zealand, for instance, uses AS/NZS2107:2016 to recommend single RT levels to meet in classrooms (determined by the size of the classroom) (Standards New Zealand, 2016). Considering the various activities performed in learning environments, it is inappropriate to apply single RT values to classrooms. The AS/NZS2107:2016 recommendation is for single design RT's, but that is simply a compromise between long and short RT's. As a consequence of these standards, architects and designers cannot ensure that the acoustics of these spaces are optimal or realise the need for IPRAT.

The preferences and needs of occupants change over time, and their comfort and pleasure depend on the perception of control over an environment. It follows that flexible, adaptive spaces will improve user comfort and IEQ, and that operable and automated technology should be encouraged in these adaptive environments. Thanks to IPRAT, the RT can be adjusted to adapt to aural situations in a dynamic or flexible space, which will result in improved acoustic comfort. By providing artificial intelligence to the technology, manual interference or human errors are reduced, and acoustic optimization is enabled in real-time. Furthermore, IPRAT can intelligently adapt acoustic properties to accommodate multi-purpose spaces, thus enabling formerly single-purpose spaces to become multi-purpose spaces. A space that is acoustically functional for more than one use will become multi-purpose, so it can reduce building footprints, thereby reducing cost and environmental impact. And finally, concentration, communitive clarity, productivity and mental wellbeing can be improved as noise is dealt with in varying ways.

In the following chapter, Manuscript 2 is presented which forms the first part of the simulation study.

Chapter 3. Developing virtual classroom environments for intelligent acoustic simulations

3.1 Prelude to Manuscript 2

The previous manuscript argued that dynamic spaces should be designed with varying Reverberation Times (RT). A literature gap was exposed for intelligently adjusting RT to suit changing space uses, and thus a unique solution was found; Intelligent Passive Room Acoustic Technology (IPRAT). IPRAT integrates Passive Variable Acoustic Technology and Acoustic Scene Classification. The manuscript proclaimed, developed and analysed IPRAT, and a use case example was provided. The following manuscript designed and created 20 virtual classroom environments, for the eventual simulation of IPRAT. Simulated architectural environments provide immense value in technology validation and optimisation in smart buildings (Hensen & Lamberts, 2019a; Rodriguez-Mier, Mucientes, & Bugarín, 2019). IPRAT as a novel, emerging technology would benefit largely from simulated environments to conduct tests that aren't resource intensive. Notably, such technology exhibits opportune application for use in classrooms, suggesting the vast benefits of simulated classroom environments for optimisation of intelligent acoustic technology (Favoino, Giovannini, & Loonen, 2017). For such simulations, typical profiles comprising of data on physical and aural NZ classroom attributes have not been holistically detailed or virtually developed. The following manuscript thus aims to develop and detail such virtual environments. Documentation exposing the physicality of classroom types are collated to detail 5 typical classroom profiles. Studies attempting to define regular aural situations in classrooms reveal 4 typical aural situations. Statistical analysis of these quantitative physical and aural classroom attributes produced 2 useful datasets for the acoustic environments. Co-variate adaptive randomization and interpolation were used to create 20 profiled NZ classrooms. This paper contributes to the research aim by offering the development, detailing and demonstration of these 'typical' NZ profiles which can be used for software simulation in both industry and academic fields; classroom architecture, classroom acoustics and acoustic optimisation. To satisfy the overall aim of this thesis, the classroom profiles provide the foundation for the acoustic simulations in manuscript 3, which demonstrate the benefits of IPRAT. I-Simpa, a pre/post-processor for acoustic codes, and Autodesk software are used to detail and demonstrate the classroom profiles.

3.2 Introduction

Computer modelling simulations are commonly used when assessing building performance measures in support of the design process. Building performance analysis (BPA) can facilitate design optimization alongside providing feedback on building design (S.-y. Chen, 2018). Building Information Modelling (BIM)-enabled BPA, e.g. computer modelling simulations provide this valuable insight into building performance in early design stages (Jin et al., 2019). It is often challenging to ensure the quality of simulation results, suggesting simulations should not generate solutions or answers but increase understanding of the implemented model (Hensen & Lamberts, 2019a). Physical architectural environments comprise of many unique independent variables and unpredictable interactions between these multiple factors (de Wilde, 2019). Simulation of the physics of the interactions is vital in understanding and accounting for their effects on building performance (Hensen & Lamberts, 2019a; Rodriguez-Mier et al., 2019). The interaction between the building performance and integrated technology can be predicted with simulations, which can also support the product development of novel technologies (Favoino et al., 2017).

Automated variable acoustics (intelligent acoustics), an emerging technology, is achieved through the integration of acoustic scene classification, a machine learning method, and variable acoustic technology. As a novel and developing technology, intelligent acoustics would benefit largely from simulated environments. Intelligence within our built environment is experienced as buildings optimally responding to occupants' needs, thus achieving significant improvements to user wellbeing, sustainability and adaptability of architecture (Clements-Croome, 2011). Artificial intelligence used in smart buildings can significantly improve occupant comfort within all main areas of Indoor Environmental Quality (IEQ) (Panchalingam & Chan, 2019). This is due to occupants having changing preferences and needs over time, which are essential factors affecting IEQ (Bluyssen, 2019). Simulating smart architectural spaces with realistic virtual environments is a prominent way to demonstrate the behaviour and response of the space. Simulated architectural environments thus provide immense value in technological optimisation and validation in smart buildings.

Intelligent Acoustics exhibits opportune application for use in classrooms, suggesting the vast benefits of simulated classroom environments for manipulation and optimisation of intelligent acoustics. Classrooms are commonly thought of as single-use spaces, presenting the primary function of teaching and learning (J. Yang, Pan, Zhou, & Huang, 2018). Nevertheless, there are numerous different acoustic events carried out in classrooms which require specific acoustic conditions to support the learning experience (Rands & Gansemer-Topf, 2017). Flexible spaces are increasing in popularity due to their ability to adapt to occupants changing needs (Søiland & Hansen, 2019). Environmental computer simulations provide timely, cost-effective solutions on the performance of such multi-use spaces for each use case (Hensen & Lamberts, 2019a).

To simulate acoustics in an architectural space, there are certain inputs which are required; software instructions and a virtual environment (Figure 3.1). The virtual environment is comprised of various physical and aural attributes. A gap in literature exists whereby virtual NZ classrooms comprising of such attributes have not been holistically detailed. Thus, this papers aim is to develop a set of virtual classroom environments, by manipulating secondary data from existing studies.

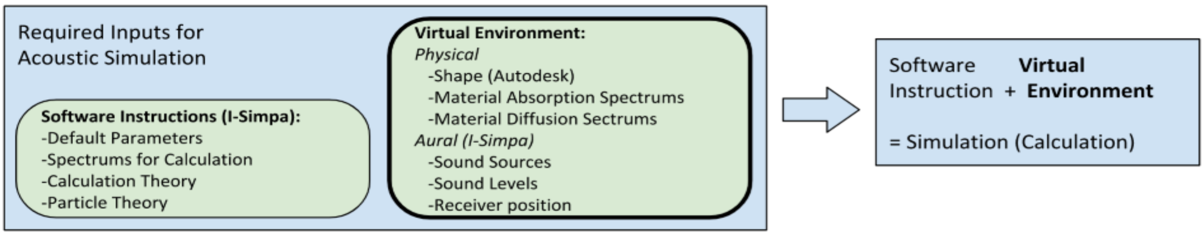


Figure 3.1. Required Inputs for acoustic simulation

This paper details the development of 20 virtual NZ classroom environments (5 classroom types cross-multiplied with 4 aural situations). First, classroom types common to NZ are investigated and explored. Documentation exposing the physicality of various classroom types are collated to detail 5 typical classroom profiles. Secondly, 4 typical aural situations arising in classrooms are revealed and defined based on existing studies. Interpolation and mode analysis are used on the quantitative physical and aural data exposed in these investigations, to extract the characteristics used in the final profiles. Lastly, I-Simpa, a pre/post-processor for acoustic codes, and Autodesk Revit and 3DSMax are used to demonstrate the final classroom profiles. 3DSMax holds the capability to create and export 3D-scene environments, for import into I-Simpa where 3D aural situations can be created. These profiles are intended for the use of industry professionals and academics who require 'typical' or 'normal' virtual classroom profiles, to save simulation time.

3.3 Methods

Accurately simulating Human-Building interaction is difficult due to behavioural diversity amongst building occupants. Building context (classroom), characteristics (physical attributes) and type of behaviour (speech) are clearly defined to alleviate as much uncertainty around the simulated interactions as possible. The tools (methods or materials) used to define each these variables, and at which phase of the research design are outlined in Figure 3.2.

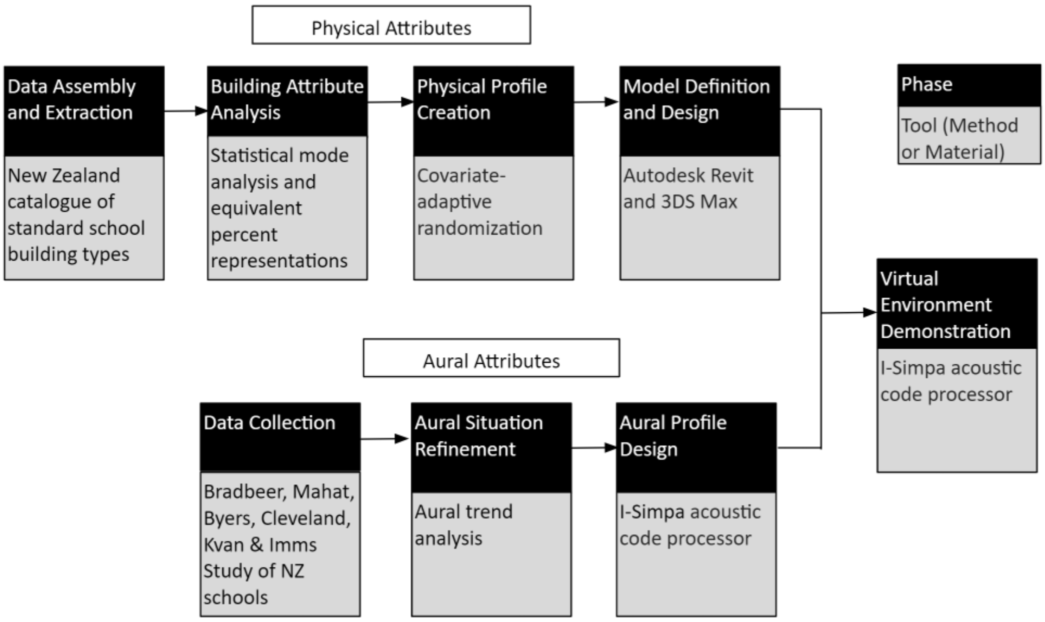


Figure 3.2. Research method phases and tools used for Virtual Environment Demonstration

3.3.1 Physical Classroom attributes

3.3.1.1 Data Assembly and Extraction

The New Zealand catalogue of standard school building types published by the Ministry of Education was used to assemble the data for this research (McNulty & McClurg, 2013). This document is one of the only records of standard school types, and outlines school typologies in the districts affected by the Canterbury earthquakes for the purpose of structural and seismic information. These typologies are very similar throughout NZ as when most school buildings were being constructed in the mid 1900's, standardized construction and design were adopted (Te Ara - the Encyclopedia of New Zealand, 1966). These typologies however do not include the more modern classrooms types constructed in the past decades. Initially, the Ministry was contacted to assure the document was up to date. The most recent version of the catalogue contains 2 sections of interest, permanent classrooms (9 buildings scheduled in the catalogue) and relocatable classrooms (15 buildings scheduled in the catalogue). The catalogue defines classroom 'types' found in a selection of schools around NZ, by demonstrating qualitative and quantitative attributes of individual classrooms in each 'type'. The catalogue details, diagrams and photographs were thus deciphered, and appropriate data was assembled. To represent the spaces accurately on Autodesk software, thorough details were required for the following classroom attributes. These included; space dimensions, roof shape, ceiling type, use of acoustic tiles, wall type and covering, insulation, floor type, glazing and furniture layout. Data not interpreted from the catalogue was floor and wall covering, as there is a regulation in NZ for classrooms to be carpeted, and standard wall covering unless otherwise specified is Gib-board. A structured criterion was put in place to ensure only applicable data was extracted to satisfy the research goals. Firstly, only data helpful to the physical acoustic profile analysis were extracted from the catalogue for interpretation. Secondly, data was only included if it was sufficiently detailed, to realistically represented the physical environments. Some level of drawing and photograph interpretation was used to extract the data, with utmost professional judgement. If any of the data was unclear, it was omitted from the profile analysis.

3.3.1.2 Building Attribute Analysis

In-depth building attribute analysis was conducted on the extracted classroom data. Firstly, the modes for each classroom attribute were found from the collected data above. The number of modes were limited by a maximum of 5, due to the creation of only 5 classroom types, and a minimum of 1, as each attribute required at least one property. After the most prominent modes were extracted (Table 3.1), the number of occurrences each mode experienced was recorded.

Table 3.1. Prominent Modes. Attribute (number of occurrences, percentage relative to other modes, equivalent integer)

Attribute No.	**Mode**	**1**	**2**	**3**	**4**
Glazing		Large glazing on North (4, 20%, 1)	Large Glazing on North and South (8, 40%, 2)	Some Glazing on all sides (2, 10%, 1)	Some-Little Glazing on N/S (6, 30%, 1)

Layout of Furniture	Multiple tables seating 4 (5, 21%, 1)	Front facing desks seating 2 or 3 (9, 47%, 2)	Continuously connected desks (1, 5%, 1)	Front facing single desks (4, 21%, 1)
Ceiling Shape	Center Ridge (13, 56%, 3)	Mono pitch (3, 13%, 1)	Flat (7, 30%, 1)	
Ceiling Structure	Long straight steel trusses (5, 23%, 1)	Large exposed Internal timber beams (7, 31%, 1)	None (10, 45%, 3)	
Wall Structure	Masonry block with reinforced concrete (2, 8%, 1)	Light timber framing (11, 42%, 2)	Fibre cement with timbre frame (13, 50%, 2)	
Dimension Length	8.9-9.2m (11, 57%, 3)	10m (6, 31%, 1)	12m (2, 12%, 1)	
Dimension Width	7.5-8m (15, 93%, 4)	6.5m (1, 7%, 1)		
Wall Insulation	Yes (5, 20%, 1)	No (19, 80%, 4)		
Ceiling Cladding	Acoustic Pinex Ceiling (10, 44%, 2)	Gib Ceiling (13, 56%, 3)		
Floor Structure	Concrete slab on grade (7, 26%, 1)	Suspended timber floor (20, 74%, 4)		
Floor Covering	Thin Carpet (24, 100%, 5)			

This number was then calculated as a percentage relative to the total number of occurrences of all modes for an attribute. Lastly, this percentage was translated into an equivalent single integer of minimum 1, to distribute each attribute amongst the 5 classroom profiles. For example, Table 3.2 shows the calculation of equivalent integers for the glazing type attribute.

Table 3.2. Glazing type equivalent integer, building attribute example

Glazing Type	No. of Occurrences	Mode Y/N	Percent	Equivalent Integer	Representation in Table 3.2
Large glazed walls to north	4	Y	20%	1	(4, 20%, 1)
Large glazed walls to north and south.	8	Y	40%	2	(8, 40%, 2)
Large glazed windows on side. Celestial windows on opposite side.	1	N	-	-	-
High level glazing to roof lantern.	1	N	-	-	-
Verandas alongside elevations. High clerestory windows.	1	N	-	-	-
Only low-level glazing.	1	N	-	-	-
Some glazing on all sides.	2	Y	10%	0.5 = 1	(2, 10%, 1)
Some/Little glazing on north and south.	6	Y	30%	1.5 = 1	(6, 30%, 1)
Total Occurrences	24	4 modes		5 instances	

3.3.1.3 Physical Profile Creation

To create the 5 profiles, covariate-adaptive randomization was used to group various combinations of classroom attributes. This is a randomization technique which stratifies baseline covariates (classroom attributes) and assigns each attribute based on others in the stratum (classroom type no.) to achieve realistic profiles (Ma, Qin, Li, & Hu, 2019). This approach was advantageous as achieving balance over many classroom attributes when the sample size is small (5 classroom types) was necessary to satisfy the research goal. Validation was achieved to ensure attributes were assigned consistently with what would be seen in a physical classroom. This was done by comparing the final classroom compositions with Valentine and Halstead (2002) building survey of NZ classrooms and the 4 ‘types’ of classroom categories they created (Table 3.3). This particular building survey was used even though it is limited to structure and ceiling covering, as it is the only of it's kind to exist in New Zealand. The 5 classroom profiles did sit very close to these 4 types. This was realized by identifying the key characteristics of the 4 classroom types, and the combinations in which they are used, and finding these same characteristics and combinations in the 5 classroom types created for the simulation. For example, the light-weight construction is paired with either acoustic ceiling tiles or a hard ceiling.

Table 3.3. Classrooms types created by Valentine and Halstead (2002), used to validate final classroom compositions

Type No.	Description
Type 1	Relocatable classrooms constructed from lightweight materials (timber framing, raised particle board floor) with an acoustically hard, pitched ceiling following the line of the roof (central ridge and 15-degree pitch)
Type 2	Relocatable classrooms (lightweight construction) with softboard acoustic ceiling tiles fixed to the underside of the trusses, forming a horizontal ceiling plane
Type 3	The older style permanent classrooms with concrete on grade floor construction and softboard acoustic ceiling tiles (perforated softboard) forming a horizontal ceiling
Type 4	The older style permanent classrooms with concrete on grade floor construction and an acoustically hard, flat ceiling (plasterboard or fibre-cement).

Crucial missing data which was not in the main document had to be collected from past studies, including absorption and diffusion coefficient spectrum of surfaces. The data was extracted from three different studies to ensure no missing data (Hodgson & Scherebnyj, 2006) (W. Yang & Hodgson, 2007) (Coffeen, 2000). Secondly, typical occupancies in the spaces were discovered; in NZ, most students are in classes of size 26 to 30 (54%) or 21 to 25 (31%) (Caygill & Sok, 2008). Thus, 5 occupancies will be simulated from these ranges, including 22, 24, 26, 28 and 30. And lastly, typical temperature, pressure and relative humidity in classrooms were not collected for this research as their effect on classroom acoustics is negligible. Honor Columbus, Principal Technical Advisor for school design in NZ, was approached to inform on typical ceiling heights and roof pitches (personal communication, May 21st, 2020). For the classrooms in question, a height of 2.7m is standard for flat ceilings, and a height of 3m at the apex was typical for pitched ceilings. It was also recommended that internal ceiling apexes range from 3-4.5m so an average should be used of 3.75m.

3.3.2 Classroom Aural Attributes

Auralization, the under-established acoustic counter-part to visual 3D rendering, is used to anticipate or predict the acoustic behaviour of a space (Pelzer, Aspöck, Schröder, & Vorländer, 2014). The data required for the design of aural situations for realistic auralization in this study were typical directivity, size (decibels), number of sources and ambient background noise of the unoccupied classroom.

3.3.2.1 Data Collection

Various aural situations in classrooms are categorized for this study using secondary data. Namely, Bradbeer, Mahat, Byers, Cleveland, Kvan & Imms (2017) conducted a study across 337 NZ schools, gathering data to categorize teaching approaches used in classrooms, for sound data collection. Although teaching methods are sophisticated and can vary over time, the data collected and categorized extensively covers the scope of this research. Furthermore, these categories are supported by Cleveland, Newton, Fisher, Wilks, Bower, & Robinson (2016), who researched environmental learning settings. Informal use of the space was not included in the study, but this included any non-teaching hours such as before school, morning tea break and lunch break.

3.3.2.2 Aural Situation Refinement

Some of these teaching approaches possess similar sound profiles and desired acoustic conditions, so are further narrowed into 4 distinct aural situations. This is due to them possessing similar characteristics, based on a) the potential number of people speaking and thus b) a hypothesized acoustic requirement (RT required). For example, both ‘teacher speaking to all children’ and ‘teacher facilitating large group discussion’ involve 1-2 people speaking at a time, and both will require a high RT, so they will not need to be distinguished apart from each other. This will both simplify and improve the simulated environments, producing only narrowly targeted results.

Not interpreted from this data, thus, to be discovered from alternative studies were the characteristics of voice level (dB) and background noise level (dB). Firstly, a German study by Berger et al. (2019) established normative speaking voice data by measuring 1274 female and 1352 male participants aged 6 to 17 years. They measured 5 voice intensities as the quietest voicing speaking voice (Level I), conversational voice (Level II), classroom voice (Level III), shouting voice (Level IV), and again the quietest speaking voice (Level V). These intensity levels are used for each aural situation. Secondly, Mealings (2019) conducted a study comparing an acoustic application ‘SoundOut’ against a sound level meter, collecting 46 unoccupied ambient noise level recordings in classrooms. This data showed ambient classroom noise levels ranging from 32-45db, with multiple mode values 34, 36 and 39. For this Auralization, a single value of 36dB will be used for background noise level.

3.4 Results

The resulting output of this paper is sufficient detail to create and simulate 5 classroom profiles and 4 aural situations. The virtual environments are demonstrated here, with explanations of each step taken to bring the virtual environments into fruition. Figures 3.3-3.5 show examples of each step in the virtual environment demonstration, from Revit to 3DS Max to I-Simpa.

3.4.1 Model Definition and Design

5 classroom profiles were created and assembled (Table 3.4) based on documented data undergone statistical analysis (Table 3.1).

Table 3.4. Physical classroom attributes

No.	Dimension	Ceiling shape, exposed structure, Ceiling material	Floor type and covering	Wall construction, insulation	Glazing	Layout of Furniture, Occupancy

1	6.5x10	Mono pitch, Long straight steel trusses, Gib Ceiling	Concrete slab on grade, thin carpet	Masonry block with reinforced concrete, no	Large glazing on North	Continuously connected desks, 25
2	8x9.2	Flat, None, Acoustic Pinex Ceiling	Suspended timber floor, thin carpet	Light timber framing, no	Some-Little Glazing on N/S	Front facing single desks, 22
3	7.5x12	Center Ridge, Large exposed Internal timber beams, Gib Ceiling	Suspended timber floor, thin carpet	Fibre cement with timbre frame, no	Large Glazing on North and South	Multiple tables seating 4, 24
4	7.5x8.9	Center Ridge, None, Acoustic Pinex Ceiling	Suspended timber floor, thin carpet	Light timber framing, yes	Large Glazing on North and South	Front facing desks seating 2 or 3, 28
5	7.5x8.9	Center Ridge, None, Gib Ceiling	Suspended timber floor, thin carpet	Fibre cement with timbre frame, no	Some Glazing on all sides	Front facing desks seating 2 or 3, 30

Note: All buildings contained a lot of art/posters on walls, cupboard and bookshelves.
Note: Typical NZ building floor to ceiling height in classrooms: 2.7m, internal apex height 3.75m.

Furniture families were imported to Revit to create the profiled classrooms' floor plans. Unique wall, floor and roof types were created to accurately model each classroom envelop. Standard Revit window and door components were used in varying arrangements for each classroom. Figure 3.3 demonstrates 2 classroom types; classroom 1 and classroom 3 modelled on Autodesk Revit.

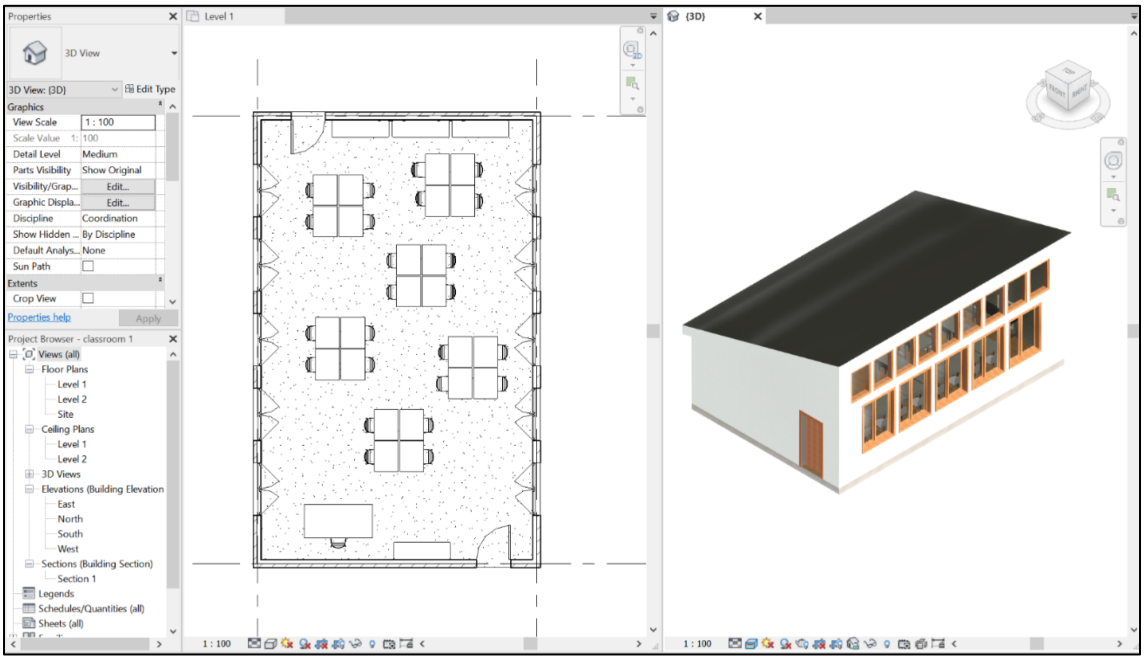


Figure 3.3. Examples - Left: Classroom 1 modelled on Revit. Right: Classroom 3 modelled on Revit

3.4.2 Aural Profile Design

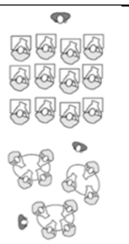
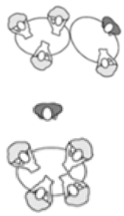
Absorption and diffusion (scattering) coefficient spectrum of building materials are detailed (Table 3.5). Expectedly, many building materials share a similar spectrum profile to other materials. Moreover, surfaces with similar coverings (though different structural properties) still share the same acoustic properties.

Table 3.5. Absorption and diffusion coefficient spectrum of building materials

Building Material	**Absorption Coefficient Spectrum (125, 250, 500, 1000, 2000, 4000, 8000Hz)**	**Diffusion Coefficient Spectrum (125, 250, 500, 1000, 2000, 4000Hz)**
Acoustic Pinex Ceiling	(0.27, 0.28, 0.36, 0.43, 0.39, 0.39, 0.45)	Use ‘carpet’ (0.06, 0.07, 0.1, 0.15, 0.15, 0.2)
Concrete slab on grade, thin carpet	(0.05, 0.1, 0.25, 0.3, 0.35, 0.4, -)	(0.06, 0.07, 0.1, 0.15, 0.15, 0.2)
Suspended timber floor, thin carpet	(0.14, 0.19, 0.21, 0.24, 0.29, 0.33, 0.49)	(0.06, 0.07, 0.1, 0.15, 0.15, 0.2)
Gib ceiling, Gib covering on masonry no insulation, Gib covering on timber framing no insulation, Gib covering on ffiber cement with timbre frame no insulation, Gib covering on timber framing insulation	(0.12, 0.09, 0.09, 0.09, 0.08, 0.09, 0.13)	Use ‘painted plywood’ (0.03, 0.03, 0.02, 0.01, 0.01, 0.01)
Glazing	(0.35, 0.25, 0.18, 0.12, 0.07, 0.04, -)	Use ‘blackboard’ (0.1, 0.05, 0.04, 0.04, 0.03, 0.03)
Wooden door	(0.15, 0.11, 0.09, 0.07, 0.06, 0.06, 0.13)	(0.6, 0.45, 0.32, 0.38, 0.3, 0.3)
Furniture (hard chairs and tables)	(0.06, 0.07, 0.09, 0.09, 0.08, 0.07, 0.07)	Use ‘wood’ (0.6, 0.45, 0.32, 0.38, 0.3, 0.3)
Occupants	(0.13, 0.16, 0.15, 0.13, 0.18, 0.25, -)	(0.62, 0.72, 0.8, 0.8, 0.85, 0.85)

The secondary aural situation data was refined into situations A-D based on analysing and grouping similar speaker and listener characteristics. For example, ‘teacher speaking to all children’ and ‘teacher facilitating large group discussion’ both have 4-6 people speaking at once, and people listening in varying directions, so are grouped together. Thus, 4 aural situations used in classrooms are profiled (Table 3.6) by defining number of people speaking and at which intensity level. Lastly, background noise level is noted at 36dB**.**

Table 3.6. Aural situation design

Aural Situation	NZ Teaching Approach	Representation	People speaking	Voice intensity	dB	I-Simpa Approach
A	-Teacher speaking to all children -Teacher facilitating large group discussion		1-2	Classroom Voice	65	1 speaker source, grid of punctual receivers
B	-Teacher facilitating small group discussion -Collaborative/shared learning supported by teacher when needed		4-6	Conversatio nal Voice	59	4 speaker sources, plane receiver at 1m height
C	-One-on-one instruction in low voice -Individual learning		0-1	Conversatio nal Voice	59	1 speaker source, plane receiver at 1m height
D	-Informal use of the space		6+	Conversatio nal Voice	59	8 speaker sources, grid of punctual receivers

3.4.3 Virtual Environment Demonstration

After detailing the 3D models on Autodesk Revit, they were linked to Autodesk 3DS Max and exported in .3ds format to allow the model import to I-Simpa. Before exporting, the models were globally de-scaled by 2.1%, as importing them to I-Simpa scaled the models incorrectly. The models were imported twice each, firstly to preserve the correct contour lines and surface material groups, and secondly to approximate the geometrical model with the default model remeshing settings. New user materials were then created in I-Simpa, using the absorption and diffusion spectrum values found above. The materials were then applied to the appropriate surfaces in each model, according to Table 3.4. Figure 3.4 details this step.

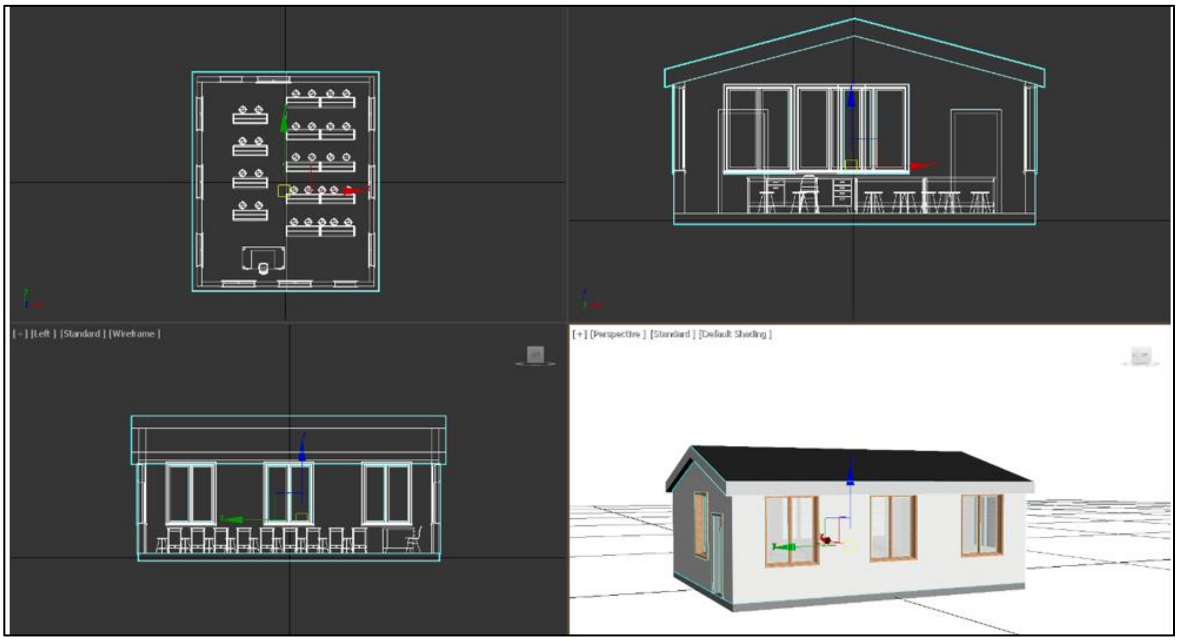


Figure 3.4. Classroom 5 linked to 3DS Max and rescaled for I-Simpa import from 3DSMax

The aural situations were then created by defining various sound sources (people speaking) and sound receivers (people listening). In accordance with Table 3.5, the sources had defined global Lw dB levels and space positions, and the receivers were created singularly in grids or as a plane, with a defined background noise level. To simulate the aural situations, the correct frequency bands were selected which match the user-defined material coefficient spectrums used in the model; 125, 250, 500, 1000, 2000, and 4000Hz. Two examples are shown in Figure 3.5. Classroom 5 has been imported into I-Simpa and aural situation A has been defined in the space. A grid of 5x6 receivers represent the students listening, and a point sound source with directivity in the YZ plane represents the teacher speaking. Classroom 2 is also displayed in Figure 3.5, demonstrating aural situation B in the 3D space. The students listening are represented by a plane receiver at 1m height in the XY plane. The teacher and students are speaking and represented by sound sources with unique vector directivities.

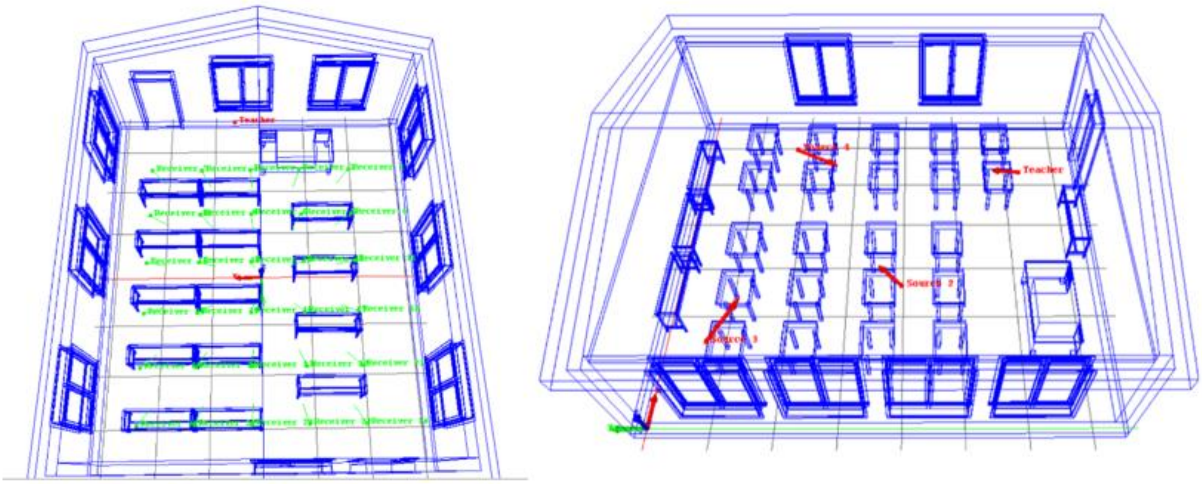


Figure 3.5. Left: Classroom 5 with Aural Situation A, showing the sound power of the teacher. Right: Classroom 2 with aural situation B (plane receiver not shown)

3.5 Discussion

In this paper, I-Simpa was used merely to demonstrate the final aural situation designs. In practise, the aural attributes of the virtual environments would prove to be an accurate software input software, however the 3D geometry input would not be. I-Simpa performs more efficiently and accurately with simplified geometries combined with precise absorption and diffusion coefficients for each geometry surface. Thus, in practise the 3D models should first be simplified to basic shapes before importing them to I-Simpa. Furthermore, interpolation should be used to obtain the coefficient spectrums for each simplified surface, to accurately represent the specific and unique distribution of objects and materials on that surface. Figure 3.6 illustrates this concept by transforming a wall made up of 3 materials with different coefficient spectrums, into a wall with one coefficient spectrum representing an equivalent proportion of the 3 combined materials. Nevertheless, the final physical classroom profiles are shown here in a detailed form for broad access and easier transferability into other architectural disciplines and simulation typologies.

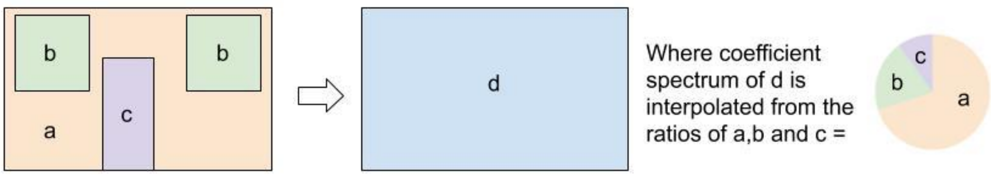


Figure 3.6. Simplification of 3D Model using interpolation for I-Simpa accuracy and efficiency

Many new classrooms in NZ are constructed as prefabricated, relocatable buildings (Dodd, Wilson, Valentine, Halstead, & McGunnigle, 2001). Unfortunately, they have received unwelcome attention due to numerous complaints from educators about the acoustic performance. The nature of discomforts for classrooms are all associated with an acoustic environment causing distress for speech or related cognitive tasks (Vilcekova et al., 2017). Students spend a significant portion of their time at school (Ministry of Education, 2019). These environments are critical to the development, growth and progression of our nation's youth, presenting a vital space where appropriate best practice acoustics should be applied. Concerningly, AS/NZS2107:200 has set out singular recommended acoustic parameters for classrooms, and this is just a compromise between the wide parameter ranges needed in classrooms (Standards New Zealand, 2016). Consequentially, there is little motivation for designers to optimise this within a range of values for different situations, leading to poor classroom acoustics. It is not appropriate to apply one acoustic condition to a dynamic space such as a classroom, as teaching approaches performed in classrooms are varied in nature. Advanced acoustic solutions are required in NZ classrooms, and one example - Intelligent acoustic technology - can now be tested using the environments designed in this paper.

Ghaffarianhoseini, AlWaer, Ghaffarianhoseini, et al. (2018) recently acknowledged the importance of intelligent technology, and how meaningful benefits for occupants and societies can arise from their integration in our built environment. It was suggested that these benefits and challenges should be continually explored and redefined. Simulations can be used to alleviate some of the challenges with designing and optimizing intelligent technology (Ali Ghaffarianhoseini et al., 2017a). Acoustic simulations present their own set of challenges. For example, incongruities exist in the field of acoustic simulation around the optimum level of detail for the simulated geometrical models. The level of detail is quantitatively defined by the number of surfaces in the model divided by the 3D volume. It is widely believed that model approximations with lower levels of detail achieve more accurate results, due to user compensation of assigning less realistic scattering coefficients to reflect actual measurements in a space (Shtrepi, 2019). Nevertheless, it stands true that highly detailed models with more realistic scattering coefficients can also achieve accurate simulation results (L. M. Wang, Rathsam, & Ryherd, 2004). This is because models with high detail levels experience lower sensitivity to scattering coefficient. Thus, the virtual environments in this paper were created using high levels of detail and realistic scattering coefficients, so when used for simulation the outputs are accurate.

3.6 Conclusion

A gap in literature exists in the development and demonstration of virtual NZ classroom environments. This paper aims to close this gap by using manipulated secondary data of physical and aural attributes, to develop 20 virtual classroom environments typical to NZ. Computer modelling simulations are commonly used when assessing building performance measures in support of the design process. Simulations can facilitate design optimization, provide feedback on building design, and increase understanding of an implemented model. Physical architectural environments comprise of many unique independent variables and unpredictable interactions between these multiple factors. Classrooms have received unwelcome attention due to numerous complaints from educators about acoustic performance. Rather than physically experimenting with new classroom technology, acoustic simulations can be deployed to save time, cut costs and reduce learning disruption.

To simulate the acoustic environments in this paper, a combination of both physical and aural data was required. Typical profiles comprising of data on physical and aural NZ classroom attributes have not been holistically detailed in past literature. This paper collated existing data to create and demonstrate a set of 5 classroom profiles. Thus, existing 'typical' NZ classroom types were investigated. Documentation exposing the physicality of different classrooms was then used to detail the 5 typical classroom profiles. Secondly, typical aural situations arising in classrooms was revealed in existing studies. Aural trend analysis was used to define 4 resulting situations to be used in the profiles, based largely on the number of people speaking and at which sound level. I-Simpa, Autodesk Revit and 3DSMax were then used for the final classroom virtual environments.

Simulating the real-time performance and evaluation of smart buildings is a prominent way to demonstrate the approximate building response and behaviour. As a novel and developing technology, intelligent acoustics would benefit largely from simulated environments, providing immense value in technological optimisation and validation. Intelligent Acoustics exhibits opportune application for use in classrooms, emphasizing the vast benefits of simulated classroom environments for manipulation and optimisation of intelligent acoustics.

This paper offers the development, detailing and demonstration of 20 NZ classrooms profiles which can be used for software simulation. Benefits are thus experienced by those who require typical classroom profiles for simulations in both industry and academic fields including but not limited to classroom architecture, classroom acoustics and acoustic optimization. Despite how this paper presents various physical and aural characteristics of *New Zealand* classrooms, this does not mean to say that classrooms in other countries would not see value in these demonstrations. Many classroom attributes could be very easily altered or transformed in some way to represent a variation of the classrooms seen here. Additionally, if the classroom profiles are used to simulate and test an architectural technology, by comparing the pre-test and post-test outputs, the statistical results would be accurate as they are presented in a relative context; the post-test data relative to the pre-test data. Thus, these profiles can be used universally, to quantify general technological effects in classrooms.

3.7 Conclusion to chapter

3.7.1 Original contribution and realization of aims and objectives

There have been 20 virtual New Zealand classroom environments developed (5 classroom types multiplied across with 4 aural situations) in this paper. There are two inputs necessary when simulating acoustics; software and a virtual environment. The virtual environment constitutes a variety of physical and acoustic attributes. The literature on virtual NZ classrooms including such attributes is lacking a holistic description. The purpose of this paper was to create virtual classroom environments by collating secondary data from existing studies. Initially, classroom types common to New Zealand were examined and explored. Various types of physical classroom documentation were analysed to show five typical classroom profiles. Secondly, four typical aural situations encountered in classrooms were defined based on existing research. Interpolation and mode analysis were used on the quantitative physical and aural data which was exposed in these investigations. Through these methods, the characteristics used in the final profiles were derived. The final classroom profiles are demonstrated using I-Simpa, a pre/post-processor for acoustic codes, and Autodesk Revit and 3DSMax. Using 3DSMax, you can create and export 3D-scene environments that can be imported into I-Simpa to create 3D aural environments. The profiles are designed for industry professionals and academics requiring 'typical' or 'normal' virtual classroom profiles. The use of these virtual classrooms is imagined to save preparation and simulation time for these professionals (Table 3.7).

Table 3.7. Manuscript 2 title, aim, objective and output(s)

Manuscript title	Manuscript aim	Objective	Output(s) or novel findings
(Manuscript 2) Developing virtual classroom environments for intelligent acoustic simulations Published in ASA conference	Establish a simulation method for testing IPRAT	Using secondary data, develop and detail 20 classroom environments ‘typical’ to New Zealand	20 classroom profiles are detailed and demonstrated using I-Simpa, a pre/post-processor for acoustic codes, and Autodesk software
		Establish a software method that can be used to simulate acoustic technology	

3.7.2 Differentiation of contribution from existing literature

It was necessary to combine physical and aural data for simulating the acoustic environments in this paper. A comprehensive description of NZ classroom attributes, including physical and aural information, has not been provided in published literature. To contribute to this field, this paper used existing data to develop and demonstrate a set of 20 classrooms. This included looking at existing 'typical' NZ classroom types. Research has been conducted on the physical characteristics of classrooms. Thus, the significant gap which was filled in this paper was defining classrooms for the use of virtual analysis. Details provided for a physical classroom will differ from those required for a simulation software. Simulation of real-time performance and evaluation of smart buildings is a prominent method of showing the approximate response and behaviour of the building. Since IPRAT is a novel technology, simulated environments would be of great value in ensuring the technology is optimized and validated. IPRAT has a robust application for classrooms, emphasizing the immense benefits of simulated classroom environments for manipulating and optimising intelligent acoustics. Thus, this paper provides value to academia, as indicated by existing literature (manuscript 1).

3.7.3 Final Considerations

There are many interacting variables in physical architectural environments. These multiple factors interact in unpredictable ways. The physics of the interactions must be simulated to understand and account for their effects on building performance. It is possible to predict the interaction between the building performance and integrated technology using simulations, which can also assist in the development of new technologies. For example, IPRAT, an emerging technology, is realized by integrating acoustic scene classification, a machine learning method, and passive variable acoustic technology. In its early stages, IPRAT would benefit significantly from simulated environments. The use of simulations can alleviate some of the challenges associated with designing and optimizing intelligent technology. Simulations of acoustic systems present their challenges. The concept of optimizing the geometrical model detail level for acoustic simulations, for example, is ambiguous. A model's level of detail is determined by the number of surfaces divided by the 3D volume. It is widely believed that model approximations that have a lower level of detail provide more accurate results because the user compensates by assigning less realistic scattering coefficients to reflect actual measurements in a space. However, it remains true that highly detailed models with realistic scattering coefficients can also yield accurate simulation results. Due to their high detail levels, models with high scattering coefficients are less sensitive. As a result, the virtual environments in this study were created using high levels of detail and realistic scattering coefficients, so when used for simulation, the results are accurate.

In the following chapter, Manuscript 3 is presented which details the data collection and analysis for the simulation study.

Chapter 4. The potential for intelligent passive room acoustic technology in classrooms: A BIM-based simulation

4.1 Prelude to Manuscript 3

The previous manuscript created and outlined 20 virtual NZ classroom environments. Using these environments, the proceeding manuscript conducts a BIM-based acoustic simulation for the first time using the novel intelligent passive room acoustic technology (IPRAT). IPRAT achieves real-time room acoustic improvement by integrating passive variable acoustic technology (PVAT) and acoustic scene classification (ASC). 20 classroom environments are accounted for and virtually configured for the study, multiplying 5 classrooms with 4 aural situations typical to New Zealand classrooms. I-Simpa acoustic software is used to perform the simulations, in which the acoustic parameters reverberation time (RT), sound clarity (C50) and sound strength (G) are analysed. The RT, C50 and G ranges achieved with IPRAT are presented, and to analyse the improvements offered by IPRAT, 'optimized' RT's were calculated for each aural situation, by manipulating C50 and G. This paper conducts a comparison of 'current,' 'achievable' and 'optimized' acoustic parameters. The thesis aim for determining the effects of IPRAT is contributed to in this manuscript, as the effect of IPRAT is simulated and statistically analysed. This reveals the potential benefits of IPRAT, and in the final manuscript, these benefits are further tested in a case study classroom. Thus, this paper is the first of two that objectively and successfully satisfy the research aim. As the first original research attempting to quantify the effect of IPRAT, this manuscript makes significant contributions to acoustic technology advancement, acoustic quality improvement, and smart acoustic control in buildings.

4.2 Introduction

Recently, intelligent passive room acoustic technology (IPRAT) has been conceptualized, achieving real-time room acoustic improvement (Figure 4.1). This achievement is realized through the integration of passive variable acoustic technology (PVAT) and acoustic scene classification (ASC) (Burfoot, Ghaffarianhoseini, et al., 2021). Functionally, ASC intelligently identifies changing aural situations, and PVAT physically varies the reverberation time (RT) using dynamic wall panels. The RT (time taken for a 60dB sound level decrease after a noise has stopped) is changed by altering the average sound absorption coefficient of the space. The wall panels achieve this varying sound absorption coefficient by using reflective and absorptive materials, and alter this parameter in real-time as they respond to the dynamic aural state of a space.

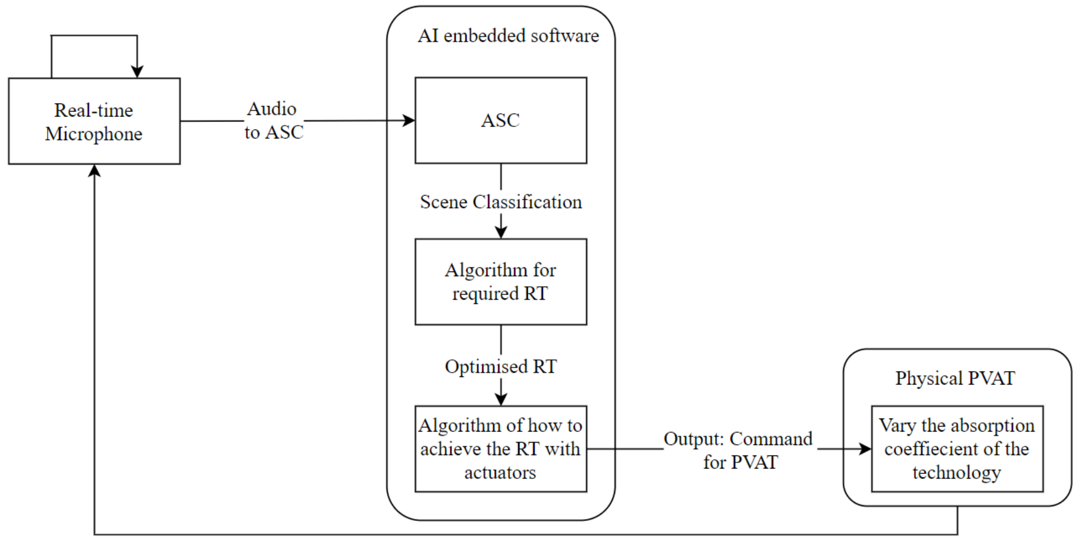


Figure 4.1. IPRAT functionality (Burfoot et al., 2021)

The inventors of IPRAT have proposed classrooms as an appropriate architectural space to improve RT, as better acoustic quality in classrooms correlates with higher academic performance (Benka-Coker et al., 2021). Additionally, background noise and/or long RT's contribute to poor listening conditions, impairing memory and learning (Ljung, Sörqvist, Kjellberg, & Green, 2009). In lecture or instruction situations, long RTs are needed to project and enhance the teacher's voice and reduce vocal strain. Alternatively, in a group or individual study situations, short RTs are needed to absorb noise and increase voice clarity. IPRAT can detect these changing aural situations, and vary the RT accordingly to improve room acoustics. Thus, the benefits are realised as reductions in teacher vocal disease and increases in student comprehension and cognition.

With the novel IPRAT, classrooms receive improved RTs for any aural situation happening in the space. But what is the ideal RT for each situation? When RT is varied, the sound clarity (C50) and strength are also affected. C50 is used to measure the clarity of speech objectively; how well you can understand speech due to sound arriving at different times and intensities to the ear canal. As sound strength (G)[dB] increases, C50 decreases. Additionally, a longer RT results in a larger G, and a lower C50. So, we must consider which values of RT, C50 and G will create the most favourable acoustic environment for each aural situation, accounting for the interdependencies between these parameters. A literature review of classroom acoustic parameters reveals better learning performance with RT values within the interval 0.4-0.9s, but most favourably at 0.6-0.7s (Minelli, Puglisi, & Astolfi, 2021). This, however, doesn't allow for changing RT's within the space. Unfortunately, the concept of optimising RT in real-time is in its infancy; there is no current literature outlining optimal values. In section 4, RT values are defined, which strategically maximise C50 or G for each classroom and aural situation, and a database for these values is created. By achieving appropriate acoustic parameters for changing aural situations, room acoustic quality is improved. In this sense, RT can be used to describe the behaviour of IPRAT, and C50 and G can be used to quantify the acoustic improvements.

IPRAT is a novel, emerging technology, and there is a need to quantify its effect on room acoustics. It is recommended to continually analyse and re-define the built environments effect on occupant wellbeing (Ghaffarianhoseini, AlWaer, Ghaffarianhoseini, et al., 2018), and this shouldn't neglect acoustic quality consideration (Ganesh, Sinha, Verma, & Dewangan, 2021). Thus, this research aims to discover the potential for IPRAT. Objectively, an acoustic simulation experiment is conducted and presented to measure the effect of IPRAT. 20 virtual environments have been considered in this research to test the IPRAT, by combining 5 classrooms with varying characteristics and 4 aural situations. The study focuses on values assumed by the acoustic parameters RT, C50 and G. These parameters allow the understanding of acoustic improvements for both teacher vocal relief and student comprehension. The IPRAT is assumed to vary RT and is represented in the simulation by 6 different absorption coefficient spectrums. For the purpose of this simulation, the panels achieve varying RT by rotating sound reflecting louvers in front of porous sound absorption panels. Thus, the 6 absorption coefficients are expressed as louver 'rotations' from 0-100% open. A comparison of 'current', 'achievable' and 'optimized' acoustic parameters reveals the benefits of IPRAT.

4.3 Background

4.3.1 Indoor environmental quality and acoustic comfort

When looking at spaces intended for cognitive functions, noise is one of the most studied Indoor Environmental Quality (IEQ) factors in relation to effects on occupants (C. Wang et al., 2021). Studies reveal acoustics as the majority factor for IEQ acceptance in university classrooms (M. C. Lee et al., 2012) and primary school classrooms (D. Zhang et al., 2019) (Bluyssen et al., 2020). Although great strides have been made in recent literature to improve the IEQ elements of indoor air quality, thermal and light comfort (Berquist et al., 2019) (Kallio et al., 2020) (Korsavi & Montazami, 2019) (Korsavi et al., 2020) (Z. Zhang et al., 2022), acoustic comfort research is trailing behind. Acoustic comfort is acknowledged in IEQ research, yet it is often neglected in the data collection and analysis stages or given less attention than other IEQ's. Furthermore, a space's 'Acoustical Quality' index considers room acoustics, vocal effort, acoustic satisfaction, and consequences of bad acoustics (Minelli et al., 2021). Many of the IEQ studies which do not neglect acoustics, do neglect the RT measurement in their assessment of acoustic comfort. Some choose to solely focus on outdoor noise pollution (Zuhaib et al., 2018) (Barrett, Davies, Zhang, & Barrett, 2015) or indoor sound level (Parkinson, Parkinson, & de Dear, 2019) (Wong, Mui, & Tsang, 2018) (Mydlarz et al., 2013) (W. Yang & Moon, 2019) (Wu, Wu, Sun, & Liu, 2020). Agreeably, Larsen et al. (2020) present an interesting criterion to assess the acoustic comfort in dwellings, made up by 'noise from surroundings 35%', 'noise from neighbouring dwellings 35%', 'noise from within the dwelling 25%' (of which 60% weighting is given to sound level and 40% to RT) and 'occupants possibilities' to adjust the acoustic IEQ 5%'. Although acoustic comfort encompasses all noise experienced in classrooms, IPRAT does not reduce noise pollution from outside the classroom, this should be considered in the envelope design. Nevertheless, in the case of classrooms using IPRAT, the RT can be optimised, and the occupants may adjust the acoustics to their preference.

4.3.2 BIM-based simulation for intelligent technology optimization

Another rising trend in the built environment is the use of BIM for building design and optimisation. Apart from the more commonly understood applications, BIM can simulate the performance of smart building technology, which literature proves should be incorporated into our built environment to maximise IEQ (Ghaffarianhoseini et al., 2019) (GhaffarianHoseini, 2013). For example, simulation optimization techniques have been used to improve the performance of Internet-of-Things networks (Kumar, Jain, & Yadav, 2020). The integration of BIM and smart building systems has also been used to maximize unique occupant thermal comfort (Birgonul, 2021), so, the same can be done for acoustic comfort. The time-savings associated with BIM adoption for technology optimisation have also been emphasized in literature (Doan et al., 2020), especially when utilised as a building element visualization and optimisation tool (Ali Ghaffarianhoseini et al., 2017b). Furthermore, simulations are especially appropriate now that lockdowns around the globe due to Covid-19 are hindering manufacturing progress and on-site research. There is a strong need to intelligently vary acoustic conditions in our modern, dynamic classroom spaces. Features of IPRAT such as sensors, real-time data monitoring and user control contribute to increasing the intelligence of a classroom (Ghansah, Owusu-Manu, Ayarkwa, Darko, & Edwards, 2020). In this study, a BIM-based simulation is used for design optimisation of the smart building element IPRAT. So, the BIM software I-Simpa is used to explore the relationship between IPRAT, room acoustics and IEQ.

4.3.3 I-Simpa simulation software

It is often beneficial to simulate the performance of the technology before developing a working prototype. In this case, we can see approximately how IPRAT will perform without having to build and train an acoustic scene classifier. The applied simulation tool for this study is I-Simpa, selected for its capabilities: custom design of various room layouts and geometries, custom aural situation simulation, surface absorption coefficient adjustments, building component modelling, and accurate measurement of RT, C50 and G. In a simulation study, it is challenging to verify experimental results without simultaneously conducting a real-life study of similar nature. Thus, it is beneficial to implement model verification and validation throughout the entire life cycle of a simulation study. Verification involves building the model right. However, validation involves building the right model (Hensen & Lamberts, 2019b). In recent literature, three acoustic modelling software were assessed by comparing modelled and measured RT data (Raymond, 2019). I-Simpa achieved modelled RTs lower than measured values in both of the simulations. However, the nature of this study involves a pre/post condition analysis, so inaccuracies experienced ‘pre’ treatment will equally exist ‘post’ treatment. Thus, I-Simpa software can still provide us with reliable comparative data as it is presented in a relative context. It cannot however be compared with relevant industry standards, as this would require the simulation values to be properly validated against measured data. The simulation method and process are outlined in Section 4.4.

4.4 Method

The benefits of IPRAT are realised when RT is uniquely improved for each classroom (1-5) and aural situation (A-D) combination. Thus, in each of the 20 virtual environment configurations, RT, C50 and G are measured firstly in the classrooms' current state and secondly when IPRAT is being used. I-Simpa acoustic software is used to conduct the simulations. However, the validation and verification of this software falls outside of the scope of research. To simulate the behaviour, performance, and benefits of IPRAT, a virtual representation of the technology is created and tested in the 20 virtual classroom environments. In this section, details on the simulation environment and processes are provided.

4.4.1 Classroom geometry and surface properties

The classroom profiles used in this study were originally received as detailed models from Burfoot, GhaffarianHoseini, Naismith, and GhaffarianHoseini (2020). These virtual environments were created based upon various physical environments described in existing New Zealand (NZ) studies, validated by comparison with international classroom profile studies. I-Simpa software prefers simplified geometries combined with precise absorption and diffusion coefficients for each surface. Thus, the detailed classroom models were simplified into basic shapes; a rectangular box within a larger classroom space (Figure 4.2). The walls are of negligible thickness, as I-Simpa only requires you to model the interior of a room. The small inside box represents the furniture and occupants (1m high, 2.5m from the front wall, 1m from all other perimeter walls).

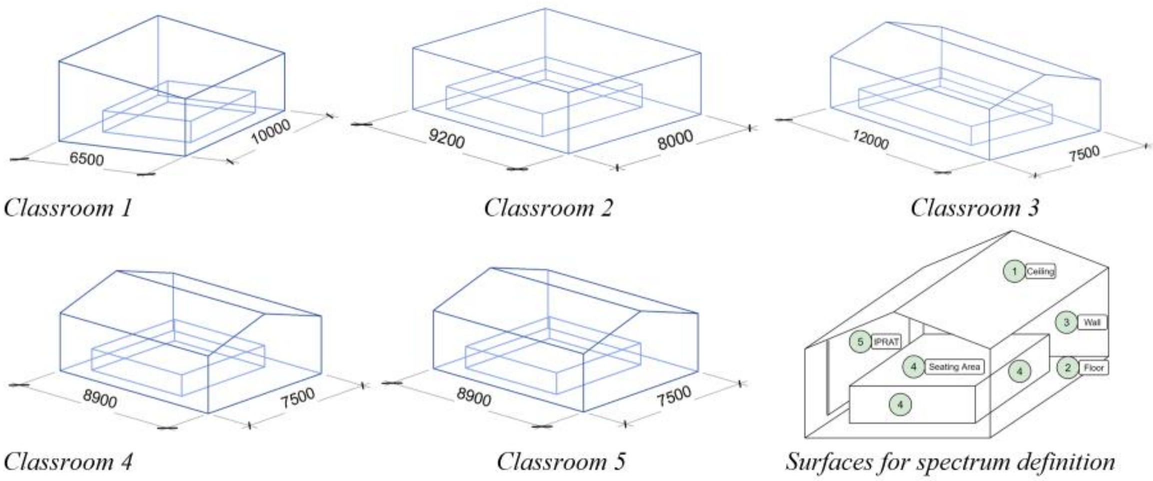


Figure 4.2. Simplified classroom geometries and surfaces

Through interpolation, the coefficient spectrums were obtained and applied to each simplified surface to accurately represent the unique distribution of objects and materials on that surface (Table 4.1). Also shown on this table are the surface characteristics for each classroom, based on the data from

Burfoot et al. (2020).

Table 4.1. Interpolated absorption and diffusion coefficient spectrums for each surface option

Surface	Spectrum Interpolation Requirements	Classroom characterised with this surface type	Interpolated Absorption Coefficient Spectrum (125, 250, 500, 1000, 2000, 4000, 8000Hz)	Interpolated Diffusion Coefficient Spectrum (125, 250, 500, 1000, 2000, 4000, 8000Hz)
1 - Ceiling	Acoustic Pinex Ceiling – no interpolation	2, 4	(0.27, 0.28, 0.36, 0.43, 0.39, 0.39, 0.45)	(0.06, 0.07, 0.1, 0.15, 0.15, 0.2)
	Gib ceiling - no interpolation	1, 3, 5	(0.12, 0.09, 0.09, 0.09, 0.08, 0.09, 0.13)	(0.03, 0.03, 0.02, 0.01, 0.01, 0.01)
2 - Floor	Thin carpet on concrete - no interpolation	1	(0.05, 0.1, 0.25, 0.3, 0.35, 0.4, -)	(0.06, 0.07, 0.1, 0.15, 0.15, 0.2)
	Thin carpet on timber - no interpolation	2, 3, 4, 5	(0.14, 0.19, 0.21, 0.24, 0.29, 0.33, 0.49)	(0.06, 0.07, 0.1, 0.15, 0.15, 0.2)
3 - Wall	Wall - Large Glazing - 63% Gib, 35% Glazing, 2% Wood	1, 3, 4	(0.201, 0.146, 0.121, 0.100, 0.076, 0.072)	(0.066, 0.045, 0.03, 0.028, 0.023, 0.023)
	Wall - Some Glazing - 73% Gib, 25% Glazing, 2% Wood	5	(0.178, 0.130, 0.113, 0.1, 0.077, 0.077)	(0.059, 0.043, 0.031, 0.025, 0.021, 0.021)
	Wall - Some/Little Glazing - 88% Gib, 10% Glazing, 2% Wood	2	(0.144, 0.106, 0.1, 0.093, 0.079, 0.084)	(0.048, 0.04, 0.028, 0.02, 0.012, 0.018)
4 – Seating Area	Seating Area – Concrete - 20% occupants, 45% furniture, 35% Thin carpet on concrete	1	(0.071, 0.099, 0.16, 0.172, 0.195, 0.222)	(0.415, 0.371, 0.339, 0.384, 0.358, 0.375)
	Seating Area – Timber - 20% occupants, 45% furniture, 35% Thin carpet on timber	2, 3, 4, 5	(0.10, 0.13, 0.14, 0.151, 0.174, 0.2)	(0.415, 0.371, 0.339, 0.384, 0.358, 0.375)
5 – IPRAT	Closed - 100% Wood		(0.15, 0.11, 0.09, 0.07, 0.06, 0.06)	(0.6, 0.45, 0.32, 0.38, 0.3, 0.3)
	20% Open		(0.18, 0.24, 0.3, 0.28, 0.26, 0.25)	(0.6, 0.45, 0.32, 0.38, 0.3, 0.3)
	40% Open		(0.21, 0.37, 0.49, 0.48, 0.46, 0.44)	(0.6, 0.45, 0.32, 0.38, 0.3, 0.3)
	60% Open		(0.24, 0.49, 0.7, 0.69, 0.65, 0.62)	(0.6, 0.45, 0.32, 0.38, 0.3, 0.3)
	80% Open		(0.27, 0.62, 0.9, 0.89, 0.85, 0.8)	(0.6, 0.45, 0.32, 0.38, 0.3, 0.3)
	Open - 99% Autex Quietspace		(0.3, 0.75, 1.1, 1.1, 1.05, 1)	(0.6, 0.45, 0.32, 0.38, 0.3, 0.3)

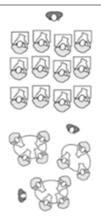
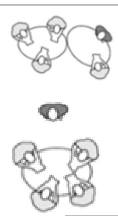
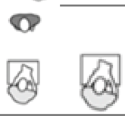
4.4.2 Representing the IPRAT

When IPRAT is not in use, all 4 walls for each classroom are considered as ‘Surface 3 – Wall’. When IPRAT is in use, 2 walls for each classroom are applied with ‘Surface 5 – IPRAT’ (the back wall and right-hand or half of the right-hand wall), and the remaining 2 walls stay as ‘Surface 3 – Wall’. For these simulations, the PVAT component of IPRAT is conceptualized as hard reflective louvers which rotate open and closed to cover or reveal a porous sound absorption material behind. When the louvers are rotated closed, the sounds waves reflect off the hard surface to increase RT. When the louvers are rotated open, the sound passes through and is absorbed by the panel behind, to decrease RT. The IPRAT is represented by spectrum coefficient interpolated in increments of 20% from closed (spectrum for ‘wood’ used) and open (spectrum for ‘Autex 50mm Quietspace Panel’ used). For the diffusion coefficient, the spectrum for ‘furniture’ is used for all rotations. Inaccuracies from this constant diffusion coefficient are minimized because, as the IPRAT rotates from ‘closed’ to ‘open,’ more surface is acting as an absorber, and sound that is absorbed is not diffused. The simulations assume that when the louvers are rotated open, 99% of the sound waves pass through to the absorption panel. In reality, the actual percentage would depend on the width and thickness of the louvers, and should be scientifically tested.

4.4.3 I-Simpa acoustic simulation

To streamline the simulation process, a blank template project was set up in I-Simpa, which included all surface materials, sound sources, and receivers. This template was then adjusted and used for each simulation, by 'enabling' the Aural Situation applicable once the 3D model was imported into the template. The surface materials were grouped into specific categories for easy application. The 4 aural situations were sourced from Burfoot et al. (2020) (Table 4.2), which are based on teaching styles typical to NZ, identified by Bradbeer et al. (2017). Within the template, the aural situations contained the number of speakers and at what sound level, but not their position in space.

Table 4.2. Aural situations used in the simulation

Aural Situation	NZ Teaching Approach	Representation	People speaking	Voice intensity	dB	I-Simpa Approach
A	**-Teacher speaking to all children -Teacher facilitating large group discussion**		**1-2**	**Classroom Voice**	**65**	**1 omni-directional speaker source, grid of punctual receivers**
B	**-Teacher facilitating small group discussion -Collaborative/shared learning supported by teacher when needed**		**4-6**	**Conversational Voice**	**59**	**4 omni-directional speaker sources, plane receiver at 1m height**
C	**-One-on-one instruction in low voice -Individual learning**		**0-1**	**Conversational Voice**	**59**	**1 omni-directional speaker source, plane receiver at 1m height**
D	**-Informal use of the space**		**6+**	**Conversational Voice**	**59**	**8 omni-directional speaker sources, grid of punctual receivers**

For this study, 5 receivers have been used in 4 aural situations, so 20 combinations have been used per classroom, allowing for accurate sound measurements (Arvidsson, Nilsson, Hagberg, & Karlsson, 2020). Several additional steps were taken before the calculation; the type of spectrum for sound sources was defined as bluit blanc (white noise - background noise type). The 'animation – meshing' tool was used to create a geometrical mesh, the particle theory property was changed to 'energetic,' and the calculation theory was changed to SSPS which involved defining the spectrums used in the simulation under the SPSS calculation properties. From the simulations, numerical data was extracted for each of the 20 configurations; global RT30, global C50 and global G. Global values were extracted, as acoustic parameters can be inaccurate at extremes of the room, and can be compared against other studies and standards which use global values. Lastly, 'calculate for each frequency spectrum' was unchecked to cut down calculation time. The simulation was then executed by a separate command to the software *(Enable SPSS calculation theory: Double click 'SPSS' under calculation and define the spectrums used. Right click 'calculation,' select 'run calculation.' Right click 'global sound levels,' select 'calculate acoustic parameters'. Double click 'acoustic parameters'* *for the results).* This brings up a spreadsheet with the parameter values at each frequency band, global and average, which can be exported to an analysis software.

4.5 Results and discussion

4.5.1 Current acoustic state of classrooms and acoustic parameter range possible with IPRAT

Following are the descriptive results of the acoustic parameters RT, C50 and G achieved with and without IPRAT for the twenty experimental conditions. This section firstly illustrates the current acoustic state of each classroom whilst not using IPRAT (Figure 4.3), and secondly, the acoustic range achieved when using IPRAT for all rotation states from 'open' to closed' (Figure 4.4). The range achieved for each classroom using IPRAT is calculated, and mean range values are derived for each acoustic parameter. This range is then directly graphed alongside the current acoustic state to demonstrate the possibilities of IPRAT (Figure 4.5).

Figure 4.3 shows the mean simulation results for RT, C50 and G for the 20 virtual environment configurations in their current state whilst not using IPRAT. Classroom 4 has the highest RT in its current state, and classroom 5 has the lowest. Classrooms 2 and 4 achieve the highest C50, and accordingly, the lowest G values. This could be explained by these being the two classrooms with acoustic ceiling tiles for Surface Type 1. This figure also reveals that C50 is lowest during aural situation A for all classrooms. However, the G does not vary significantly between the aural situations.

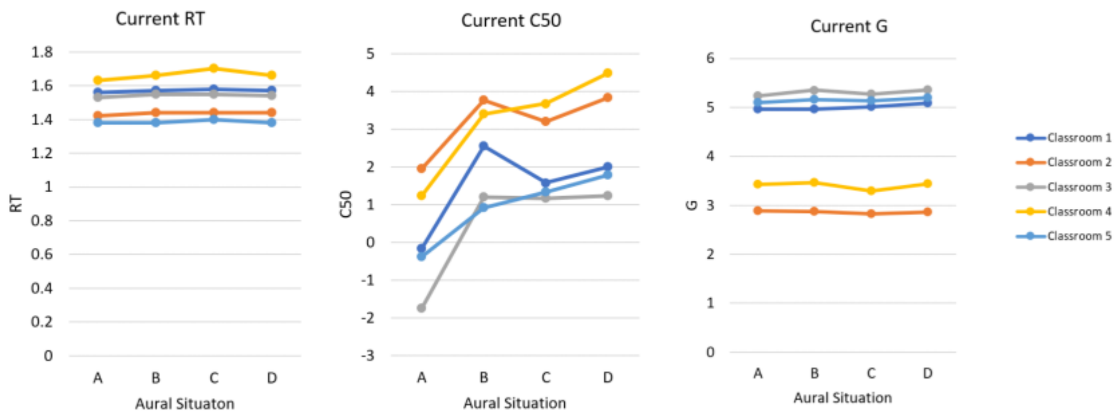


Figure 4.3. Current acoustic state of classrooms (not using IPRAT)

Figure 4.4 illustrates the RT range achievable whilst using IPRAT at various settings from 'Open' to 'Closed,' based on the simulation outputs in each classroom. Derived from these graphs, a summary of the ranges achievable for each classroom using IPRAT is provided in Table 4.3. The range was calculated by finding the difference between the value achieved when IPRAT is 'open,' and when IPRAT is 'closed.' For example, classroom 2 achieves a maximum RT of 0.80s when IPRAT is 'closed', and a minimum RT of 0.43s when IPRAT is 'open.' Thus, the RT range for classroom 2 is 0.80s – 0.43s = 0.37s.

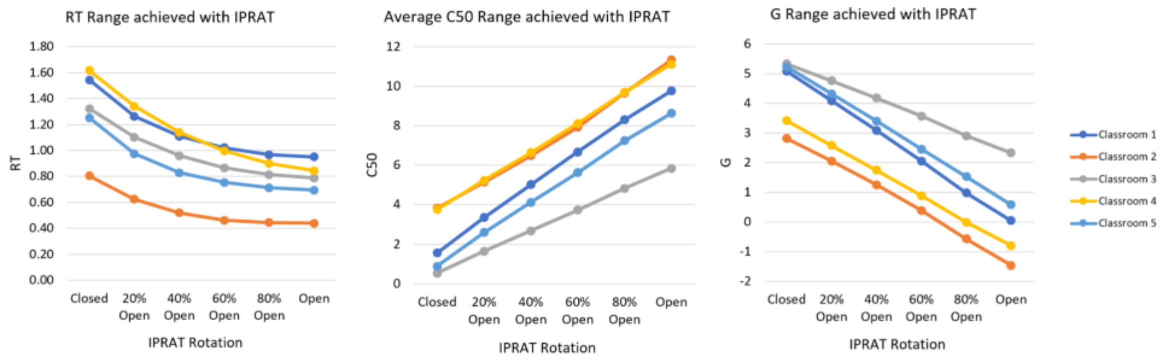


Figure 4.4. Acoustic parameter range achieved when using IPRAT

Table 4.3. Acoustic parameter mean ranges achieved when using IPRAT, derived from Figure 4

Classroom	Mean RT range (s)	Mean C50 Range (dB)	Mean G Range (dB)
1	0.60	8.21	5.04
2	0.37	7.50	4.29
3	0.54	5.31	3.01
4	0.77	7.36	4.22
5	0.56	7.74	4.66
Mean	**0.57**	**7.22**	**4.24**

The mean can be used to segregate the sorted samples into statistically significant and statistically insignificant (if any) groups (Mbachu, Egbelakin, Rasheed, & Shahzad, 2017). Classroom 4 achieves the most extensive RT range at 0.77s, whilst classroom 2 achieved the smallest RT range at 0.37s. Classroom 4 had the highest current RT, which could explain why it achieved the largest potential improvement. Classroom 2 was the only subject with a flat roof, and had the lowest sound strength in its current state. The largest C50 and G ranges are achieved by classroom 1, which could be due to the carpet-covered concrete floor characteristic or the smallest dimensions. The smallest C50 and G ranges were achieved by classroom 3, which had the longest dimensions of the rooms. All classrooms could further increase these ranges by having more extensive IPRAT wall coverage. Likewise, the achievable ranges would be decreased by reducing the IPRAT coverage.

Thirdly, in Figure 4.5 the range achieved with IPRAT (from Figure 4.4) and the current mean parameter values (from Figure 4.3) are indicated for each classroom. This demonstrates the existing acoustic state against the potential acoustic states attainable with IPRAT. This figure shows the potential improvements in RT, C50 and G whilst using IPRAT. In the next section, the optimal IPRAT rotation is calculated based on these achievable ranges.

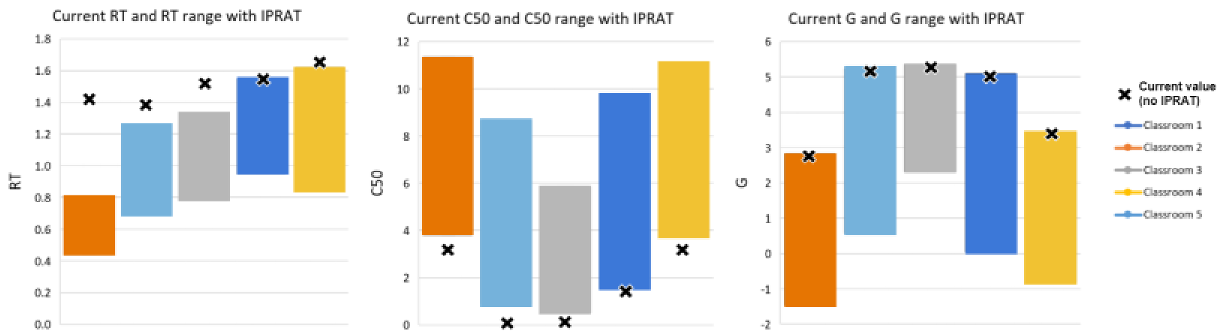


Figure 4.5. The current mean acoustic state of classrooms (not using IPRAT) indicated against acoustic parameter range attainable when using IPRAT

4.5.2 Optimal IPRAT rotation (and acoustic parameters) for each aural situation

The acoustic quality in an educational or highly cognitive space can be determined by how clearly the occupants understand the speech that is meant for them. Thus, a certain RT is defined for each virtual configuration, which optimises C50 and G within the ranges achieved with IPRAT. In quiet study situations - aural situation C and D - C50 is important, so we should minimise G (to do this, we minimise RT by rotating IPRAT 'open'). In lecture situations - aural situation A - G should be maximised to offer vocal relief to teachers (to do this, we maximise RT by rotating IPRAT 'closed'). In group working situations - aural situation B - both C50 and G are important in varying amounts; each teacher and class type will have their preferences. For these improvements, IPRAT should be rotated to some state between 'open' and 'closed.' First, the relationship between RT, C50 and G was derived from the trendlines in Figure 4.4 for each classroom. Table 4.4 shows these relationship equations. The relationships are expressed as equations in x, where the x-axis represents the IPRAT rotation.

Table 4.4. Relationship equations for Aural Situation B, where optimal IPRAT rotation = x

Classroom	C50 (dB)	G (dB)	RT (s)
1	$C50 = 1.67x + 1.04$	$G = 6.07 – 1.01x$	$RT = 0.03x^2 - 0.32x + 1.83$
2	$C50 = 1.56x + 2.64$	$G = 3.80 – 0.89x$	$RT = 0.02x^2 – 0.22x + 0.99$
3	$C50 = 1.09x + 0.22$	$G = 6.02 – 0.60x$	$RT = 0.03x^2 - 0.32x + 1.83$
4	$C50 = 1.5x + 2.32$	$G = 4.31 – 0.85x$	$RT = 0.02x^2 – 0.32x + 1.89$
5	$C50 = 1.58x – 1.43$	$G = 6.21 – 0.95x$	$RT = 0.03x^2 – 0.33x + 1.53$

Note: Aural situation A optimal rotation = 'closed'. Aural situation C and D optimal rotation = 'open'.

Next, a simplified method was adopted where C50 was optimised at 5.0dB, x was calculated, and with this x value, the corresponding G and RT could be determined. The equations were derived from trendlines between exact data points on Microsoft excel software with an accuracy (R^2) of 0.99 or above. Figure 4.6 reveals these optimised RT, C50 and G values achieved with IPRAT for each aural situation.

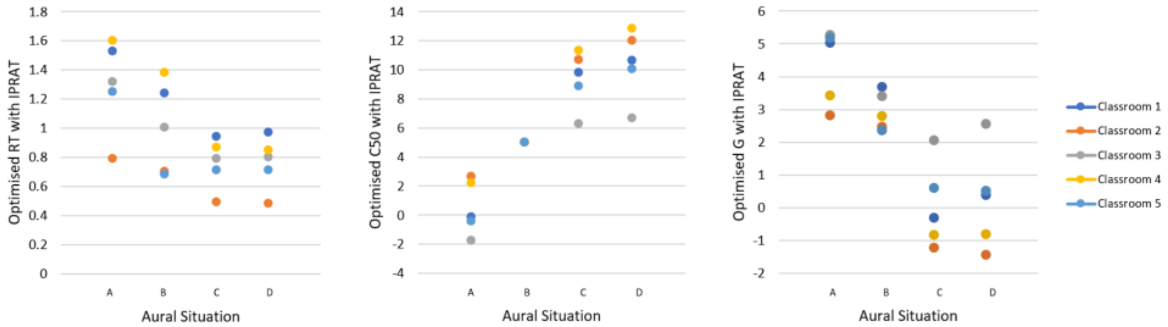


Figure 4.6. Optimised acoustic parameters for each classroom and aural situation combination

It is recognised that if the technology were deployed in a live classroom, each teacher and class type would have individual preferences to trial with between 'open' and 'closed' for group working situations. Thus, this is not an exact science, but values have been selected here to demonstrate the options available for these virtual configurations. It is also acknowledged that there will be aural situations that fit between the 4 situations described in this study in a live classroom. For any of these 'in between' states, teachers and students can again experiment with a rotation that works best for them.

It is widely believed that model calibration can improve the validity of simulation results. Unfortunately, it is difficult to calibrate models to correctly account for input parameter uncertainty or inaccuracy (Hong, Langevin, & Sun, 2018), and I-Simpa relies upon numerous input parameters. Model calibration can be done manually or automatically, but I-Simpa does not have a function for automated calibration. Furthermore, manually calibrating the models in our simulations cannot be done due to the scarcity of I-Simpa simulation data previously compared to real acoustic measurements. Thus, it is not beneficial or advisable to attempt model calibration at this early stage in I-Simpa literature. This study, however, has the potential to provide future research simulations with a base for model calibration.

4.5.3 The potential for IPRAT

The mean difference for each acoustic parameter from current to optimised state is shown in Table 4.5, for each classroom variable and each aural situation variable. Figure 4.7 illustrates these current acoustic parameters for each classroom, compared with optimised values, demonstrating the improvements achieved with IPRAT for each aural situation. Visually, we can see the reductions in RT and G achieved with IPRAT, and the increase in C50. Aural situation A maximised RT to optimise the acoustic state, which meant these values are the closest to the current acoustic states of the classrooms without IPRAT.

Table 4.5. Mean improvements achieved with IPRAT (difference between 'current' and 'optimized' values)

	Mean Difference						
Classroom	**RT**	**C50**	**G**	**Aural Situation**	**RT**	**C50**	**G**

1	-0.40	4.85	-2.81	**A**	-0.21	0.34	0.01
2	-0.82	4.40	-2.22	**B**	-0.52	2.64	-1.43
3	-0.56	3.58	-1.99	**C**	-0.77	7.20	-4.25
4	-0.49	4.64	-2.27	**D**	-0.76	7.77	-4.16
5	-0.55	4.97	-2.99				
Overall Mean Difference	**-0.56**	**4.49**	**-2.46**				

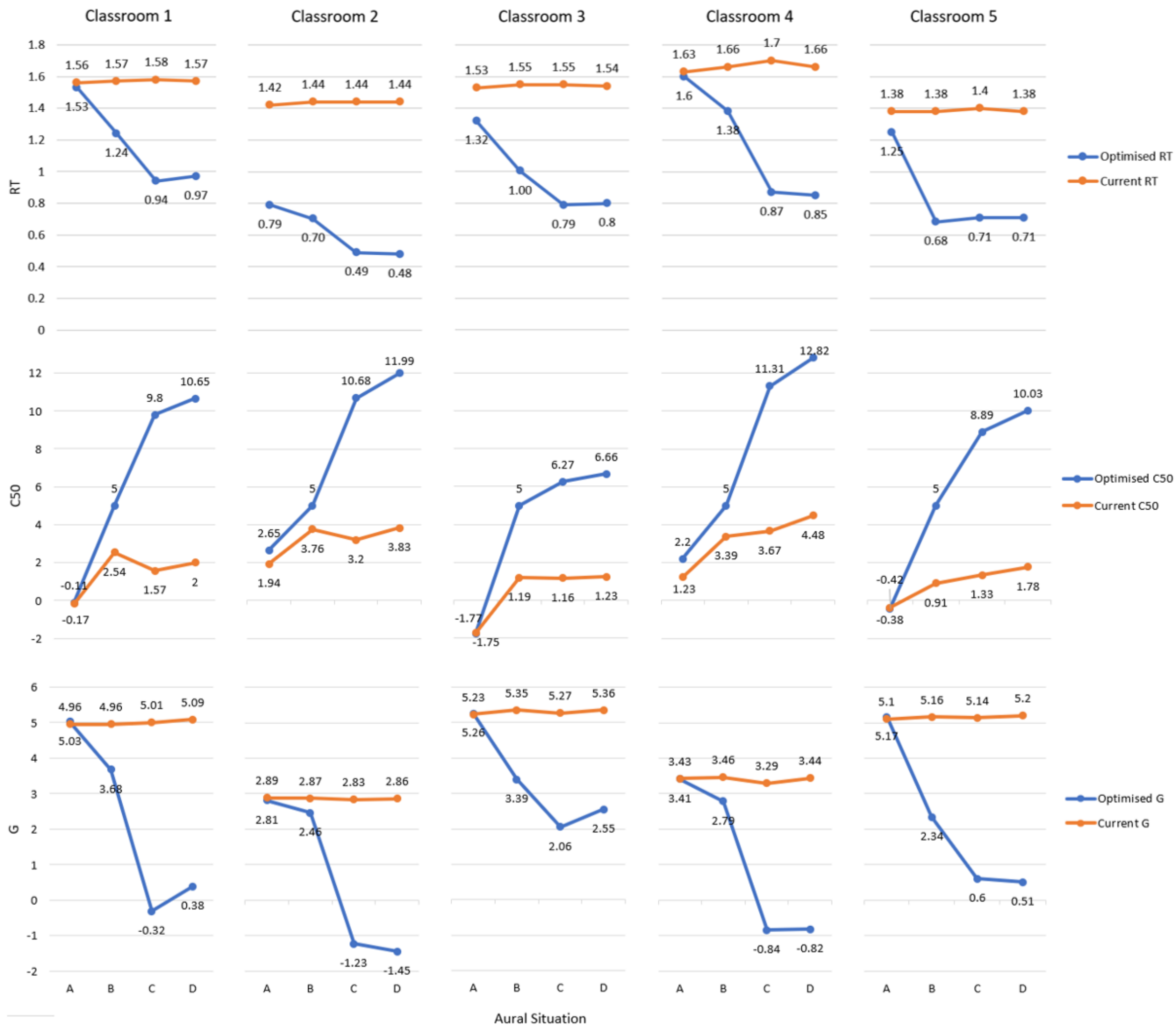


Figure 4.7. Current (no IPRAT) vs. optimised (with IPRAT). Top: RT. Middle: C50. Bottom: G.

The data were analysed using IBM SPSS software (version 27; SPSS Inc., New York, NY). Using the Shapiro-Wilk method, the data sets for RT ($p=.11$ before and $p=.16$ after) and C50 ($p=.53$ before and $p=.28$ after) were found to be normally distributed. Thus, a pairs sample t-test was conducted to evaluate the impact of IPRAT on RT and C50. The results showed a significant decrease in RT before ($M=1.52$, $SD = 0.10$) to after ($M = 0.96$, $SD = 0.33$), $t(19) = 8.65$, $p<.001$ (two-tailed). The mean decrease in RT was 0.56 seconds with a 95% confidence interval ranging from 0.43 to 0.70. The Cohen's d statistic (1.94) indicated a very large effect size (Cohen, 2013). Secondly, the results showed a significant increase in C50 before ($M=1.85$, $SD = 1.58$) to after ($M = 6.33$, $SD = 4.36$), $t(19) = 5.98$, $p<.001$ (two-tailed). The mean increase in C50 was 4.49dB with a 95% confidence interval ranging from -6.06 to -2.92. The Cohen's d statistic (-1.34) indicated a very large effect size. The data for G ($p=.00$ before and $p=.20$ after) was not found to be normally distributed. Thus, a related-samples

Wilcoxon signed-rank test was conducted to evaluate the impact of IPRAT on G. The results showed a significant decrease in G before (M = 4.35, SD = 1.04) to after (M = 1.89, SD = 2.16), Z = -3.58, p<.001. The mean decrease in G was 2.46dB.

4.6 Conclusion

In this research, the improvements achieved by IPRAT are obtained by comparing current, achievable and optimal values for each acoustic parameter RT, C50 and G. Results highlight that acoustic improvements using IPRAT in classrooms is promising. For example, when using IPRAT, in group discussions and quiet study where the sound should be absorbed, the RT can be reduced to as low as 0.49 seconds. In the same classroom, the RT can be increased to as high as 0.79 seconds for a lecture where a teacher needs to project their voice. This range of 0.3 seconds allows for improved acoustic conditions in the same classroom space, for changing aural situations. The most extensive RT range achieved using IPRAT was 0.75 seconds – which could significantly increase student comprehension while reducing teacher vocal strain.

When comparing the current (no IPRAT) versus optimal (using IPRAT) acoustic values, the following improvements are attained: a mean RT reduction of 0.56 seconds, a mean C50 increase of 4.49dB and a mean G decrease of 2.46dB. This is based on the assumption that the PVAT can achieve a varying absorption coefficient, and that the ASC can correctly categorise each aural situation in a classroom. The nature of this data involves a pre/post condition comparison, so inaccuracies experienced from the BIM-based software have little effect on the relative comparative results. As an extended contribution of this paper, a detailed account of the BIM-based acoustic simulation method using I-Simpa is provided. I-Simpa is an open-source software with a shortage of precedents, detailed methods and software validation in literature. Thus, the method can be used by academics looking to perform similar acoustic simulations involving classroom spaces, aural situations, or initial technology validation.

This study is the first of its kind to explore the potential for IPRAT. To further advance the literature, a physical prototype should be developed and tested in a chamber or closed room. The behaviour of PVAT should be evaluated by measuring various acoustic parameters in a space. Furthermore, research for this novel technology should not be limited to classroom spaces. Benefits will be realised in any flexible, dynamic or multi-use architectural space in the built environment, especially in smart environments where human comfort is prioritized (Amirhosein Ghaffarianhoseini et al., 2017). Lastly, although the study considers classroom environments typical to New Zealand, the contributions can be helpful for professionals in other parts of the world, also looking to improve classroom acoustics using smart technology. Additionally, the BIM method explained for this research can be followed regardless of geographical considerations. This stands true as long as the appropriate alterations have been made to the classroom characteristics and aural situations, as the effect of IPRAT is unique for each classroom geometry and aural situation.

4.7 Conclusion to chapter

4.7.1 Original contribution and realization of aims and objectives

It is important to continuously analyze and re-define the built environment's effect on occupant wellbeing, and acoustic quality shouldn't be overlooked. The new technology, IPRAT, has the potential to revolutionize room acoustics. Thus, it is necessary to analyze and quantify its effect. This paper aimed to discover the potential for IPRAT. Specifically, this research examined the effect of IPRAT using acoustic simulation, where 20 virtual environments were simulated by combining 5 classrooms with varying characteristics and 4 acoustic scenes. RT, C50, and G were the acoustic parameters considered in this study. These parameters can be used to determine the effects of improved acoustics for both teacher vocal relief and student comprehension. The IPRAT was assumed to vary RT and was represented in the simulation by six different absorption coefficient spectrums. The simulation was conducted in I-Simpa and the method for this simulation was detailed to provide a novel research output. In this simulation, sound reflecting louvers were rotated in front of porous sound absorption panels to control RT. Therefore, the six absorption coefficients were expressed as louver rotations from 0-100% open. The optimised acoustic parameters were derived from relationships between C50, RT and G. These relationships and optimal RT's contribute a unique database to literature. IPRAT's advantages were discerned – for the first time - from a comparison of "current," "attainable," and "optimized" acoustic parameters. In this way, the effects of IPRAT are quantified, providing a valuable contribution to academia (Table 4.6).

Table 4.6. Manuscript 3 title, aim, objective and output(s)

Manuscript title	Manuscript aim	Objective	Output(s) or novel findings
(Manuscript 3) The potential for intelligent passive room acoustic technology in classrooms: A BIM-based simulation Published in CONVR conference	Determine the effect of IPRAT on acoustic comfort using simulation	Simulate IPRAT in 20 aural environments, statistically analysing the effect of IPRAT on RT, C50 and G	An acoustic simulation method in I-Simpa software is presented for initial technology validation
			The quantified improvements of IPRAT on acoustic parameters RT, C50 and G is presented
			A database of RTs which improve acoustic quality for 4 aural situations typical to classrooms is provided

4.7.2 Differentiation of contribution from existing literature

In the existing literature, intelligent passive room acoustic technology (IPRAT) has been conceptualised, achieving real-time room acoustic improvement. By integrating passive variable acoustic technology (PVAT) with acoustic scene classification (ASC), a breakthrough is achieved. Using dynamic wall panels, ASC intelligently identifies changing acoustic situations, while PVAT physically varies reverberation time. Furthermore, another piece of existing literature details a set of virtual classroom environments. This paper takes the concept of IPRAT from manuscript 1, and the environments and methods described in manuscript 2. For the first time, IPRAT is simulated, and the technologies' benefits are quantified. The use of variable acoustic technology has been simulated in the past, but never intelligent technology. Likewise, simulations of pre and post-acoustic treatment have been performed using passive acoustic panels, but never with IPRAT. Existing literature has described studies that use I-Simpa to conduct acoustic simulations. However, this literature has never provided a detailed account of the method, set up, process and resulting outputs. Manuscripts 2 and 3 differentiate themselves against other studies using I-Sipma, in the level of detail provided to replicate the simulations.

4.7.3 Final Considerations

Using IPRAT, classrooms receive improved RTs for any aural situation taking place in the space. But which RT is the best for different scenarios? Variations in RT also alter the clarity (C50) and strength of the sound. C50 measures speech clarity objectively. It measures how understanding speech is affected by the arrival time and intensity of sound in the ear canal. The C50 decreases as the sound strength (G)[dB] increases. In addition, a longer RT leads to a larger G, as well as a lower C50. Thus, we need to consider what values of RT, C50, and G will create the most favorable acoustic environment for each aural situation, taking into account their interdependences. According to a literature review of classroom acoustic parameters, students learn better at RT values between 0.4 and 0.9s, but most favorably between 0.6 and 0.7s. These findings do not encourage RT's to be changed within the classroom. Optimisation of RT in real-time is a relatively new concept; there is no current literature outlining optimal values. Using the simulation results in this study, a database for RT's which strategically maximise C50 and G was created. C50 is important in quiet study situations, so we should minimize G in aural situations C and D (to minimize RT, the researchers rotate IPRAT 'open'). G should be maximised in lecture situations - aural situation A - to offer vocal relief to teachers (to do this, RT is maximised by rotating IPRAT ‘closed’). When working in a group setting - aural situation B - both C50 and G are important in varying degrees; every teacher and class type will have their preferences. The IPRAT should be rotated to a state between 'open' and 'closed' to achieve these improvements. First, the relationship between RT, C50 and G was derived from the simulation results. Then, C50 was optimized at 5.0dB, x was calculated, and with this value G and RT were calculated. This completed the database for each aural situation, albeit simplified, to provide a comparison between actual, achievable and optimal acoustic states. In reality, the variation of states achieved with IPRAT would be individually optimised for each space and its occupants.

In the following chapter, Manuscript 4 is presented which details the case study.

Chapter 5. Intelligent Passive Room Acoustic Technology in Classrooms: A Pilot Case Study

5.1 Prelude to Manuscript 4

The previous manuscript outlined an acoustic simulation method in I-Simpa software for initial technology validation. Using this method, IPRAT was simulated for the first time in 20 aural environments. A database of RTs which improve acoustic quality for 4 aural situations typical to classrooms was created, and the RT, C50 and G ranges achieved with IPRAT in classrooms were determined. Thus, the quantified improvements of IPRAT on acoustic parameters RT, C50 and G were analysed. After confirming the benefits of IPRAT using simulations, the next step was to build and test a prototype in a case study classroom. The following manuscript thus details a pilot case study that works toward quantifying the benefits of IPRAT. To quickly recap: Intelligent Passive Room Acoustic Technology (IPRAT) is a novel architectural device, used in buildings to automatically vary the acoustic conditions of a space. IPRAT is realised by integrating two components: Passive Variable Acoustic Technology (PVAT) and an intelligent system. The PVAT passively alters the room's Reverberation Time (RT) by changing the total sound absorption in a room, and the *intelligent system* detects sound waves in real-time to identify the optimal RT. This case study analyses the benefits of IPRAT by prototyping and testing the PVAT component of the system. The study is conducted in an existing tertiary classroom located at Auckland University of Technology, in New Zealand (NZ). The PVAT is prototyped, and the RTs are measured according to international standards before and after classroom installation. The acoustic measurement method used is a cost-effective prototyping tool, good for where pre and post conditions are of primary concern. This paper contributes to the research aim as IPRAT offers statistically significant improvements in RT. Still, the key benefits are realized in its' ability to vary RT for different classroom situations. The RT recommendations for two room types outlined in the NZ acoustic standards are satisfied when using IPRAT in a single classroom space. By optimally varying RT, the acoustic comfort during both classroom study and classroom lecture is significantly improved. The improvements in acoustic comfort due to IPRAT are statistically significant. The combination of manuscripts 3 and 4 objectively satisfies the overall thesis aim, by testing and quantifying the benefits of IPRAT.

5.2 Introduction

Reverberation Time (RT) - the time taken for sound in a room to decrease by 60dB in seconds (International Organization for Standardization, 2009) – can be altered by adjusting the physical variables of a space; volume, geometry, diffusion coefficient, or sound absorption coefficient. Intelligent Passive Room Acoustic Technology (IPRAT) is a novel architectural device, allowing buildings to automatically vary the acoustic conditions of a space. IPRAT is realized by integrating two components: *Passive Variable Acoustic Technology (PVAT)* and an *intelligent system*. *PVAT* passively alters the room acoustics by changing the total sound absorption in a room (Esmebasi et al., 2017). In doing so, the RT is changed and thus the sound strength and clarity are altered. The *intelligent system* detects sound waves in real-time to identify the acoustic situation, and the RT is adjusted accordingly based on pre-programmed algorithms. IPRAT - the synthesis of these two components can dramatically improve acoustic comfort, as RT is automatically optimized for any detected aural situation.

Varied RT's are rarely adopted in rooms, as acoustic standards recommend only one acoustic state, depending on the type of room and the cubic volume (International Organization for Standardization, 2009). However, it is becoming increasingly understood that to maximize acoustic comfort in a classroom, the acoustic conditions of the space should be variable. So, when the classroom changes from a study environment into a lecture environment, the optimal acoustic state also changes. Assuming this, maximizing acoustic comfort in these spaces requires variable acoustics. For this study, two room types are of interest - outlined in the NZS Acoustic Standards - 'Rooms for Speech' and 'Speech/Lecture' (Standards New Zealand, 2016). The recommended RT for 'Speech/Lecture' is slightly longer than that for 'Rooms for Speech'. Giving a classroom one 'trade-off' RT will therefore sacrifice the benefits of achieving either or both optimal RT's. With a variable RT, it is possible to optimize the RT in both a classroom study situation and a lecture situation. In this paper, the resulting RT's achieved with the IPRAT prototype can be benchmarked against these two recommended RT's to see how the acoustic conditions are improved.

5.2.1 Background Literature

IPRAT was first conceptualized by Burfoot, Ghaffarianhoseini, et al. (2021). The intelligent technology was found to be an appropriate progression from past literature, as PVAT was gradually becoming more intelligent to reach an optimal RT. Previous to IPRAT, the most advanced PVAT comprised of a system that would measure or estimate the RT in a room, and adjust the sound absorption in the space according to pre-programmed RT databases for the building use. IPRAT advances this technology as it can detect the RT *and* classify the aural situation – to determine how the building is being used – and automatically optimize the RT to suit. It is recommended that IPRAT be used in classrooms, as these spaces constantly require changing RT's to optimize acoustic comfort. When a teacher is delivering a lecture, a long RT will aid in projecting the teacher's voice. This has the benefit of reducing teacher vocal disease and increasing student comprehension. Alternatively, when students are working individually or in groups, a short RT will reduce noise and aural distractions in the space to help with student concentration.

After the proclamation of IPRAT in 2019, 2 relevant studies have been published to further its development. Firstly, a method is documented to simulate the potential acoustic benefits of IPRAT (Burfoot et al., 2020). The study gathers existing documents to create a set of virtual classrooms environments, outlining the physicality and acoustic situations typical of 20 types of New Zealand classrooms. The method provided future researchers with the precise inputs to conduct a thorough simulation study using IPRAT in the 20 classroom environment. Secondly, a paper is published which conducts such simulations to analyse the potential effects of IPRAT in these NZ classrooms (Burfoot, Naismith, GhaffarianHoseini, & GhaffarianHoseini, 2021). This study reveals the improvements of RT, sound clarity, and sound strength in a range of classroom aural situations when using IPRAT. Because past literature has demonstrated the potential the IPRAT can have for acoustic comfort in a classroom, the next step is to test a prototype. Thus, this paper outlines the build, test, and analysis of a pilot IPRAT prototype, used in a medium-sized tertiary classroom.

5.2.2 Objective

This paper aims to evaluate the acoustic improvements when using IPRAT in an existing tertiary classroom located at Auckland University of Technology, in New Zealand. This is a pilot case study, the first of its' kind attempting to quantify the benefits of IPRAT. Naturally, the potential acoustic improvements from IPRAT can be determined by only installing the PVAT component of IPRAT, and by manually adjusting it rather than utilizing an intelligent system. Such simplified methodology is adopted for this case study, to understand the potential significance of IPRAT without adopting a time and cost-intensive strategy. For this study, the PVAT is built by overlaying reflective, rotating louvers over sound absorption panels. The method and prototype development are outlined in section 2. RTs are measured according to international standards before and after installing PVAT in the classroom, with the results outlined in section 3. The results are analysed to quantify the potential improvements to classroom acoustic comfort, were IPRAT be used.

5.3 Materials and Methods

5.3.1 Classroom Selection

An existing tertiary classroom WS101 located at Auckland University of Technology's city campus in New Zealand is selected for this case study (Figure 5.1). The classroom is currently not in use but is designed with front-facing tables. There is a large whiteboard and 2 doors on either side of the classroom, with no windows to the outside. The floor is tiered at 4 different heights, and the ceiling slopes down toward the whiteboard. The ground material is industrial carpet on concrete, the walls are Gib board and the ceiling is made up of metal ceiling tiles and Gib board. One wall is made of painted exposed brick blocks.

Figure 5.1. Selected classroom WS101 at AUT. Left: Right-hand side of the classroom. Middle: Left-hand side of the classroom. Left: Ceiling

Figure 5.2 provides photos of the selected classroom modelled on Autodesk Revit. This classroom was selected due to its manageable dimensions, complex floor and ceiling geometry, and accessibility for research use. Preliminary RT testing also indicated poor current acoustic conditions, meaning acoustic intervention would provide tangible benefits for this classroom. The space also contains a long, empty back wall which made setting up the prototype easier.

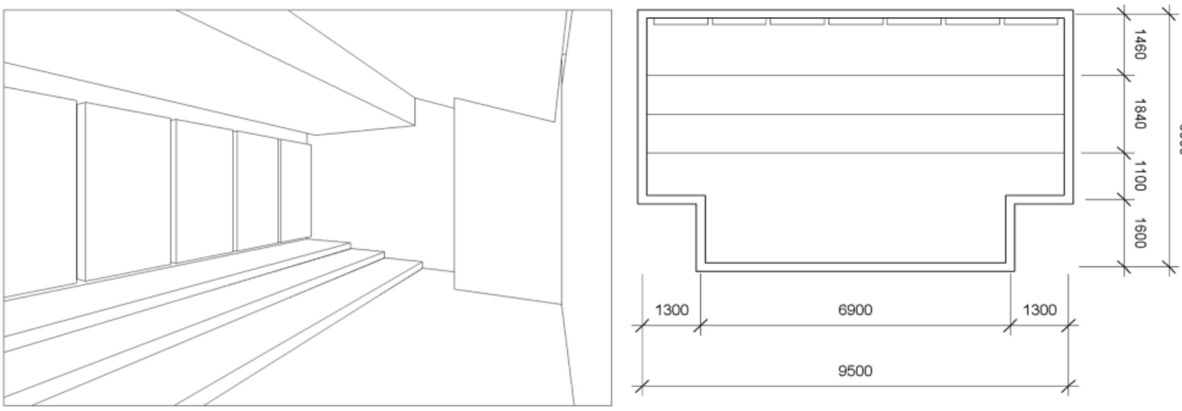


Figure 5.2. Left: Interior of selected classroom modeled on Autodesk Revit, showing floor and ceiling geometry and the panel locations. Right: Selected classroom floorplan as viewed from above, and panel locations on the back wall. Volume: 170m3

5.3.2 Development of Prototype

To alter RT, passive techniques can be used to change the total sound absorption area of a space. The prototype development was constrained by the availability of materials and economic feasibility. For this study, the selected PVAT design was to place thin rotating reflector louvers in front of porous/fibrous absorption panels. This achieves variation in absorption as the reflectors rotate either closed; parallel to the absorber surface to reflect all sound, or open; perpendicular to the absorber to allow sound to pass through and be absorbed by the panel behind, or any state in between (Figure 5.3).

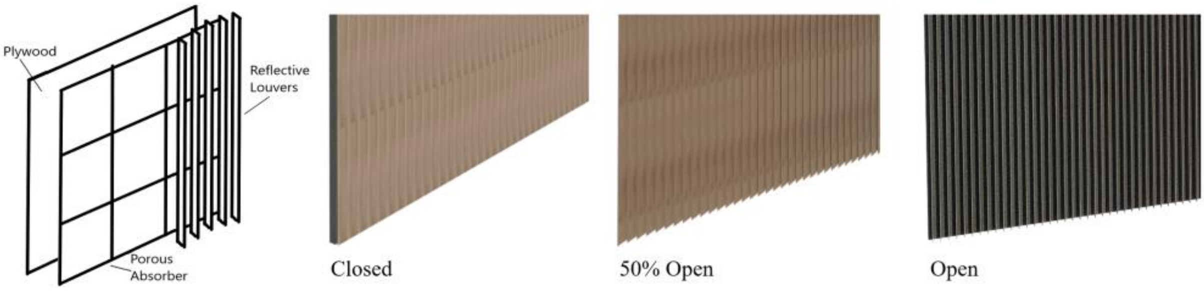


Figure 5.3. Left: Selected PVAT design concept. Right: PVAT rotations to achieve varying RT

The prototype included several material components. Firstly, large acoustic sound absorption panels are used to dampen reverberation. It was important for these panels to have the highest noise absorption capabilities. Autex industries manufacture high quality, professional standard panels, and donated 7x 1.22x2.44m panels for the project. Secondly, 200x thin polish-finished wooden slats at 0.05 x 2.4m overlay the sound absorption panels to reflect and increase reverberation. These slats were sourced from a Venetian blinds manufacturer.

For the slats to rotate, 600x custom parts were designed and 3D printed as there were no suitable off-the-shelf parts to purchase. This hardware was screwed onto the slats after pilot holes were drilled, and a rod was threaded through which rotates perpendicular to the slats. A threaded worm gear is used to translate this perpendicular rotation of the rod to drive the slat rotation. Samples of the slats, screws and rod were gathered to finalize the dimensions and functionality of these hardware parts. The parts were modelled on Autodesk software, converted to stereolithography format, scaled in Fusion 360 software (Cloud-Powered 3D CAD/CAM Software for Product Design | Fusion 360, 2018) and sliced in Cura software (Ultimaker BV Cura version 4.13, 2021). A few design iterations optimized the parts to perform effectively and minimize the filament used (Figure 5.4). For the printing, an eco-filament made of recycled plastic was used.

Figure 5.4. Left: Iterations to reduce the amount of filament needed for the 3D printed parts. Right: Fixing the parts, slats and plywood structure

Lastly, a plywood backing was used to structurally connect the louvers with the sound-absorbing panels (Figure 5.5). After designing the structural backing, the plywood was cut to size. The overhanging sections were secured with glue and apart from the initial test subject, the rest of the elements were screwed together. This meant, once disassembled the plywood pieces could be re-purposed by the university's art department for laser cutting.

Figure 5.5. Left: Structural plywood backing design. Right: Constructing the backing

The louvers were then attached to the structural plywood overhang, and the absorption panels screwed to the plywood for ease of disassembly. Minimal screws were used, to cover the lowest proportion of absorption area (Figure 5.6).

Figure 5.6. Fixing the absorber panel to the plywood backing, using design for disassembly techniques

The achievable RT alteration depends upon the surface area covered by the panels, which is limited based on resources and installation access. For this study, 7x panels were constructed measuring 2.88m^2 each, covering 20.16m^2 of (approximately) 120m^2 wall, floor and ceiling surface area (Figure 5.7). This covered 16.8% of the total surface area in the space. The least intrusive setup for the PVAT was to lean the panels vertically against the back wall, so no permanent damage was made to the classroom. Figure 5.7 also demonstrates the panel's 3 key test states; open, 50% open, and closed. Here, '50%' refers to rotating the louvers 45deg from their closed state.

Figure 5.7. Final set up of 7x PVAT panels in case study classroom, and panels showing open, 50% open, and closed rotations

5.3.3 Measurement Equipment

Three Android applications were identified for RT measurement and were used in conjunction to confirm the validation of the individual applications. The first application is a real-time analyzer (RTA) called AudioTool for Android, created by Julian Bunn, developed by Bofinit and released in 2014. This application uses A- and C1 weighting networks and measures the drop in sound pressure level after an impulse signal is created loud enough to trigger the RT measurement. AudioTool makes a wideband measurement and individual octave band measurements, by passing the data through a base of IIR octave filters for specific frequencies. The RT is displayed in a table and can be exported for each measurement (Figure 5.8). The Schroeder integral is used to detect the peak and drop in SPL. "I haven't seen a free spectrum analyzer app that delivers such high resolution" (2011, p. 1, Brent Butterworth). The accuracy of RTAs can be increased with calibration, however is not crucial when relative measurements only are of consideration (Barakat, 2016). In this app, the T15 was used: the time of intensity drop between 5dB below the peak to 20dB below the peak, multiplied by 4.

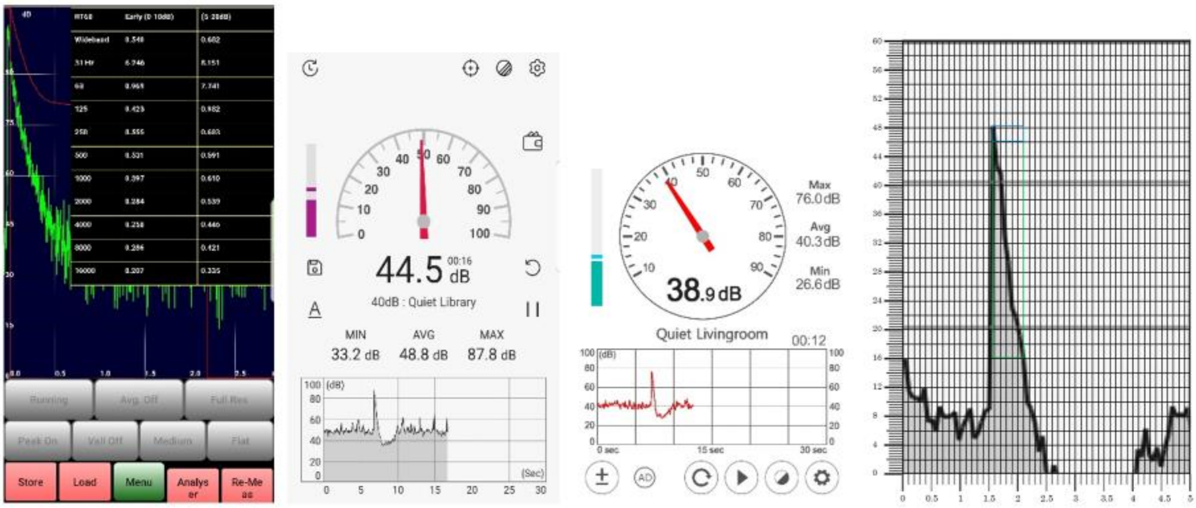


Figure 5.8. Far-left: Audiotool user interface post-measurement. Middle left: SPL app 1 Sound Meter – Decibel user interface post-measurement. Middle right: SPL app 2 Sound Meter user interface post-measurement. Far-right: example of deriving T30 for SPL apps

The second 2 applications are 'Sound Meter – Decibel' by Melon Soft and 'Sound Meter' by KTW Apps with very similar functions. As Figure 5.8 demonstrates, even the user-interfaces function in the same way. Only one previous study in academic literature has used the app by KTW (Corder et al., 2020). Android devices have been criticized in view of audio capabilities, due to a fragmented market with many different devices, operating versions and specification qualities (Sakagami, Satoh, & Omoto, 2016). It should be noted that the accuracy of these apps is inconsistent, and cannot be used in a compliance situation (McLennon, Patel, Behar, & Abdoli-Eramaki, 2019). However, for this study, the 2 apps provided a secondary measurement to increase understanding of the problem statement. The sound meters use a smartphone and internal or external microphone to measure and record on-screen the real-time dB (Figure 5.8). This recording time should be a minimum of 5 seconds plus the expected RT. From here, the plots are manually evaluated to derive the T30 by evaluating the decay curve from 5dB to 35dB below the peak SPL. According to ISO standards BS EN IEC 60268-16:2020, if this method is used a visual "best fit" line may be substituted for a computed regression line (International Organization for Standardization, 2020). The 'best fit' line must approximate a straight line, and it is recommended to adjust the time scale, so the 'best fit' line is approximately 45deg. To derive the "best fit" line, a grid was superimposed on the SPL plots (Figure 5.8), showing dB on the y axis and time (s) on the x-axis.

Using Android applications for the measurements proved to be the most cost-effective option saving on both sound calculation software and measurement hardware. The Android device used was a Samsung Galaxy S8, performing as an efficient acoustic measurement device with fast processing speeds and capabilities. Using calibrated external microphones for sound measurement from a smartphone application will increase the reliability of the results and is a necessity (Roberts, Kardous, & Neitzel, 2016) (Celestina, Hrovat, & Kardous, 2018). To improve the accuracy of the RT measurement, the i458C Free Field Digital Omnidirectional Microphone by MicW of BSWA Technology Ltd. was used. This is an omnidirectional condenser mic with a frequency response of 20Hz-20kHz. It is designed for SPL measurement (max 125dB) and real-time analysis from a smartphone, and is calibrated to meet IEC 61672-3 Class 2 sound level meter standards, to comply with ISO 9001:2008 with a measurement sensitivity uncertainty of +-0.30dB (MicW i458C for Android | Sweetwater, serial number: 585019, calibration: 22/12/2020, 25 degrees Celsius, 65% relative humidity, 101.3kPa. Such measurement setups have been shown to comply with relevant International Electrotechnical Commission and American National Standards Institute sound level meter standards (Celestina, Kardous, & Trost, 2021). The benefits arise for both accuracy and precision, given the external microphone is calibrated (Kardous & Shaw, 2016).

5.3.4 Research Procedures

According to ISO standards, 4 omnidirectional sound source positions at 1.5m above the floor were identified where sounds would occur naturally in the space. Similarly, 4 microphone locations were defined where sound would be naturally received in the space at 1.2m high (for rooms for speech), at least 2m apart and 1m from any wall (Figure 5.9). Impulse responses were generated by popping a balloon with a needle, producing a peak SPL over 45dB above the background noise level (International Organization for Standardization, 2009). For the 2 SPL apps, only 4 combinations of sound source and received locations were used. The results from the evenly spaced seating array and 3 microphones were averaged (International Organization for Standardization, 2009). The measurements were taken in an unoccupied state in October and November of 2021, and the temperature and relative humidity in the room during the measurement was not accounted for as pre and post-condition measurements were taken. Additionally, the psychoacoustical effects of these physical phenomena are excluded from the scope of the study but do present an interesting research opportunity for future studies. Data were collected for a variety of classroom acoustic conditions (Table 5.1). Aside from the IPRAT states 'Open', '50%' and 'Closed', 3 other conditions were measured. The room was measured when no panels were in the space: 'No IPRAT', when using the absorber panels alone: 'Soft Panels', and when rotating the slats open toward the centre of the space (rather than perpendicular to the absorber panel): 'Centred'. The 'Centred' state was to test whether the RT would be further reduced than if the louvers were simply 'Open'. Larger quantities of data were collected for the 4 IPRAT-in-use states as this contributed to the key objectives of the paper. To alter the PVAT rotation, the louvers were manually rotated by the researcher in the specified increments.

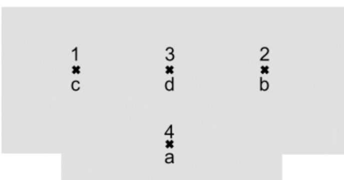


Figure 5.9. Microphone measurement locations (1-4), sound source locations (a-d)

Table 5.1. Description of IPRAT measurement states and quantities per app

Name	Description	Total measurements taken per app and sound source-receive combinations used		
		SPL app 1	**SPL app 2**	**AudioTool**
No IPRAT	The classroom in its original state, void of IPRAT	0	3 – 1a, 1b, 1d	3 – 1a, 1b, 1d
Soft Panels	Only the sound absorption panels are placed on the classroom walls	0	2 – 1a, 1b	2 – 1a, 1b
Open	The panel louvers are rotated perpendicular to the absorption panels, allowing sound to pass through	4 – 1a, 1b, 2a, 2c	4 - 1a, 1b, 2a, 2c	12 – 1a, 2a, 3a, 1b, 3b, 4b, 2c, 3c, 4c, 1d, 2d, 4d
Centred	The panel louvers are rotated to open toward the centre point of the classroom	"	"	"
50%	The louvers are rotated at a 45deg angle to the absorption panels	"	"	"
Closed	The louvers are rotated parallel to the absorption panel, blocking sound from passing through	"	"	"

5.4 Results and analysis

As recommended by (International Organization for Standardization, 2009), the measurement results for source and microphone positions were combined to give spatial average values. The data from each app was averaged arithmetically by taking the mean individual RT's for all the independent source and microphone positions. Using Excel and SPSS software, no outliers were identified in the SPL App 1 and 2 datasets (Figure 5.10), however, 6 outliers in the AudioTool data were identified. For each RT reading, AudioTool allows you to analyze the RT of each frequency band from 31-16,000Hz. But because the researchers are looking at mid-frequency RT for this study, the relevant bands were 125-4000Hz. For these identified outliers, normal results were shown for all frequency bands except 125Hz, which showed unrealistically large values. Often this can happen at lower frequencies, even though the reading was correct and complete for all other frequencies. This is due to the SPL processor not receiving a complete sound reading, so will end up distorting the Global RT value. Thus, rather than removing these outliers, the 125Hz RT reading was adjusted to reflect similar values from neighbouring readings (Table 5.2). The effect of these changes is illustrated in Figure 5.11.

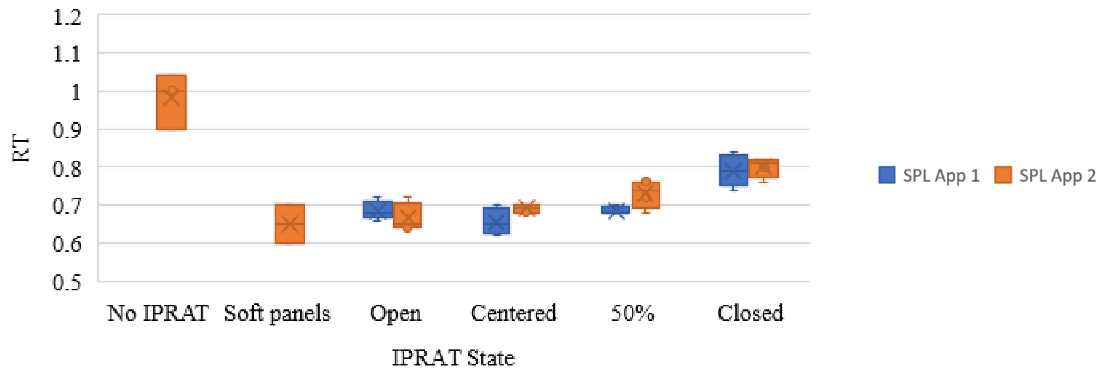


Figure 5.10. RT data for SPL App 1 and 2

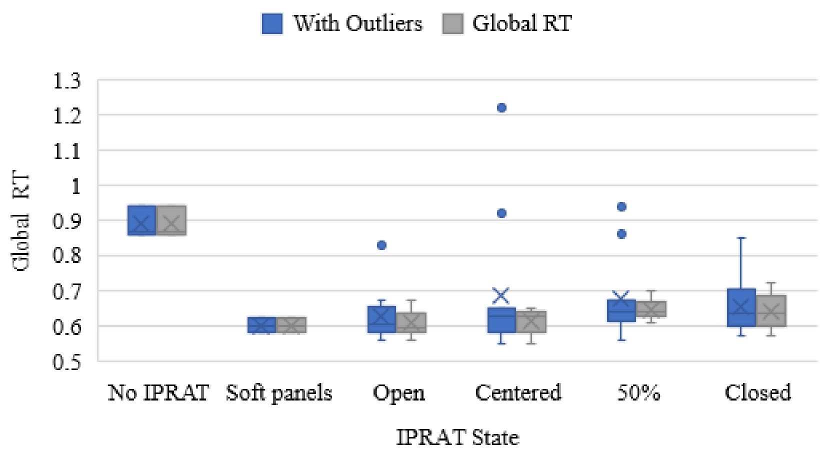


Figure 5.11. Audiotool data preparation – before and after remove outliers in the 125Hz frequency range

Table 5.2. Original and new outlier values for Audiotool RT at 125Hz

IPRAT State and location	Original RT at 125Hz	New RT at 125Hz
Centred 1a	2.55	0.84
Centred 1b	4.3	0.87
Open 4c	2.28	0.82
50% 1a	2.9	1.12
50% 1d	2.1	1.07
Closed 1a	2.27	1.35

5.4.1 Linear Regression

The data were analysed using IBM SPSS software (version 27; SPSS Inc., New York, NY). Regression is used in this analysis to understand the statistical relationship between variables. If there is a favourable and significant correlation between IPRAT state and RT, the beneficial effects of the technology can be confidently affirmed. Thus, the null hypothesis here is that rotating the IPRAT does not affect the corresponding RT. To test this, each IPRAT state is compared relative to each other. After which, these states are also analyzed against the state of not having IPRAT installed, for SPL app 2 and Audiotool only. A Shapiro-Wilk analysis showed normality of the data, however from Levene's test, the data is not found to have homogeneity of variance: $F(5,84) = 4.188$, $p = .002$. There was a statistically significant difference between groups, as determined by One-way ANOVA ($F(3,76) = 5.592$, $p = .002$). However, since the data violates the homogeneity of variances, this test can produce errors. Thus, a Welch ANOVA was carried out instead of a one-way ANOVA. There was a statistically significant difference between groups as determined by Welch ANOVA ($F(3,41.445) = 4.723$, $p = .006$). A Games-Howell post-hoc test of between-subject effects confirmed this statistical significance $F(3)=5.592$, $P=.002$, with a Partial Eta Squared=.181, meaning IPRAT state explains 18.1% of the variance of RT. The results from the Games-Howell multiple comparisons reveal a statistically significant difference between IPRAT states: 'closed and centred' p=0.032, and 'closed and open' p=0.039. SPL app 1 was then removed for another set of tests so the researchers can include data from 'No IPRAT' and 'Soft panels'. There was a statistically significant difference between groups as determined by Welch ANOVA ($F(5,18.396) = 16.944$, $p = .000$). The Games-Howell post-hoc test also reveals that 'No IPRAT' is statistically different from all other states, with p=<0.001. This is visualized in Figure 5.12. Interestingly, there was no statistically significant difference between 'Open' and 'Centred' states.

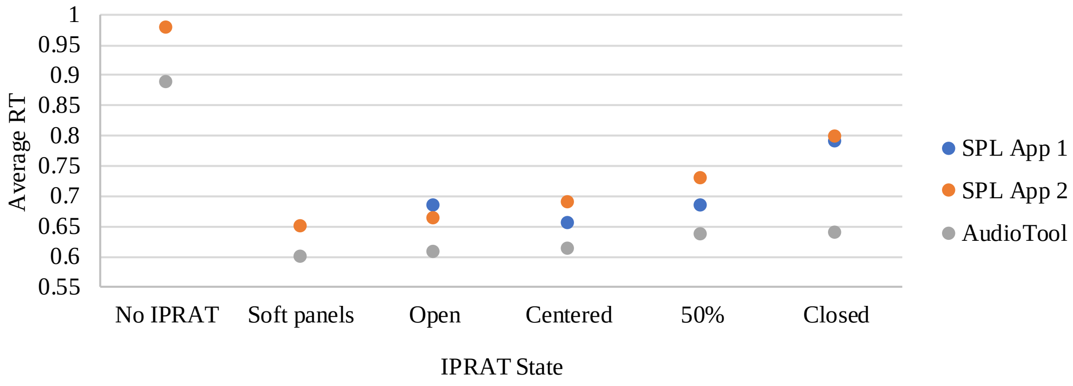


Figure 5.12. Mean RT values for each app, demonstrating significant differences between 'No IPRAT' and all other IPRAT states, 'Closed' and 'Open, and '50%' and 'Centred'

5.4.2 Multi-variate Analysis

For multi-variate analysis, since the researchers do not have homogony of variance, a Welch *t-Test* - also known as an Unequal Variance *t-Test* or Separate Variances *t-Test* – must be used. It was interesting to test whether the microphone location or sound source location for the RT tests has a significant effect on the output. When testing for these variables, the data is separated into 'Audiotool' and 'SPL app 1 and 2', as Audiotool included more measurement locations. For SPL apps only, testing microphone locations t(1,29.395)=.349, p=.559 and sound source locations t(2,15.774)=.043, p=.958 showed no statistical significance. This data is displayed in Figure 5.13, and it can be visually confirmed that no specific measurement positions determine a higher or lower RT across IPRAT states.

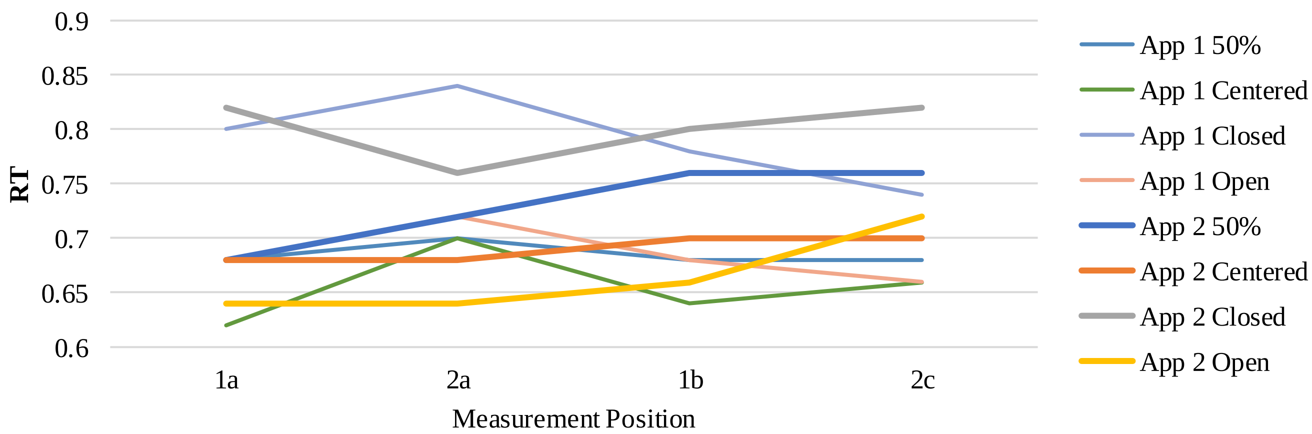


Figure 5.13. RT for each measurement position for SPL App 1 and 2

Similarly, for Audiotool, no statistical significance was found for microphone location $t(3,24.165)=.346$, $p=.762$ or sound source location $t(3,24.341)=.154$, $p=.926$. Figure 5.14 demonstrates the random spread of Audiotool data across measurement positions.

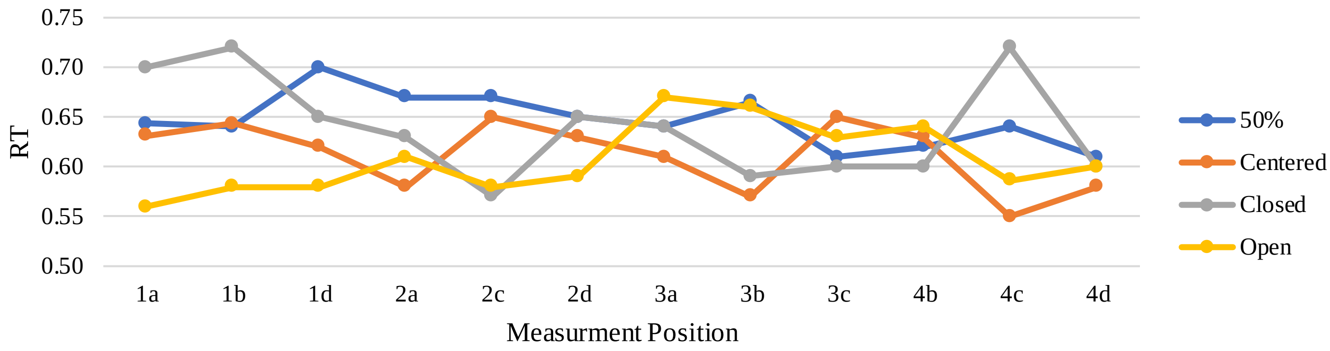


Figure 5.14. RT for each measurement position for AudioTool

These results are welcomed, as it means there was little special variance in the classroom measurements in different parts of the room. It is interesting to note, however, that in microphone location 4, the 'Open' and 'Centred' IPRAT states follow very similar trends, which is expected of the data as the IPRAT states both provide the space with a high sound absorption area. This raises the question of whether the microphone readings were incorrect at locations 1, 2 and 3, especially positions 2 and 3 where the distinction between IPRAT states appears very random.

5.4.3 Effectiveness of IPRAT when in use

Using the mean RT's for IPRAT states 'Open', '50%' and 'Closed' only, the researchers can theorize the effectiveness of the prototyped technology when it is in use in the classroom (Figure 5.15). For this demonstration, 'Open', '50%' and 'Closed' are numerically recoded as rotation percentages 0%, 50% and 100% respectively. In these states, an average RT's overall inclusive of all app data are described, and a line of best fit is found. From this relationship, the researchers can theorize the RT at other IPRAT rotations in-between 0-50% and 50-100%. It should be mentioned that states 'Open', 'Centred' and '50%' all significantly increase the diffraction in the space. Diffraction has an effect on RT, especially at lower frequencies. However, this study does not directly address the effect of diffraction as it falls outside of the scope, but it could be addressed in future work.

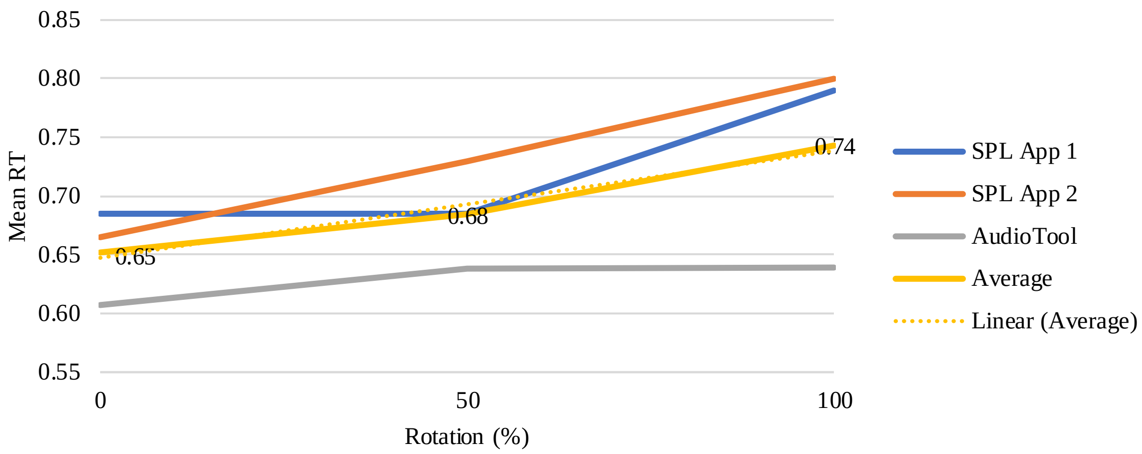


Figure 5.15. Mean RT's for IPRAT in use, and average RT across all apps

Based on the average RT's line of best fit, we can derive the relationship between IPRAT rotation and RT as: RT=0.000911*(rotation) + 0.6475 (R^2 = 0.971). This is true when IPRAT covers 16.8% of the room surface area, as is the situation for this case study. This coverage gives a potential RT variance of 0.1s between rotations 0-100%. We also know that when IPRAT covers 0% of the space, this relationship can be described by: RT=0.935, and we get an RT variance of 0s. Using these 2 known data points we can extrapolate various potential relationships between IPRAT coverage and RT variance (Figure 5.16).

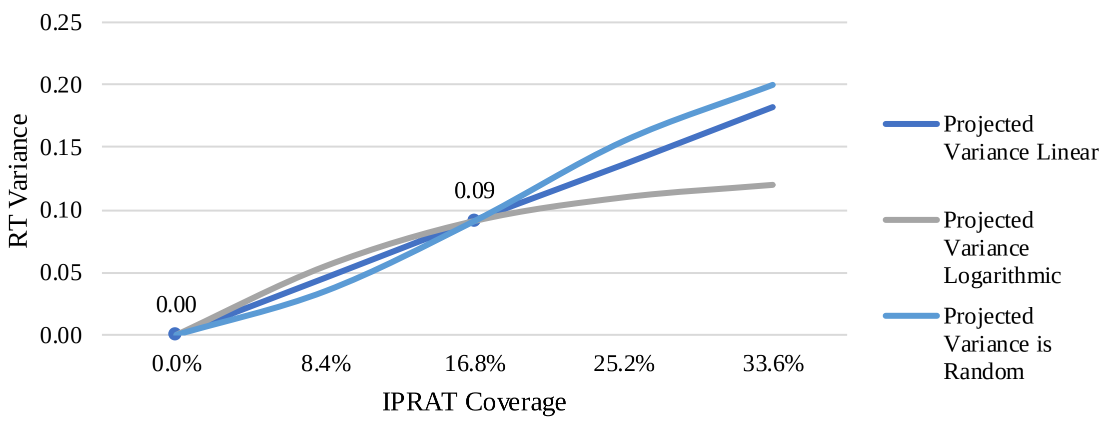


Figure 5.16. Using 2 known data points to theorize potential relationships between IPRAT coverage and RT

Due to the unpredictable and random nature of acoustic behaviour in rooms, it is unlikely that this relationship will be linear**.** More likely, this will manifest as a logarithmic or more randomized relationship as IPRAT coverage tends toward 100% and the RT variance tends toward zero. Nevertheless, let's assume a linear relationship. As IPRAT coverage increases, and we see an increase in RT variance, the RT for each IPRAT rotation will also decrease. This is theorized by reproducing the trend from 0% to 16.8% coverage (Figure 5.17). So, for double the amount of IPRAT coverage, the minimum and maximum achievable RT when rotating the IPRT open to closed are 0.36 and 0.54 seconds respectively. Although this is highly theoretical and is based on assuming a linear relationship, according to Sabine's formula for RT this relationship is linear (Sabine & Egan, 1994).

Nevertheless, it would be interesting to see a future study determine the nature of these RT values as they tend toward an IPRAT coverage of 100%. After which, a trade-off could be determined which increases the rooms' ability to vary RT without being material and cost intensive. It is important to keep in mind that due to the absence of people and furniture in the space, RTs will be higher than what they would read in an occupied classroom setting. This would bring the RT at 0.0% down, meaning it would require less IPRAT coverage to achieve optimal acoustic conditions.

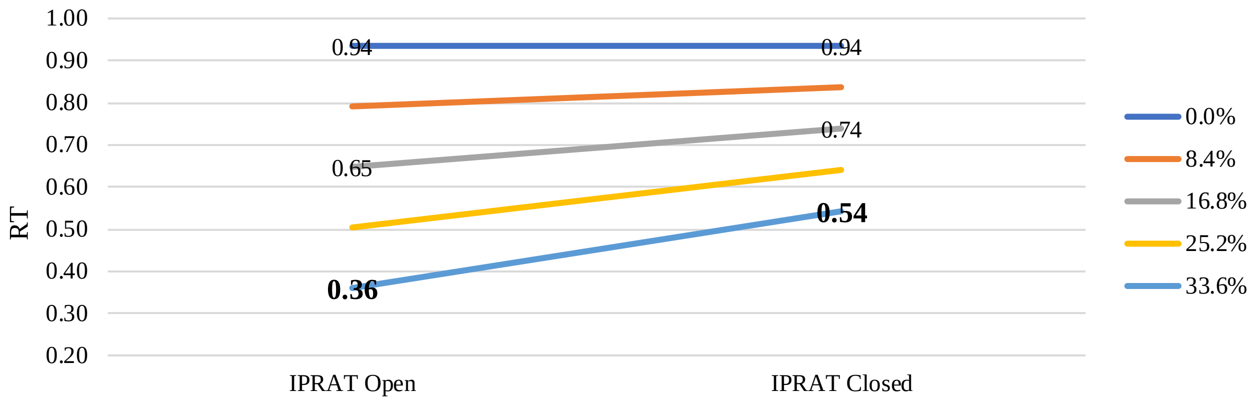


Figure 5.17. Predicting the minimum and maximum RT's with more IPRAT coverage

5.4.4 IPRAT benchmarked against acoustic design standards

When there is no IPRAT, the classroom has a constant RT of 0.935s. If this were scrutinized against acoustic standard AS/NZS 2107:2016, a single RT value would be recommended, as 0.55s for 'Rooms for Speech' (classrooms). The classroom would therefore be considered to have poor current acoustic conditions. With soft panels only, the RT is reduced to a static 0.65s. This is a significant improvement from the existing 0.94s RT. However, this doesn't recognize classrooms as dynamic spaces, which is why our study went a step further to propose the benefits of using IPRAT to achieve lower RTs as well as the ability to vary RT between higher and lower values. So, when using IPRAT the RT is reduced closer toward this 0.55s, however, the real benefits of IPRAT are further realized by its ability to vary the RT. The second room type of interest provided in AS/NZS 2107:2016 is 'Speech/lecture' room types, where RT should equal 0.7s. Although this standard is not intended for classrooms, it is argued by Burfoot, Ghaffarianhoseini, et al. (2021) that the RT should be able to meet this recommendation when the classroom is being used for lectures. The reason current standards don't recognize this is because they assume classrooms to have fixed RTs, even though this sacrifices acoustic comfort during classroom study, lecture, or both. So, at a room volume of 170m^3, AS/NZS 2107:2016 recommends a mid-frequency RT of 0.55 for 'Rooms for Speech', and 0.7 for 'Rooms for 'Speech/Lecture' (Standards New Zealand, 2016). In its current state the classroom RT is far too long to satisfy either 'Rooms for Speech' or 'Speech/Lecture' (Figure 18). However, if we use the linear equation relating IPRAT coverage and RT, we can propose that at 20.5% coverage the RT can be varied between 0.58 and 0.70s (0.94-0.0173*20.5=0.58 and 0.94-0.0119*20.5=0.70). This comes a mere 0.03s and 0s away from matching the industry standards for both room types. Thus, it can be confidently concluded that by using IPRAT, the conditions of both room types can be satisfied – increasing the acoustic comfort in both classroom learning and classroom lecture.

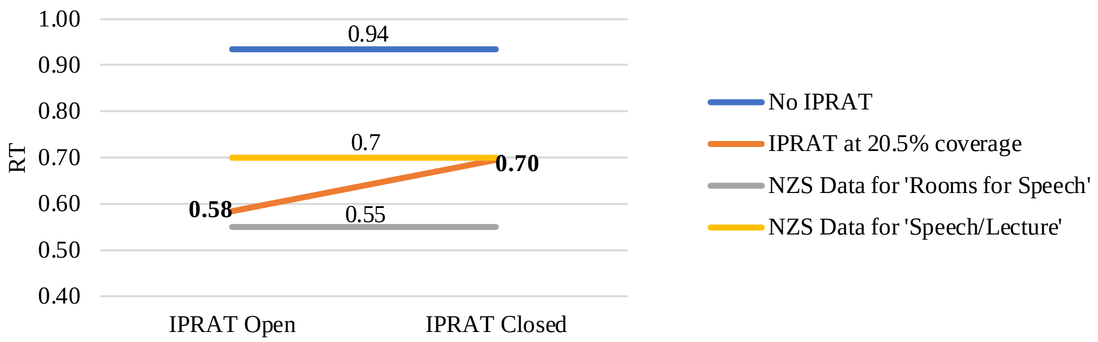


Figure 5.18. IPRAT satisfying the recommended RT for both 'Rooms for Speech' and 'Speech/Lecture'

5.5. Conclusion

In this study, a prototype wall panel that alters its sound absorption to change the RT of a room was built and tested in a tertiary classroom. An initial evaluation of the classroom in its current state revealed the existence of poor acoustic conditions in the classroom, caused by high RTs. The poor acoustics are also attributed to the classrooms' inability to vary acoustic parameters for changing aural situations. The classroom - like most others around the globe - experiences one static acoustic state, neglecting to recognize classrooms as flexible, dynamic spaces. When using the prototype, however, apart from varying the RT, the RT is also significantly reduced compared with the existing RT which was too long. Thus, the benefits of IPRAT arise in 2 ways. Firstly, the RT is generally reduced to a more comfortable level. And second, the RT can be varied to suits changing classroom situations; A longer RT can be achieved during lecture situations, and a shorter RT can be used during classroom study situations. When using the prototype, the classroom is prescribed with a range of RTs it can achieve: at 16.8% PVAT surface area coverage, an average RT variance of 0.1s was achieved. By quantifying the benefits of using PVAT, the researchers can confidently assume these same benefits are achieved with IPRAT. The research thus confirmed that whilst using IPRAT, the classroom becomes a more flexible, multi-use space, with the ability to optimize the acoustic conditions for different classroom environments. Additionally, if we increase the amount of surface area coverage, we can achieve an even greater reduction and variation of RT. The most exciting discovery in this paper is that at 20.5% IPRAT coverage, the RT can be varied between 0.57s and 0.70s. NZS Acoustic Standards recommend RTs of 0.55s for 'Rooms for Speech', and 0.7s for rooms for 'Speech/Lecture'. IPRAT allows for the near-perfect satisfaction of these two recommended RTs, and thus acoustic comfort is improved in both situations 'classroom study' and 'classroom lecture'. It is encouraged that future studies continue this line of research toward the eventual development of IPRAT and its' acceptance into mainstream architecture. For example, research could test other PVAT rotations between 0-100%, and varying amounts of IPRAT surface area coverage. Ultimately, studies should quantify the effects experienced by the room in an occupied state.

5.6 Conclusion to chapter

5.6.1 Original contribution and realization of aims and objectives

In this paper, an existing tertiary classroom at Auckland University of Technology was used to evaluate the acoustic impact of using IPRAT. In this pilot study, IPRAT's benefits were quantified for the first time. If only the PVAT component of IPRAT is installed and manually adjusted rather than using an intelligent system, it is still possible to determine the potential acoustic improvements from IPRAT. Therefore, such a simplified methodology was employed in this case study to understand the potential significance of IPRAT without adopting a time and cost-intensive strategy. For this study, reflective, rotating louvers were overlayed over panels that absorb sound to make up the PVAT. This prototype was built, and RTs were measured according to international standards before and after installing PVAT in the classroom. The results were then analyzed to quantify the potential improvements to classroom acoustic comfort, where IPRAT be used. The manuscript contributes a unique prototyped technology, as well as results of tests conducted in the classroom (Table 21).

Table 5.3. Manuscript 4 title, aim, objective and output(s)

Manuscript title	Manuscript aim	Objective	Output(s) or novel findings
(Manuscript 4) Intelligent Passive Room Acoustic Technology in Classrooms: A Pilot Case Study Submitted to xxxx	Determine the effect of IPRAT on acoustic comfort using a case study	Deploy a IPRAT prototype in a tertiary classroom by constructing and testing only the PVAT component	The prototype development is outlined, as well as an acoustic measurement method which uses Android applications
		Use IPRAT in a case study classroom by adjusting the prototypes sound absorption, and quantify the benefits	The key benefits of IPRAT are realized in its ability to vary RT, and are statistically significant. Additionally, benefits are realized in an overall RT reduction.
		Analyse the performance of IPRAT against industry standard guidelines, and optimise the improvements achieved with IPRAT	Design optimisation for using IPRAT in classrooms is provided, and by using IPRAT in a single space, the recommended RTs for two room types outlined in the NZ Acoustic Standards can be satisfied

5.6.2 Differentiation of contribution from existing literature

IPRAT was first conceptualized by Burfoot, Ghaffarianhoseini, et al. (2021). The intelligent technology was found to be an appropriate progression from past literature, as historically, PVAT was gradually becoming more intelligent. Before IPRAT, the most advanced PVAT used a system that estimated or measured the RT in a room and adjusted the sound absorption. The adjustment was made according to pre-programmed RT databases for different building uses. In this sense, IPRAT advances past technology since it can automatically detect and classify the aural situation based on how the building is used, and optimize the RT accordingly. It is recommended that IPRAT be used in classrooms, since these spaces constantly need different RT's to optimize acoustic comfort. A long RT will assist a teacher in projecting their voice during a lecture. This will reduce teacher vocal disease and increase student comprehension. A short RT can also help students concentrate when working individually or in groups by reducing noise and aural distractions in the area.

To advance IPRAT's development after its proclamation in 2019, two relevant studies have been published. Firstly, a method is described to simulate the possible benefits of IPRAT. The study collects documents to create a set of virtual classroom environments that illustrate the acoustics and physicality of 20 types of classrooms typical to New Zealand. This method was described for future researchers to conduct an in-depth simulation study using IPRAT in the classroom environments. Secondly, a paper is published which conducts such simulations to analyze the potential effects of IPRAT in these NZ classrooms. Using IPRAT, this study found improvement in RT, sound clarity, and sound strength in a range of classroom aural situations. Considering that past literature has demonstrated the IPRAT's potential for acoustic comfort in a classroom, the next step was to test a prototype. Thus, this paper outlined the build, test, and analysis of a pilot IPRAT prototype, used in a medium-sized tertiary classroom. A key difference between this study and the previous one is that it measures a physical prototype rather than a simulation.

5.6.3 Final Considerations

IPRAT is not present in the classroom, so the classroom has a constant RT of 0.935s. If this were examined against acoustic standards, 0.55 seconds would be recommended in this classroom ('Rooms for Speech'). Therefore, the classroom's current acoustic conditions are poor. By using only soft panels, the RT is reduced to 0.65 seconds. That's a significant improvement from the existing 0.94 second RT. However, it does not take into account the dynamic nature of classrooms. Because of this, our study went a step further to propose the use of IPRAT as a method for achieving lower RT's as well as the ability to vary RT between higher and lower values. Thus, when IPRAT is used, the RT is closer to this 0.55s, although the real benefit of IPRAT is its ability to vary the RT. Second, RT should be 0.7 seconds for 'Speech/lecture' room types. The RT should follow this recommendation when a classroom is being used for lectures, even though this particular standard is not intended for classrooms. It is because current standards assume classrooms should have fixed RT's, which sacrifices acoustic comfort during study sessions, lectures, or both. NZS Acoustic Standards recommend a mid-frequency RT of 0.55 for 'Speech Rooms', and 0.7 for 'Speech/Lecture Rooms' at a room volume of 170m3. As it stands, the classroom RT is far too long to satisfy the requirements of either 'Rooms for Speech' or 'Speech/Lecture'. We can propose that at 20.5% coverage, the RT can range between 0.58 and 0.70 seconds, by using the equation relating IPRAT coverage to RT. This is just 0.03 and 0.00s away from matching the industry standard for both room types. By using IPRAT, it can be confidently concluded that the conditions of both types of rooms can be satisfied - resulting in an increase in acoustic comfort during classroom learning and classroom lectures.

In the following chapter, Manuscript 3 and 4 are statistically analysed against each other, and thesis conclusions are formed.

Chapter 6. Discussion, conclusions, and implications

Around the globe, building occupants are being over-simulated with environmental noise, pollution, compromised air quality and indoor excitations. The work of professionals in the construction and architectural industries is to increase the indoor environmental quality for all occupants, in meaningful and sustainable ways. Much work has been done improving the light, air and thermal quality of indoor spaces. The acoustics of spaces are often designed as an afterthought, or in some cases, neglected entirely. This is a huge cause for concern, as the benefits of an acoustically-considered space particularly in places like educational environments, are numerous. Though occupants cant 'see' or 'visualise' sound in buildings, it holds great importance to the mental clarity and wellbeing of building occupants. Whether decreasing noise pollution in residential buildings to improve sleep, or increasing sound clarity in a lecture theatre, the acoustic conditions of a space are critical to a well-performing building, and the benefits are often hard to measure. Because of this neglect and significance, acoustic comfort takes the forefront in this research.

By optimising RT for an indoor spaces' intended use, the acoustic comfort can be improved. So, this stands true for multi-use or dynamic spaces as well. If a space holds more than one intended use, the optimal RT should be achieved in this one space, for both space uses. Of all the flexible and dynamic spaces, one which presents a significant need for these varying RT's are classrooms. In a lecture situation, without a long RT, teachers are raising their voices for extended periods of time and are developing vocal diseases. Also, without this sound travel, students can struggle to hear and comprehend their lessons. The pitfalls of this are lower student engagement, understanding and achievement. On the other hand, when students are engaged in group study or individual study, excess noise from long RT's can be distracting and disruptive. This dramatically decreases student concentration, and again achievement in school. The solution to mitigate these issues is to vary the RT between short and long values.

For these spaces, it is therefore required to have the ability to vary RT. In the past, this has been achieved using manually intensive methods, making it difficult to quickly vary RT in the middle of a lesson. In board room spaces, technology has been trialled, which is more automated and motorized. Advancing a step further than this, and presenting a current gap in the literature, we get IPRAT. This technology can detect and classify the way in which a space is being used (by measuring the sound waves and classifying the 'aural situation') and vary the RT optimally to suit. As a novel and unique solution, conceptualized in the first part of this research, it was, therefore, both significant and meaningful to conduct research studies to prove the effectiveness of IPRAT. Thus, the research question for this thesis was: *what is the effect of IPRAT on classroom acoustic comfort?*

6.1 Novel Research Outputs

The research question has been successfully answered in this thesis, and each manuscript contributes to industry and academia in a novel and significant way.

The first manuscript, ‘The Birth of Intelligent Passive Room Acoustic Technology: A Qualitative Review’ aimed to determine the rationale for IPRAT. A best-evidence synthesis and prior art search were conducted to determine the highest level of intelligence for passive variable acoustic technology. It was discovered that dynamic spaces should be designed with varying RT’s however, a literature gap exists for intelligently adjusting RT to suit changing space uses. The unique IPRAT solution was conceptualised, which integrates PVAT and Acoustic Scene Classification. Thus, IPRAT was proclaimed, developed, and analysed, and a use case example for IPRAT was provided. The findings from manuscript 1 strongly suggested the need to test or prototype IPRAT.

The second manuscript, ‘Developing virtual classroom environments for intelligent acoustic simulations’ aimed to establish a simulation method for testing IPRAT. Using secondary data, 20 classroom environments ‘typical’ to New Zealand were detailed and developed. Additionally, a software method was established which could be used to simulate acoustic technology. The 20 classroom profiles were detailed and demonstrated using I-Simpa, a pre/post-processor for acoustic codes, and Autodesk software. With these virtual environments, it was suggested that IPRAT should now be simulated, to demonstrate its potential to improve acoustic comfort.

The third manuscript, ‘The potential for intelligent passive room acoustic technology in classrooms: A BIM-based simulation’ aimed to determine the effect of IPRAT on acoustic comfort using simulation. IPRAT was thus simulated in the 20 environments established in manuscript 2, statistically analysing the effect of IPRAT on RT, C50 and G. The output of this manuscript firstly included an acoustic simulation method in I-Simpa software presented for initial technology validation. Secondly, the quantified improvements of IPRAT on acoustic parameters RT, C50 and G were determined. Last, a database of RTs which improve acoustic quality for four aural situations typical to classrooms was derived. In this simulation, the benefits of IPRAT were found to be statistically significant, and it was recommended that future research physically prototypes the technology.

The fourth and final manuscript ‘Intelligent Passive Room Acoustic Technology in Classrooms: A Pilot Case Study’ aimed to determine the effect of IPRAT on acoustic comfort using a case study. An IPRAT prototype was deployed in a tertiary classroom by constructing and testing only the PVAT component. The IPRAT was tested by adjusting the prototype's sound absorption. The benefits to acoustic comfort were quantified, and the performance of IPRAT was analysed against industry standard guidelines. The prototype development was outlined, as well as an acoustic measurement method that uses Android applications. The key benefits of IPRAT were realized in its ability to vary RT, and were statistically significant. Additional benefits were realized in an overall RT reduction. Lastly, design optimisation for using IPRAT in classrooms was provided, and by using IPRAT in a single space, the recommended RTs for two room types outlined in the NZ Acoustic Standards were satisfied.

The collation of these four manuscripts sufficiently answers the research question *what is the effect of IPRAT on classroom acoustic comfort?* In the following section, the statistical outputs from the manuscripts are summarised and compared against each other, to further strengthen the thesis and explain the benefits of IPRAT.

6.2 Differentiation from Existing Literature

In existing literature, PVAT is currently able to achieve a high level of intelligence through programmable automated systems thanks to various successes in industry and academia. A range of PVATs can reduce RT manually; for example, by adding reverberation absorption chambers, by lowering a ceiling or by increasing acoustic absorption with rotating panels, rolling curtains, or hinged flaps. Compared to manual solutions, automation has improved acoustic comfort, providing greater adaptability and efficiency in varying acoustic environments. In comparison, IPRAT includes an integrated intelligent system. The PVAT component which exists in literature is not novel when standing on its own. The second component provides the PVAT with intelligent capabilities, making IPRAT a novel concept. A set of microphones around the room is required to detect sound waves in the space in real-time, specifically the SPL. The SPL is then transformed into an output, interpreted by the ASC. Based on the SPL recordings, the ASC is trained to recognize which acoustic 'scene' is taking place. Based on the acoustic scene, a pre-programmed algorithm calculates the optimised RT for that acoustic scene. This RT value is expressed as the ‘required rotation’ (0-90 degrees). Ultimately, the rotation is communicated via Wi-Fi to a mechanical actuator, which rotates the louvers as specified to reach the perfect RT. Opportunely, a user command or interface is not required to make this intelligent classification from the microphone to the louver.

Incorporating this intelligent system with PVAT creates the novel IPRAT solution. The use-case described in manuscript 1 is also a novel contribution, as it is proposed for the first time how the benefits of IPRAT could be realised in a classroom. With regards to the ASC, the methods used to develop and train the model would not be novel. It is a fact of using an ASC in a classroom for room acoustic optimisation, which is a novel concept. In this sense, using an ASC for a RT application would be the first of its kind, and planting this seed in the built environment literature is a small, unique contribution. After which, it was necessary to combine physical and aural data for simulating the acoustic environments in manuscript 2. A comprehensive description of NZ classroom attributes, including physical and aural information, has not been provided in published literature. To contribute to this field, this paper used existing data to develop and demonstrate a set of 20 classrooms. This included looking at existing 'typical' NZ classroom types. Research has been conducted on the physical characteristics of classrooms. Thus, the significant gap which was filled in this paper was defining classrooms for the use of virtual analysis.

Manuscript 3 takes the concept of IPRAT from manuscript 1, and the environments and methods described in manuscript 2. For the first time, IPRAT is simulated, and the technologies' benefits are quantified. The use of variable acoustic technology has been simulated in the past, but never intelligent technology. Likewise, simulations of pre and post-acoustic treatment have been performed using passive acoustic panels, but never with IPRAT. Existing literature has described studies that use I-Simpa to conduct acoustic simulations. However, this literature has never provided a detailed account of the method, set up, process and resulting outputs. Manuscripts 2 and 3 differentiate themselves against other studies using I-Simpa, in the level of detail provided to replicate the simulations. Considering that manuscript 3 has demonstrated the IPRAT's potential for acoustic comfort in a classroom, the next step was to test a prototype. Thus, manuscript 4 outlined the build, test, and analysis of a pilot IPRAT prototype, used in a medium-sized tertiary classroom. A key difference between this study and the previous one is that it measured a physical prototype rather than a simulation.

The results from this study compare classrooms with no IPRAT, with classrooms using IRAPT. This creates a rage of achievable RTs as the technology tested uses variable absorption profiles. Existing studies in literature test single RT values, and usually aim to improve the singular RT for the entire classroom with some form of acoustic treatment. Additionally, existing studies usually use qualitative acoustic optimisation, asking teachers which classroom acoustics they prefer, and getting children to perform listening tests. For example, Valentine (2002) conduct a pre- post-acoustic treatment study, and find the values improve from 0.69s to 0.43s in an unoccupied room. Again, only single RTs are achievable in the study. This research study is also helpful as it compares NZ classroom types to those overseas. The main differences found are that overseas classrooms are not permitted to use carpet tiles, so generally have higher RTs. They also usually have less noise generated from students in the classroom, and outside the classroom, but more mechanical noise. NZ schools typically open windows for ventilation, so intrusive noise from outside is an issue. Due to overseas classrooms having constant background mechanical noise, they often use signal to noise ratio as an important acoustic parameter. In NZ schools however, RT is typically the most important parameter to deliver acoustic improvements. Thus, although this RT optimisation research is transferable to overseas, such benefits may not be received as substantially as they would be for NZ classrooms.

6.3 Synthesis of statistical findings

This thesis revealed a set of significant findings for the simulation study and the case study individually. It is now important to compare these findings and draw further conclusions about the significance of this research. Individually, the two studies present significant improvements to acoustic comfort when using IPRAT, however it is important to compare the studies. This can reveal similarities or disparities between the data sets, to explain the accuracy of the results. It will also reveal any major differences in findings, to expose the validity of the results. If the two datasets agree with each other, the research aim will be more confidently confirmed.

Statistical analysis cannot, however, be easily performed for this data comparison, as the sample size and nature of the data vary significantly from the two studies. For example, in the simulations, C50 and G were analysed. This was to try and understand which acoustic parameter values would maximise acoustic comfort most appropriately for each aural situation. Thus, this C50 and G data helped to determine optimal RT values. However, this data cannot be compared with the case study research, as the only parameter measured in the case study was RT. Therefore, in this section, only the data for RT values will be synthesized. The nature of this data for both the simulations and case study includes 'current' RT in the existing classroom when not using IPRAT, a new range of achievable RTs when IPRAT is in use, and a theorised 'optimal' RT in varying situations. This data can finally be compared with the New Zealand acoustic design standards.

6.3.1 Simulation study data from manuscript 3

In the simulation, the improvements achieved by IPRAT were obtained by comparing current, achievable and optimal values for each acoustic parameter RT, C50 and G. Results highlight that acoustic improvements using IPRAT in classrooms is promising. When comparing the current (no IPRAT) versus optimal (using IPRAT) acoustic values, the following improvements are attained: a mean RT reduction of 0.56 seconds, a mean C50 increase of 4.49dB and a mean G decrease of 2.46dB. Additionally, the classrooms' ability to vary RT delivered benefits to acoustic comfort. When using IPRAT, in group discussions and quiet study where the sound should be absorbed, the RT can be reduced to as low as 0.49 seconds. In the same classroom, the RT can be increased to as high as 0.79 seconds for a lecture where a teacher needs to project their voice. This range of 0.3 seconds allows for improved acoustic conditions in the same classroom space, for changing aural situations. The most extensive RT range achieved in the study using IPRAT was 0.75 seconds – which could significantly increase student comprehension while reducing teacher vocal strain.

The raw simulation data to compare manuscripts 3 and 4 can be extracted from Figure 6.1. In this figure, the range achieved with IPRAT and the current mean parameter values are indicated for each classroom. This demonstrates the existing acoustic state against the potential acoustic states attainable with IPRAT. The extracted data is only the potential improvements in RT, as this is the acoustic parameter that can be compared with the case study data.

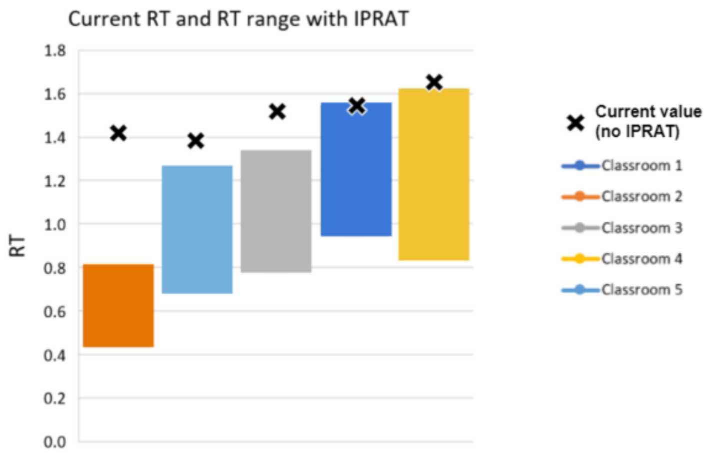


Figure 6.1. The current mean acoustic state of classrooms (not using IPRAT) indicated against RT range attainable when using IPRAT

6.3.2 Case study data from manuscript 4

In the case study, the improvements to acoustic comfort were quantified by comparing the current RT with the achievable RT when using IPRAT. When there is no IPRAT, the classroom has a constant RT of 0.94s, and by soft panels only, the RT was reduced to a static 0.65s. This is a significant improvement from the existing 0.94s RT, with a mean RT reduction of 0.29s. However, this didn't recognize classrooms as dynamic spaces, which is why our study went a step further to propose the benefits of using IPRAT to achieve lower RT's as well as the ability to vary RT between higher and lower values. So when using IPRAT, the mean RT achievable for open and closed states was 0.65s and 0.74s, respectively. Thus, the mean reduction of RT was 0.24s (slightly less significant than when using soft panels only) however the RT range achieved with IPRAT was 0.1s.

The crucial data from the case study research to be used for the comparison between manuscripts 3 and 4 can be extracted from Figure 6.2. This figure indicates the RT with no IPRAT (0% IPRAT coverage), and the RT achieved when the IPRAT is open and closed (16.85% surface area coverage of IPRAT). Although presented differently to the simulation data in Figure 6.1, the nature of the data is similar, so the two studies can now be analysed against each other.

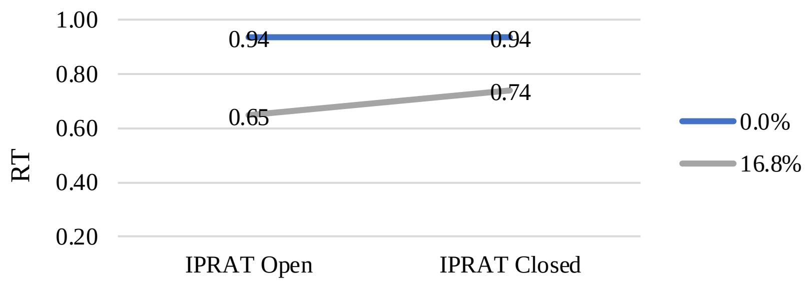


Figure 6.2. Minimum and maximum RT achieved with and without IPRAT

6.3.3 Comparison of simulation and case study data

The simulation study involved 5 classroom spaces of varying volumes (classrooms 1-5), and the case study involved only one classroom (classroom 6). Figure 6.3 shows the current RT values for each classroom compared to the ASNZS recommended high and low RT's. These recommendations are based on the classroom volume, so they differ slightly for each classroom. The ASNZS RT values differ only slightly between each classroom, and it is dependent on the classroom volume. This figure explains that the RT is too high in every classroom, and those from the simulation study (classrooms 1-5) are higher than the case study classroom (classroom 6). The RT in the physical classroom is likely a more realistic value than those in the simulation, and this is explained further below. Differences in current RT values are found between the 5 simulation classrooms due to geometrical and material differences in each space. This was crucial for the research to understand the effects of IPRAT is varying classroom characteristics. The difference between 'RT speech' and 'RT lecture' for each classroom is similar across all classrooms.

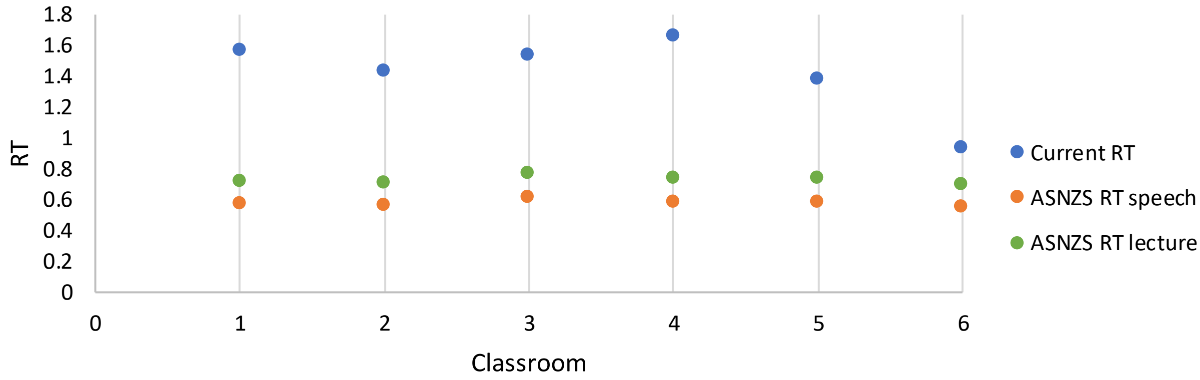


Figure 6.3. Current RT values versus ASNZS recommended RT values

Secondly, the current RT for each classroom is plotted alongside the achievable RT when using IPRAT (Figure 6.4). The difference between the data points 'IPRAT Open' and 'IPRAT Closed' represents the range of RT's that classroom achieved when using IPRAT. We can see from this figure that classrooms 1-5 from the simulation study achieve significantly larger RT ranges than classroom 6 from the case study. Furthermore, most of the simulation classrooms (all but classroom 2) present 'IPRAT Closed' values which look very similar to their current RT values. This is because, in these classrooms, the sound absorption of the existing wall was similar to the sound absorption of the panels in their closed state. However, for the case study classroom, the difference between the current RT and the 'IPRAT Closed' RT is more significant than the IPRAT range. This observation is more accurate, because, in reality, the panels in their closed state didn't act as perfect sound reflectors, as they did in the simulations. Similarly to figure 6.3, the data points presented here are likely more accurate for the physical classroom than for the virtul classrooms. Nevertheless, the data is very useful in communicating the effects of RT for varying classroom characteristics. In all classrooms, 'IPRAT Open' has a shorter RT than 'IPRAT Closed', and in all classrooms the RT is shortened when using

IPRAT in either state. The RT different between Open and Closed for classroom 6 looks small, however, we will see in following sections that this difference in fact presents an opportune RT range for a classroom under ASNZS guidelines.

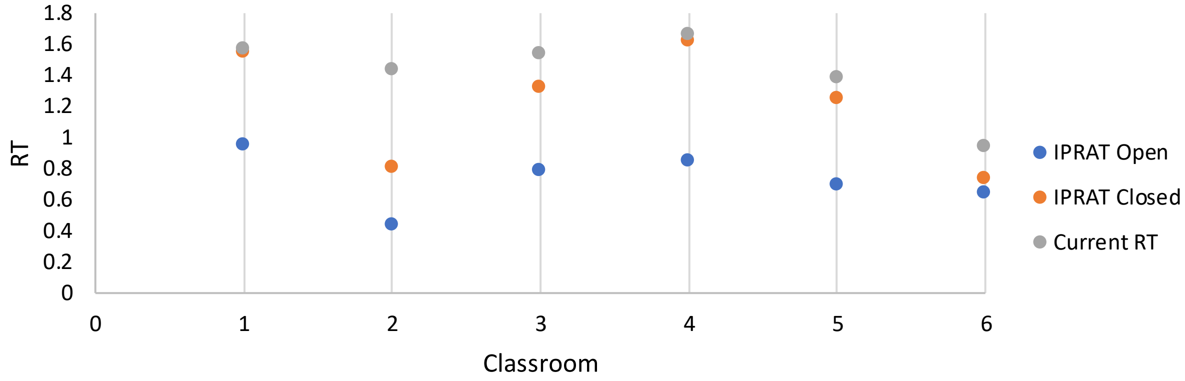


Figure 6.4. Current RT values versus RT values achieved with IPRAT

Finally, the IPRAT RT range achieved for each classroom is compared with the ASNZS recommended RT values (Figure 6.5). We can see that classroom 2 from the simulation study can, in fact, perfectly optimise the RT to meet both ASNZS recommendations, and even vary the RT higher and lower than this is desired. Additionally, classrooms 5 and 6 experience some cross over between what is achieved and recommended. And as shown in manuscript 4, adjusting the amount of IPRAT surface area coverage of classroom 6 can almost perfectly achieve the recommended ASNZS RT values for both room types. On the contrary, classrooms 1, 3 and 4 achieve RT ranges which are too high to meet the ASNZS recommendations well. It is important to remember here that the RT ranges achieved with the virtual classrooms are likely exaggerated, and a more realistic range is achieved in the case study classroom. We can also understand from this figure that the RT ranges achieved in Classrooms 1-5 are larger than what would be required to optimise RT in a classroom. The proposed range extracted from ASNZS is much smaller than the range achieved with IPRAT in every virtual classroom. Additionally, these IPRAT ranges mostly sit much higher than the ASNZS ranges. This helps us understand that if these values were truly accurate, the classrooms could benefit from additional surface absorption in the space to lower the RT of both IPRAT Open and Closed.

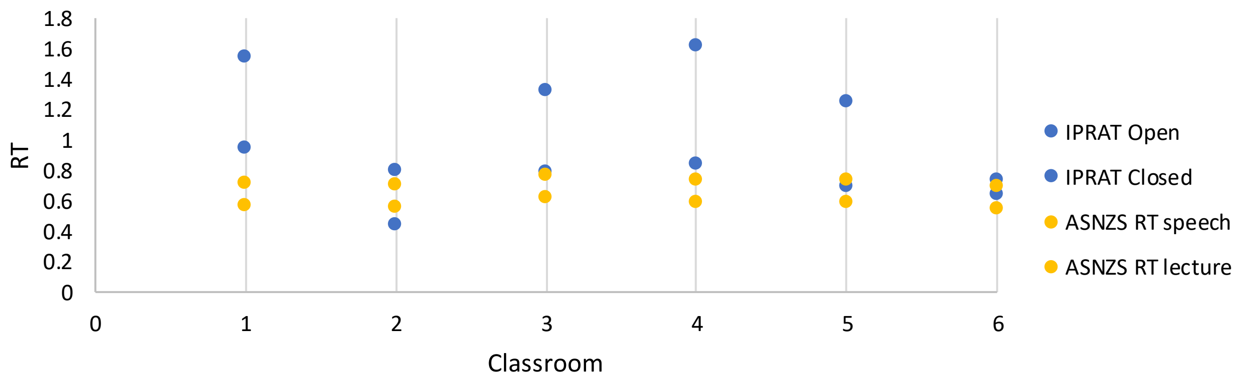


Figure 6.5. IPRAT in use versus ASNZS recommended RT values

Using this data, the researchers can further clarify these comparisons by finding the average values of the 5 simulation classrooms (Table 6.1). In this way, the visualisations created for the two studies hold a more direct and understandable correlation. It should be noted that the case study classroom had an IPRAT surface area coverage of 16.8%, whilst the average simulation classroom had an IPRAT coverage of 18%.

Table 6.1. Average RT values and other data for a direct comparison between the simulation classrooms and the case study classroom

Study	Volume	ASNZS RT speech	ASNZS RT lecture	Current RT	IPRAT Open	IPRAT Closed	RT range achieved	Mean RT reduction
Simulation at 18% coverage	226m3	0.59	0.74	1.53	0.74	1.31	0.57	0.49
Case Study at 16.8% coverage	170m3	0.55	0.7	0.94	0.65	0.74	0.1	0.25

It is clear from Table 6.1 that the results from the simulation are much more significant than those from the case study. This can be explained by the theoretical nature of the simulation, which could exaggerate the results without considering losses and abnormalities experienced in a real classroom: for example, acoustic flaws can arise, such as flutter echoes, room modes and focussing. Flutter echoes occur when sound is reflected back and forward against 2 hard surfaces. Room modes and focussing occur when sound is concentrated in certain places due to the room's geometry. The IPRAT panels for the case study were placed on the back wall as much as possible to reduce these unwanted acoustic flaws. However, they are unavoidable in such a hard-surfaced space. Another reason why the result differs is that the IPRAT panels perform perfectly in the simulation in their ability to change from a very low absorption to a very high absorption coefficient. In reality, however, it was discovered in the case study that these results are less pronounced. When the IPRAT is ‘open’ although sound can pass through the louvers to be absorbed, a lot of the sound will hit the perpendicular louvers anyway, and be reflected back into the space. Furthermore, when the IPRAT is ‘closed’ the louvers do not present as perfect acoustic reflectors, as they are made of a very thin, softwood. Thus, the range of RT achieved in the case study was 0.1s, whereas, in the simulation with a theoretically ‘perfect’ absorption variation, a range of 0.57s was achieved. Additionally, because such a large range was achieved in the simulation, the mean RT reduction when using IPRAT was much higher (0.49s) than the mean RT reduction in the case study (0.25s).

Despite the simulation study achieving a more significant RT reduction and RT range, when we compare it with the ASNZS recommendations, the case study data is much more significant. At a room volume of 170m^3, NZS Acoustic Standards recommends a mid-frequency RT of 0.55 for 'Rooms for Speech', and 0.7 for ‘Rooms for 'Speech/Lecture' (Standards New Zealand, 2016). Using the equation relating IPRAT coverage and RT from manuscript 4, the researchers can propose that at 20.5% coverage, the RT can be varied between 0.58 and 0.70s. This comes a mere 0.03 and 0.00s away from matching the industry standards for both room types. Thus, it can be confidently concluded that by using IPRAT in the case study classroom, the conditions of both room types can be satisfied – increasing the acoustic comfort in both classroom learning and classroom lecture (Figure 6.6).

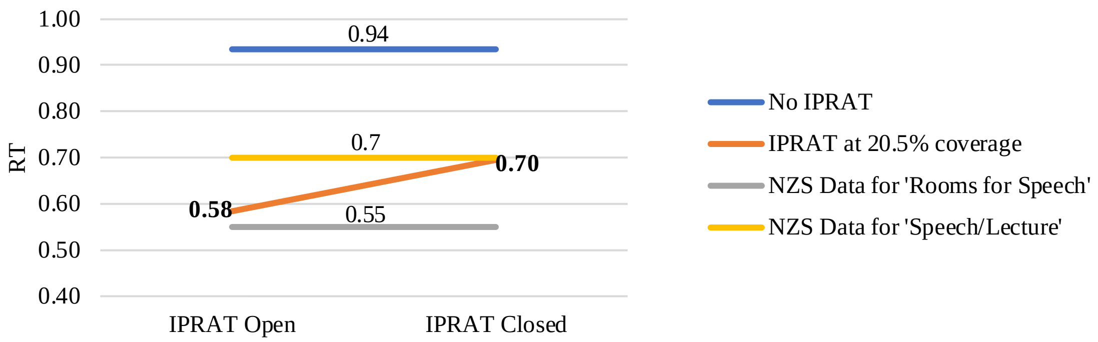


Figure 6.6. Case Study: IPRAT satisfying the recommended RT for both 'Rooms for Speech' and 'Speech/Lecture'

If we create the exact visualisation for the simulation data, it becomes apparent that the values are not as fitting for the ASNZS recommendations as those from the case study. At a mean room volume of 226m^3, NZS Acoustic Standards recommends a mid-frequency RT of 0.59 for 'Rooms for Speech', and 0.74 for 'Rooms for 'Speech/Lecture' (Standards New Zealand, 2016). The IPRAT in the simulation achieves a mean RT range between 0.74s and 1.31s. This is a dramatic 0.15 and 0.57s difference from the standards recommendations (Figure 6.7). Thus, the acoustic comfort is not as optimised for the simulations as for the case study.

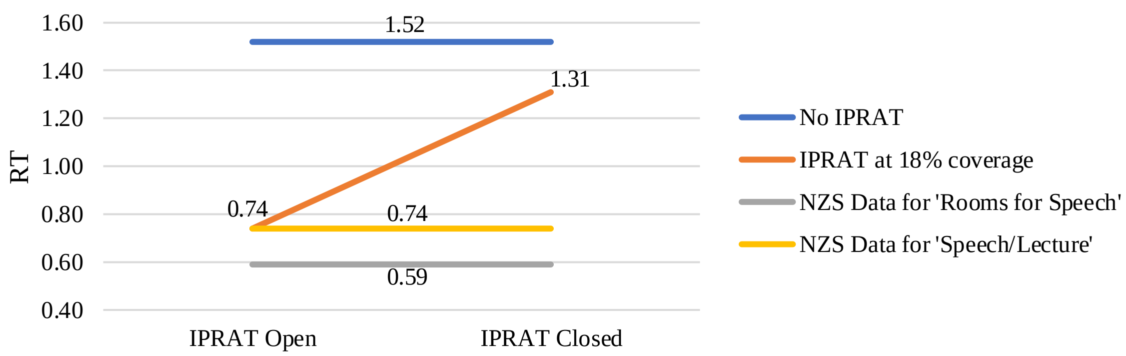


Figure 6.7. Simulation Study: IPRAT satisfying the recommended RT for both 'Rooms for Speech' and 'Speech/Lecture'

At a minimum, these classrooms can significantly lower the RT from what was currently very high RTs in the existing classrooms. Also, if by chance the RT's recorded in the simulations were inaccurate and too high, then the ranges achieved here would also be lowered, and would more likely meet the ASNZS recommendations.

6.3.4 How these results compare with similar research studies

The final RT range resulting from this research was between 0.58s and 0.70s for the case study, and between 0.74s and 1.31s for the simulation. This gives a variance of 0.12s and 0.57s respectively. It is interesting to compare these results with other technology which aims to vary RT. As discussed in section 2.4, there are a few developed technologies with this similar function (figure 6.8). First, the

Tessellations were used in a study which resulted in a range of 1.09s and 0.35s, however is was stated that this was unreliable, non verified data. Second, the Triffusor technology is in fact a patent, so no research was conducted on this. Last, the Evoke was tested and could achieve RT variance however the nature of the study was different. Rather than adjusting one room property and measuring a changing RT, the researchers adjusted the room properties of absorption and volume at a ratio to keep the RT as 1.00s. So, as they increased the volume they also increased the absorption. Thus, the RT range was not tested in this study.

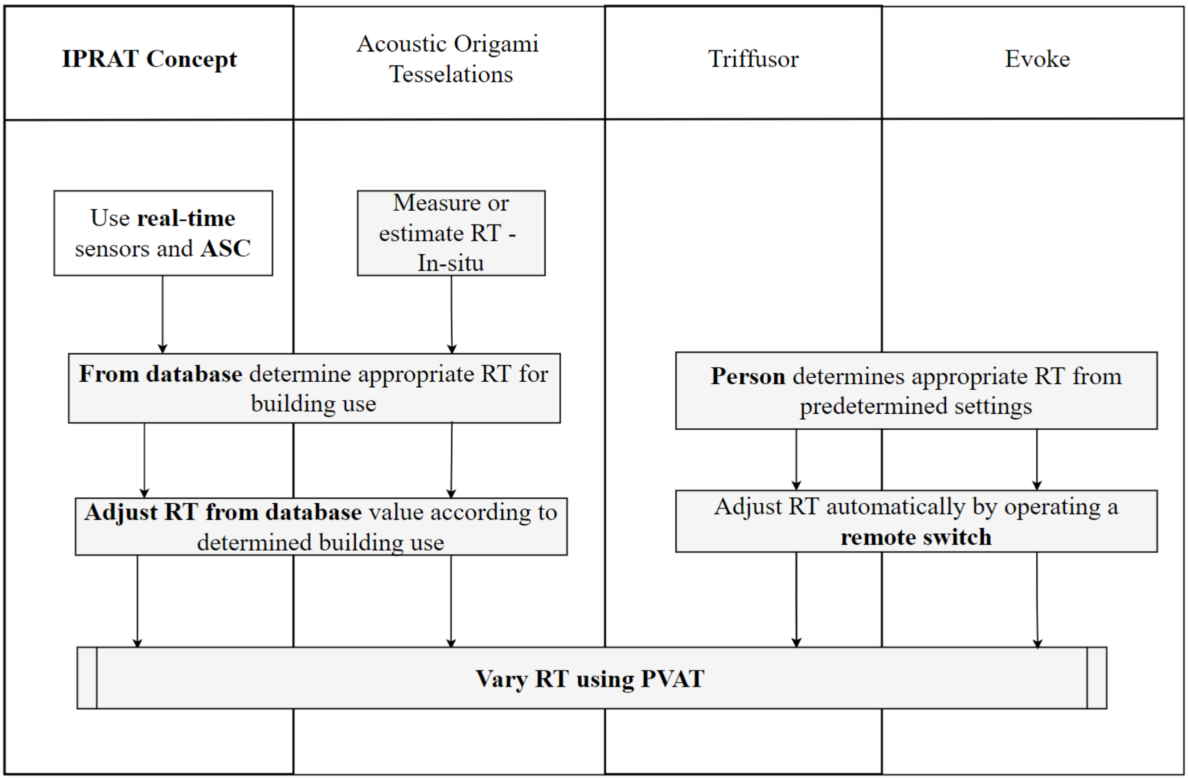


Figure 6.8. Behaviour of IPRAT compared with existing PVAT (illustration by the authors)

6.4 Practical Implications

The research in this thesis can be generalised to New Zealand. The study includes analysis of six classrooms. The first five classrooms were part of the simulation study, and the New Zealand catalogue of standard school building types published by the Ministry of Education was used to assemble this data (McNulty & McClurg, 2013). The most recent version of the catalogue contained 2 sections of interest, permanent classrooms (9 buildings scheduled in the catalogue) and relocatable classrooms (15 buildings scheduled in the catalogue). The catalogue defined classroom 'types' found in a selection of schools around NZ, by demonstrating qualitative and quantitative attributes of individual classrooms in each 'type'. Thus, these classrooms are not specific to any particular location within New Zealand. The sixth classroom was analysed for the case study, and was located in Auckland. However, the physical changes to acoustics in a room are more effected by building geometry and materials, rather than location and climate. In fact, climatical factors are negligible to room acoustic measurements. In this way, the research can be generalised to New Zealand, and other countries can also benefit from the data as long as they account for specific geometrical or material differences between their space and the spaces described in this thesis.

6.4.1 Educational acoustics in New Zealand

An interesting resource provided by the New Zealand government - Designing Quality Learning Spaces (DQLS) - outlines requirements for building quality learning environments for schools (Ministry of Education, 2020). The purpose of these documents is to:

> "Set mandatory minimum requirements for the acoustic design that are appropriate to and consistent across school facilities, create spaces and environments that are comfortable and support the educational delivery process across different teaching styles and practices, set a basis for evaluating the acoustic design of school buildings, set methods for evaluating acoustic performance when undertaking Post Occupancy Evaluation (POE) and facilitate school design that represents best value for expenditure while supporting educational outcomes"

In the second version of this document published in 2016, the Ministry has recommended ways to improve the acoustics of classrooms when a problem arises (Table 6.2). This information indicates some acoustic issues that can arise in classrooms, and some possible interventions to remedy this. For example, it is recommended to reduce RT when students have hearing impairments, or if background noise is high. It is recommended to include acoustic reflectors if teachers are struggling to project their voices. This fundamentally contradicts itself, as it recommends both increasing and decreasing RT, without recommending variable acoustic technology. And it is very likely that by intervening with one issue, you can remedy this issue but cause a new issue to arise. For example, if the teacher is struggling to project their voice, so you install acoustic reflectors, the RT may now be too high, result in excess reverberation. The acoustics of classrooms can never be truly optimised, without treating them as dynamic spaces, with varying needs.

Table 6.2. Common situations and possible interventions to remedy them (Ministry of Education, 2020)(Version 2)

Indication	Possible interventions
High background noise level from outside sources	Improve acoustic performance of façade, or shield façade from noise source
High background noise level from inside sources	Remove, replace or mitigate sound source(s)
High background noise level from adjacent spaces	Reduce reverberation time by installing absorptive panels/materials within spaces AND Improve acoustic performance between spaces
Excess reverberation	Reduce reverberation time by installing absorptive panels / materials
Teachers find it difficult to project their voices	Reduce internal background noise AND consider acoustic reflectors (specialist advice required)
Some students have hearing impairments	Reduce internal background noise AND Reduce reverberation time AND Consider an assistive listening device (for example, FM / Bluetooth)

Since then, a new version of this document has been released in 2020 – version 3 - which instead recommends fixed RT values. For classrooms less than 300m3 in a primary school should have an RT of 0.4-0.5s, and in a secondary school should have an RT of 0.5-0.6s. However, this is a minimum requirement, like most mandates are. The purpose of this research was to explore a technology that could work to optimise acoustics beyond minimum requirements.

6.4.2 Implications for vulnerable students

Under the Education and Training Act 2020, it is a requirement in NZ schools to design inclusive spaces with well-designed, well-balanced acoustics. Students with learning difficulties, hearing impairment, autism, students speaking a second language and blind or low-vision children all require additional consideration for classroom acoustics. This is because they are likely more sensitive to noise. They often need to concentrate more than other children, get more distracted, or struggle more with comprehension. It is recommended for these children to have separate break-out study areas with carefully designed acoustics. In reality, however, not every classroom can have multiple, acoustically separated areas, or the additional support required to effectively use separate areas simultaneously. These recommendations will only manifest in new or retrofitted classrooms. This thesis holds great significance for all vulnerable students, as it explores a novel option to remedy poor classroom acoustics in smaller spaces that don't or can't include break-out areas of acoustic separation.

Of additional significance for this research are the implications it holds for Tamariki Māori (children of Māori ethnicity). The New Zealand hearing screening statistics indicate that being of Māori descent significantly increases your risk factor for hearing impairment when entering both preschool and primary school (McLaren, 2008) (Figure 6.8). This is a devastating reality for these Tamariki, who, through no fault of their own, begin school already at a physical disadvantage to the average New Zealand student. Pacific Island students are also at a greater risk for hearing impairment (McLaren, 2008). The research done as part of this thesis to improve acoustic conditions for all students, is therefore holding even more significant importance to these minority groups.

Reporting period	Preschool (3 years old) Tympanometry Failure (%)				New entrant (to primary school) Failure (%)			
	Overall	Maori	Pacific Is	Other	Overall	Maori	Pacific Is	Other
1983	15.5	*	*	*	19.2	*	*	*
1993-4	*	16.4	12.5	7.5	*	13.9	14.7	7.2
1999-0	5.7	11.6	9.3	4.3	*	13.1	16.4	5.1
2000-1	6.3	13.1	11.4	4.7	6.4	11.3	10.9	4.5

* denotes figures that cannot be obtained.

Reporting Period	Preschool (3years old) tympanometry - Failure %(Referrals*)						New entrant (primary school) – Failure % (Referrals*)					
	Overall	Maori	Pac Is	Asian	Pakeha Euro	Other	Overall	Maori	Pac Is	Asian	Pakeha Euro	Other
2001-2	7.8	11.8	14.9	7.2	7.1	5.3	7.8	12.1	17.1	5.0	4.3	6.1
2002-3	6.9	11.1	14.3	5.7	3.4	4.4	8.1	12.6	16.1	5.6	3.9	7.2
2003-4*	7.1	10.5	11.3	5.9	4.8	5.7	6.5	9.9	13.1	4.5	3.7	4.6

2003-2004 period the terminology changed from "failure" to "referral" as shown by *)

Figure 6.8. The New Zealand hearing screening statistics (McLaren, 2008)

6.4.3 Design recommendations for professional practice

The use of IPRAT in the future built environment is highly possible. Technology rarely seizes to progress and advance, so it is almost inevitable that eventually, the built environment will be fully intelligent in all aspect technologically possible. We have seen now that IPRAT is in fact possible, but the adoption of this technology may not be immediate. Firstly, the space required in a room for IPRAT to occupy, to perform effectively, is significant. This will need to be overcome by incorporating the technology into the design from an early stage, most probably for new builds only. Trade-offs will need to be made between wall space, wall aesthetics, other wall hangings, glazing and allowing room furniture to be pushed against a wall. Every project would present a unique set of conditions to design with, and acoustic engineers would be required to offer expertise in the use and instalment of the technology. To retrofit the technology into existing spaces, certain requirements would be a blank wall which is not used for teaching activities or windows. Due to these requirements, you may not be able to cover enough wall space with the technology to achieve the optimised RTs for each space use.

Secondly, the need for this technology has not been formally expressed or requested in industry. IPRAT is a big leap from current main-streamed acoustic design, so it is more likely for the technology to progress and be adopted in smaller increments. Thirdly, the cost to develop and refine IPRAT will be large, and the time investment will be substantial. This is another argument for a slower progression of intelligent acoustic technology development and adoption. To ease the industry into automated and controllable acoustics, a simpler technology is recommended by the authors. This comprises of the same PVAT with mechanical actuators, but which is remotely controlled by an occupant. Guidelines and recommendations can be provided to the occupants on how to optimise the use of the technology. After or alongside this industry adoption, the PVAT can be automated further by programming it to respond to basic sound level in a room. This would not optimise the acoustic comfort and may not suit every building space, but could provide improvements to a manually remote controlled system. Nevertheless, the industry has a long way to come before building owners and architects fully realize the need for this technology and can justify the extra budget in order to optimise acoustic comfort (figure 6.9).

Barriers within current practise	**Lessons and recommendations for the future**	**Key industry personal**
Acoustic comfort is largely neglected within IEQ. Acoustic optimisation is perceived as a complicated design aspect and thus is often avoided as a core topic in architecture curriculum.	Acoustic comfort should be taught in all architectural courses as having equal importance to other IEQ's. The discomfort associated with poor acoustics for varying space uses should be understood by students.	**Academics**
The acoustic design of spaces is often neglected, as it is set as a low priority. Clients wont intuitively budget for acoustic design. Acoustic optimisation is often an afterthought. When designed for, the acoustics of a space is considered, a trade off is made for varying space uses.	The acoustics for varying space uses should be optimised. Acoustic engineers should be employed on project teams to advise the most appropriate technology to achieve the varying acoustics.	**Designers**
The development of variable acoustic technology is slow, and the current technology in development is unaffordable. No technology is in development which would provide intelligent optimisation.	Engineers should continue to test and develop variable acoustic technology, with the goal being to create affordable variable acoustic options.	**Engineers**
Acoustic standards recommended singular acoustic states for flexible and dynamic spaces., including classrooms.	Acoustic standards should reflect the changing acoustic needs for flexible and dynamic spaces, beginning with recommended classrooms acoustics	**Policy Makers**

Figure 6.9. Barriers and lessons for key industry personnel

6.5 Future research directions

Many outputs from this thesis will be useful for future research works (figure 6.10).

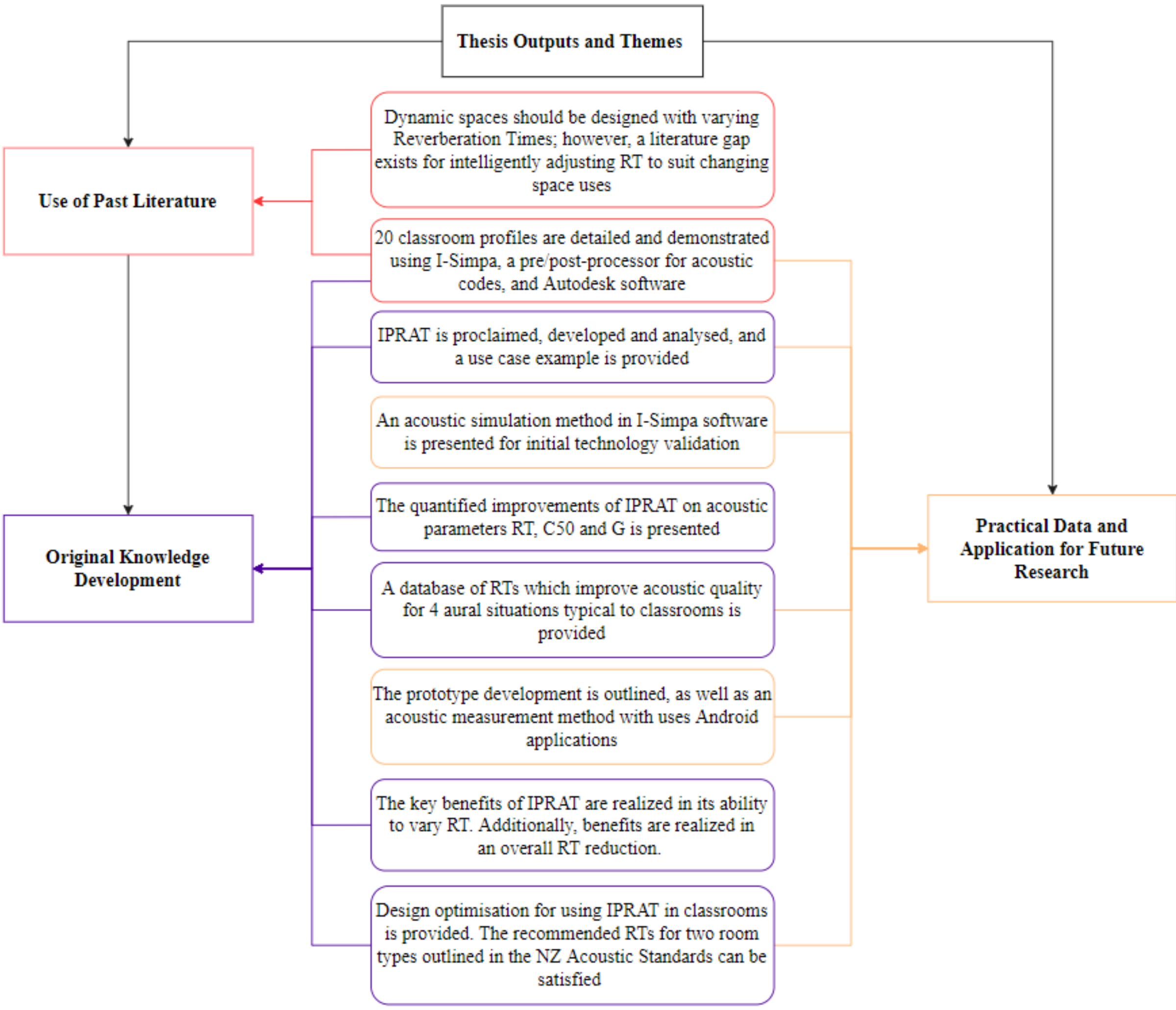


Figure 6.10. Thesis outputs and themes including practical data and application for future research

6.5.1 IPRAT prototype progression

Future studies should work toward developing a functional IPRAT prototype. In this study, only the PVAT component was tested in the case study. Training and building an acoustic scene classifier for a classroom will be very time intensive. Before this model is trained, it would be beneficial to add a smaller level of intelligence to the PVAT first. For example, the next step could be to add a smart component to the prototype, which can rotate the louvers via a smart phone app, for optimized control and precision. For this, stepper motors can be connected to the rotation rods and an Arduino board is used to control their rotation. The Arduino board should be programmed to achieve the required rotation and given Bluetooth connectivity for remote control via a smart phone. This is a cost-effecting solution to give the PVAT smart control. Once this technology is validated, the IPRAT prototype should include an acoustic scene classifier to detect aural situations.

In order for the acoustic scene classifier to accurately identify the acoustic 'scene', it must be trained with data sets containing SPL recordings of each of the proposed acoustic scenes. This training can be implemented by adapting a Support Vector Machine (SVM) and using trial-and-error. SVM's extract and engineer selected audio features from SPL recording datasets. The SPL recordings should be 3 seconds long to ensure successful detection in dynamic spaces where aural situations can change quickly. The number of recordings required to maximize the SVM will depend on the successful results of each evaluation.

With these sound recordings, various quantitative data should be extracted and coded numerically. The audio features to extract for this SVM application are: zero-crossing rate, energy, the entropy of energy, spectral centroid, spectral spread, spectral entropy, spectral flux, spectral roll-off, mel frequency cepstral coefficients, chroma vector and chroma deviation. The features should be trialled, and an appropriate combination found to maximize the model's success. For transferability, the pitch should not be chosen as a feature, as it varies for different aged building occupants. Speech intelligibility differs for different age groups (D. Yang & Mak, 2021).

From here, patterns can be recognised to form the basis of the machine learning model. The model should be improved and include many different sound parameters to improve its classification accuracy. Then, the model should be tested in a live classroom. This research could, in fact be done independently of the PVAT prototyping. Thus, once the classifier is complete, it can be integrated with the smart PVAT described above to complete a functional IPRAT prototype.

6.5.2. PVAT materials

Prototyping different PVAT options can result in different outcomes for IPRAT that might be more or less effective and thus, future studies should look into them. Experimenting with different absorber and reflector materials could help to optimise the technology. Additionally, different materials could offer benefits to higher or lower frequency RT's. Additionally, certain materials perform better at absorbing sound at different frequencies. To demonstrate this, the case study RT data was plotted for each mid-frequency band (Figure 6.11). You can see that the RT at lower frequencies is longer. By optimising the RT at different frequencies using different materials, with different absorption spectrums and diffraction, the global RT can be improved to suit the situation.

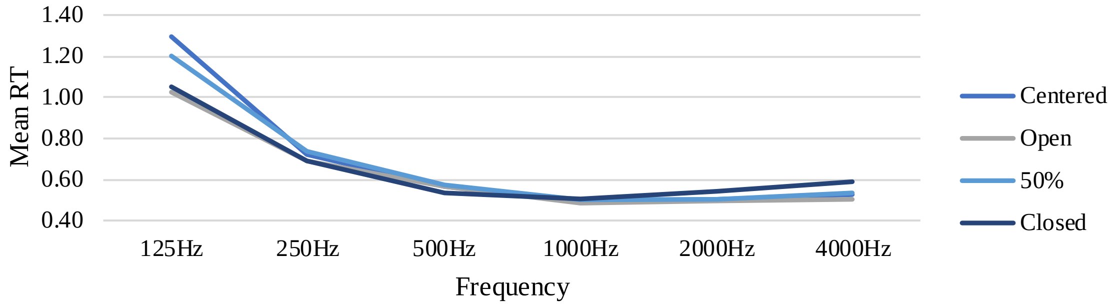


Figure 6.11. Mean RT at different frequency bands for case study data

6.5.3 IPRAT benefits

Going a step further, the IPRAT benefits should not only be quantified in terms of acoustic parameter improvement, but the effect on people should be studied, both quantitatively and qualitatively. For example, questionnaires or interviews could be used to understand how people respond to the IPRAT technology, and which benefits they consciously realize. Another interesting way to test the technology would be to have study participants do a series of listening, comprehension and concentration tasks whilst using the IPRAT in a normal, live classroom. These test results can be compared with the students completing the same tests without the use of IPRAT. For future studies, using EEG technology, we can also measure their brain responses to the applied intelligent acoustic technology, to monitor their level of stress, relaxation, focus, or other qualities. In this way, the actual benefits to acoustic comfort in classrooms using IPRAT can be realized.

Future studies should also aim to experiment with the instalment of this technology in various existing classrooms spaces. This will further the understanding of the use of this technology for acoustic retrofit, including how to have a low impact on the function and layout of each space. The use of higher quality measurement equipment is also necessary for future research. Existing spaces should also be examined from a quantitative perspective in further detail to see which space types will benefit the most from IPRAT.

6.6 Disruption due to Covid-19

The original research plan in 2019 was to test a prototype in a live classroom environment, with teachers and students partaking in regular classroom activities. This plan was disrupted due to Covid-19, given the new approach several NZ universities, including AUT, adopted for teaching online. As a result, the research was significantly limited in its ability to collect the originally intended datasets. The data collection relied on observing classroom spaces in their normal, natural state. There were no planned face-to-face lessons for the rest of Semester 1 2020, and it was unknown if such classes would recommence in Semester 2 2020 or not. Based on a secondary announcement, the primary mode of delivery for the second semester of 2020 at AUT would also remain online. There was also a possibility that if classes did commence back with face-to-face learning, they would be altered in some way to adhere to social distancing protocols or reduction in class sizes than what would be normal proportional to the physical size of the classroom. Furthermore, there could have been fewer students in the spaces than normal due to New Zealand border restrictions. If face-to-face learning commenced in 2021 and the research could have been reliably undertaken, it would be 12 months behind schedule. The accuracy of the data relied on the classroom spaces being used in a normal occupied setting, so any of the above circumstances would disrupt this requirement. Thus, the research plan was adjusted to include an extensive simulation study, and a smaller case-study component which would test a prototype in an unoccupied setting. Nevertheless, the construction of this prototype was also disrupted in the 2021 New Zealand lockdowns, meaning the louvers had to be manually rotated rather than this rotation being automated. Luckily, this did not negatively affect the collected data in any way. Additionally, the original research aim was satisfied using the new methods adopted due to Covid-19 outbreaks and lockdowns.

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Chapter 7. Appendices

Appendix 1. Acoustic discomforts addressed in the literature regarding inappropriate RT

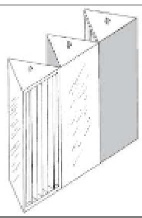
Table 7.1. Summary of RT discomforts from literature

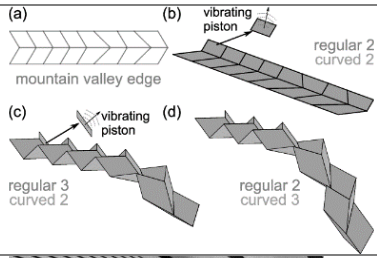
RT Condition	Acoustic Discomfort	Discomfort Explained with Source(s)
A Long RT Increases Exposure to Noise	Exposure to long or high-intensity noise can be damaging to hearing health	The first issue found associated with long RT is the subsequent increases in noise exposure. Lupăşteanu et al. (2018) discovered high intensity or long duration noise exposure could affect the human body negatively. This could cause hearing health impairment, temporary threshold shift, or noise-induced hearing loss, as described by Selamat and Zulkifli (2016). Noise contributes perpetually to occupational disease, including workers in a hospital environment due to the extensive sound pollution from mechanical devices, medical equipment, workers and patients (Loupa et al., 2019).
	High noise can create fatigue and decrease in cognitive performance	Another side effect of increased noise exposure is its' adverse implications on employee efficiency. Studies by Asadi et al. (2017) and Morales and Manocha (2018) found levels of efficiency to decrease in spaces with distracting noise, concluding that high noise levels harm the fatigue levels and thus productivity of employees in the workspace. Abbasi et al. (2018) additionally proved that mental and visual fatigue, as well as psychological stresses, increased rapidly when exposed to low-frequency noise of 65–75 dBA.
A Long RT can Create the 'Lombard Effect.'	Occupants feel stressed and overwhelmed by noise, especially vulnerable occupants; elderly, disabled, autistic	Secondly, long RT is found to increase sound levels enough to initiate the 'Lombard Effect.' This occurs when people in a space increasingly speak louder (increase the Signal-to-Noise Ratio (SNR)) to be heard over the existing noise levels in the space (Urbán, Zrneková, Zaťko, Maywald, & Rychtáriková, 2016). Board rooms often have high RT's due to their typically rectangular shape. This results in excess ambient noise when more than one person is speaking, resulting in a substantial acoustic build-up of signal noises reverberating in the space (Gramez & Boubenider, 2017). High sound levels in buildings can also pose a safety hazard or annoyance issue (Mahmud et al., 2018). Public address signals could be unheard by occupants, for instance, in evacuations, natural disasters, attacks, or merely closing times and transport departures, as reported by Samaras and Ferreira (2019).
	Excessive noise in classrooms makes teachers speak louder	A correlation was found by Rabelo et al. (2019), relating vocal dose in women and excessive noise in a space. Moreover, Rollins, Leishman, Whiting, Hunter, and Eggett (2019) suggested teachers put themselves at risk for developing a vocal disorder. Rabelo et al. (2019) indicated that as background noise increases, teacher vocal effort increases, and distress arises in both teachers and students. A study by Bottalico (2017) similarly measured teachers' increase in vocal effort in reverberant spaces, and found that they were raising their voices based on their perceived RT.
A Long RT can Decrease Speech Intelligibility	Decrease of understanding and communication clarity - children feel tired and lose concentration and motivation when learning	The third issue associated is long RT was decreased speech intelligibility or STI. A decrease in STI decreases communication clarity (John et al., 2016), making comprehension and understanding difficult. Similarly, this poor acoustic design is associated with hindering concentration in educational and commercial institutions, making effective communication problematic (Golmohammadi, Aliabadi, & Nezami, 2017). Correspondingly, speech intelligibility affects phonetic learning, the process of learning through sound stimuli, taking place when a second language is being learned (Munro, 2016). Reverberation in a space can distort or confuse sound making it especially challenging to learn, particularly for adults (Vlahou et al., 2019). Equally, Kitapci and Galbrun (2019) confirmed a positive relationship between STI and subjective speech intelligibility scores for students in Hong Kong classrooms, whose education system was taught in English rather than Mandarin. These intelligibility scores decreased when speaking their non-native language (D. Yang & Mak, 2018).
	Speech is not intelligible, so audiences do not enjoy	Moreover, the quality of a musical or theatrical performance depends heavily on the stage's acoustic condition hence the RT, measured from the audience's perspective as well as the performer's perspective (Panton et al., 2017). This is

	a performance	because performers must accurately hear their voices or instruments for their natural feedback system to make improvements (Suyatno et al., 2019).
A Long RT can Boost Disruptive or Chaotic Environments	Increase of chaotic environment causes a general sense of discomfort for the occupant	Furthermore, along RT was found to unfavourably boost disruptive or chaotic environments. Subtle noise differences in our environments relative to the spaces' normal sound levels (SNR) is noticed by humans and interpreted as distractions (Renz, Leistner, & Liebl, 2018). Occupants exposed to high levels of ambient noise are subsequently more irritable and sensitive when it comes to hearing signal noises from inside or outside the building (Park & Lee, 2019). This frustration causes a general sense of discomfort for the occupant, and thus a low overall environmental comfort (Setunge & Gamage, 2016). Acoustic masking is often needed in open-plan offices, emitting wasteful sounds into a room purely to increase ambient noise for speech privacy (Hongisto & Keränen, 2018).
	Increase of chaotic environment causes adverse effects on children's development	Additionally, the mental health of adolescents and children was reported to be negatively associated with noise and noise sensitivity, especially for those children in low socioeconomic categories (Lim et al., 2018). Gao et al. (2018) studied a childcare centre, and participants were not satisfied with the acoustic conditions of the space, as it was not well insulated from external and internal noise. Subsequently, the unfavourable acoustic environment led to adverse effects on children's development, vision, hearing, and psychology.
A Short RT can limit how Sound Travels in a Space	An increased mental effort from students – strain and ill motivation experienced	In contrast, it was found that when RT is too short, voices and sounds are not enhanced by reverberation, resulting in adverse acoustic effects. Hurtig et al. (2016) suggested that when SNR is low, short RT's can make communication clarity difficult, as the sound dissipates too quickly within the space. Additionally, the mental performance and wellbeing of children in classrooms could be detrimentally impacted (Klatte et al., 2017). In a classroom with a low RT, the mental effort required for students to listen to the teacher is increased (Amlani & Russo, 2016). These findings correlated negative academic performance and wasted mental energy, pointing towards an optimum RT increasing academic performance.
	Music is not enhanced or drawn-out so loses its' pleasantness	Similarly, without a short RT, music, or voice, is not enhanced or drawn-out, so it loses its' pleasantness (Cairoli, 2018). Thus, theatre companies risk losing revenue as audiences may not enjoy a performance to its full potential. Designing for the correct RT in a large hall is, however, controversial as discomforts could arise due to many other acoustic symptoms (Alibaba & Ozdeniz, 2019). Often, multiple acoustic techniques have to be combined to achieve appropriate conditions to alleviate the various acoustic discomforts that arise in large halls.

Appendix 2. Summary of existing PVAT solutions

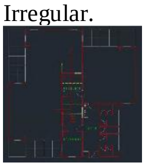
Table 7.2. PVAT solutions

Level of Intelligence	PVAT	Illustration	Source(s)
None	Manual Portable	Any curtain or acoustic screen	Howarth and Robinson (2017) Inácio (2018) Holzman et al. (2010)
	Manual Fixed	No Illustration	Cairoli (2018)
Programmable motorized, controlled remotely	Triffusor		D'antonio (2002)

Acoustic Origami Tessellations		Zou and Harne (2017) X. Yang (2017)
Evoke		Adelman-Larsen (2018).

Appendix 3. Additional data for creating the 5 virtual classroom environments

Table 7.3. Appropriate data assembled based on The New Zealand catalogue of standard school building types

Classroom/ PMIS code:	**Dimensions**	**Roof Structure/ Shape & Ceiling Cladding**	**Floor Structure. Covering = Carpet for all.**	**Wall Structure and covering**	**Glazing**	**Layout of Furniture**
CANTY - Permeant	9m x 7.2m or 9x9m with mono pitch roof variation. 3m height.	Centre ridge along building length, 10-15deg. Corrugated steel supported on timber trusses. Gib Board between trusses with Pinex acoustic tile on sloping section.	Concrete slab on grade or suspended timber floor with load bearing concrete foundations.	Light timber framing with summerhill stone, clay brick or masonry concrete block. No insulation. Painted Gib covering.	Large glazed walls to north, 2m height.	Multiple tables seating 4
CANTINT - Permeant	9m x 7.2m. 4m height	Mono pitch roof. Pinex acoustic tiles on ceiling	Concrete slab on grade.	Light timber framing. Pinex acoustic tiles on end wall. Minimum or no insulation	Large glazed walls to north and south.	Front facing desks seating 2 with gap down centre.
DOM - Permeant	7.8x10m. 3.8m height.	Timber trusses ridged centrally. Heavy tile roof or corrugated steel. Roof angle 20-30deg. Gib board ceilings.	Suspended timber floor with concrete perimeter foundation walls.	Light timber framing. No insulation. Gib board walls.	Fully glazed front façade.	Multiple tables seating 4
NEL1 - Permeant	Unclear. 4m height.	Corrugated metal roofing with timber frame or trusses. Gib ceiling.	Suspended timber floor with concrete perimeter foundation walls. Or concrete slab on grade.	Timber frame. Gib board.	Large glazed windows on side. Celestial windows on opposite side.	Front facing desks seating 3 with gap down centre.
OPAIR - Permeant	Irregular. 	Pyramid roof with central roof lantern. Internal timber trusses. Pinex ceiling tiles.	Concrete slab on grade.	Timber framed with fibre cement sheet. Minimal insulation. Gib board.	High level glazing to roof lantern.	Few tables seating 4.
VRNDA - Permeant	55m2 square (7.5x7.5m) 3m height.	Corrugated Steel. 30deg pitch centre ridge. Gib board ceiling in some cases. Unclear what other cases look like.	Suspended timber floor on piles and continuous perimeter foundations.	Timber framing, Gib board covering.	Verandas along north walls and large sliding doors. High clerestory windows.	Unclear.
S68Generic - Permeant	Unclear.	Flat butynol roof. Timber or steel rafters and timber ceiling without covering.	Concrete slab floor.	Masonry block or brick veneer with reinforced concrete block structure. Minimal insulation.	South facing clerestory windows. Irregular spaced	Front facing desks seating 2 in 3 columns.

					windows on other walls.	
Whanau - Permeant	Unclear.	Corrugated metal roofing on exposed gang nail trusses. Gib board ceiling in some cases. Unclear what other cases look like.	Suspended timber floor on piles and continuous perimeter foundations.	Timber framing. Gib board.	Verandas alongside elevations. High clerestory windows.	Desks in continuous formation around room, Stools used. Or, irregular shaped desks with computer in groups of 4.
150 - Permeant	Unclear. Approx. 7x12m. Height 3m.	Corrugated metal roofing with timber frame or trusses. Gib board ceiling.	Suspended timber floor with perimeter concrete foundations.	Timber framing. No insulation.	Large glazed walls to north.	Front facing desks seating 2 with gap down centre.
Aranui - Temporary	7.5x10m. 3m height.	Corrugated metal with central ridge beam. Pinex acoustic tiles.	Suspended timber floor with folded “Scott web” bearers	Asbestos fibre cement. No insulation.	Large glazing both sides.	Single desks arranged continuously around room in 2 semi-circles.
CEB1 - Temporary	8x9.2m	Corrugated metal with central ridge beam. Pinex ceiling tiles.	Suspended timber floor	Asbestos fibre cement. No insulation.	Some glazing on north and south	Straight rows of back-to-back computer setup.
CEB2 - Temporary	8 or 7.5m wide. 8x9.2m 2.9m between portals	Corrugated metal. Gang nail timber portal frames at 3m centres with metal capping. Pinex ceiling tiles.	Suspended timber floor with piles under portal frames.	Walls built in panels between portals. Asbestos fibre cement. No insulation.	Some glazing on north and south	Unclear.
CEB3 - Temporary	7.5x8.9m	Corrugated metal. Gang nail timber portal frames at 3m centres with metal capping. Gib board ceilings.	Suspended timber floor with piles under portal frames.	Walls built in panels between portals. Asbestos fibre cement. Insulated.	Glazing on north and south. Aluminium glazing.	Front facing tables seating 2 or 3, in 3 columns.
CEB4 - Temporary	7.5x8.9m	Corrugated metal. Gang nail timber portal frames at 2.9m centres with metal capping. Gib board ceilings.	Suspended timber floor with piles under portal frames.	Walls built in panels between portals. Asbestos fibre cement. Insulated.	Large, high glazing on north and south.	Front facing tables seating 2 or 3, in 3 columns.
LAING - Temporary	7.5x8.9m	Corrugated metal. Gang nail timber portal frames at 2.9m centres. Gib board ceilings.	Suspended timber floor with piles under portal frames. May be built on concrete slab.	Fibre cement with corrugated metal below windows. Insulated.	Large glazing on North and South.	Desks set up in long L shaped rows.
NAYL - Temporary	7.5x9m. or 7.5x22m.	Timbre trusses ridged centre along length. Corrugated steel roof. Flat ceiling Gib board.	Suspended timber floor.	Light timber framing. Fibre cement cladding. Insulated.	Only low-level glazing.	Unclear.
Opus - Temporary	10x7.6m or 10x3.8m with fibre cement panel in middle. 2.6m stud height.	Light weight colour steel. Timber trusses. Flat plywood ceiling diaphragm with acoustic tiles.	Suspended timber floor.	Timber frame with corrugated colour steel and fibre cement.	Double glazed, some glazing on all sides.	Front-facing tables seating 2 or 3.
OEB1 - Temporary	8.13x8.6m	Lightweight steel on steel trusses. Pinex ceiling.	Suspended timber floor.	Timber structure. Asbestos fibre cement. Plasterboard to walls. No insulation.	Large aluminium windows on north and south.	Single desks facing front, not connected.
OEB2 - Temporary	6.5x10m	Lightweight steel on Timber purlins on steel trusses. Monopitch roof.	Suspended timber floor.	Timber structure. Asbestos or plywood cladding.	Large glazing on north and south.	Unclear.

				Plasterboard to walls. No insulation.		
OEB3 - Temporary	9x7.5m	Lightweight steel on Timber portals. Pinex ceiling.	Suspended timber floor.	Timber structure with timber weatherboards. No insulation.	Some glazing on north and south.	Front-facing tables seating 2 or 3
WSW - Temporary	Unclear.	Timbre trusses ridged centre along length. Corrugated steel roof.	Suspended timber floor. On timber piles.	Light timber framing. Cladding steel or fibre cement weatherboard-type.	Little glazing on north and south.	Unclear.
Portacom - Temporary	Up to 12m long.	Colour steel insulated roof panels on steel portal frames. Reflective metal ceiling.	Suspended timber floor.	Steel cladding. Insulated.	Little glazing on north and south.	Unclear.
UNIT - Temporary	10x7.5m	Corrugated metal roofing on timber portals at 3.2m. Some with flat ceiling. Pinex ceiling.	Suspended timber floor.	Timber framed walls. Hardboard weatherboards. No insulation.	Only low-level glazing on north and south.	Multiple tables seating 4.
Woolston - Temporary	Unclear	Corrugated metal roofing on steel trusses.	Concrete slab.	Timber frame with fibre cement cladding and concrete gable ends.	Large glazing on north and south.	Front-facing tables seating 2.

Note: All buildings contained a lot of art/posters on walls, cupboard and bookshelves.

Appendix 4. Additional I-Simpa Instructions to software

When importing the model to 3dsmax, do not link it, or combine objects. Secondly when importing into I-Simpa, be sure to repair the model and activate tetgen. Upon importing, check the dimensions of the model and create a plane receiver at the correct height (1.2m works the best for animations).

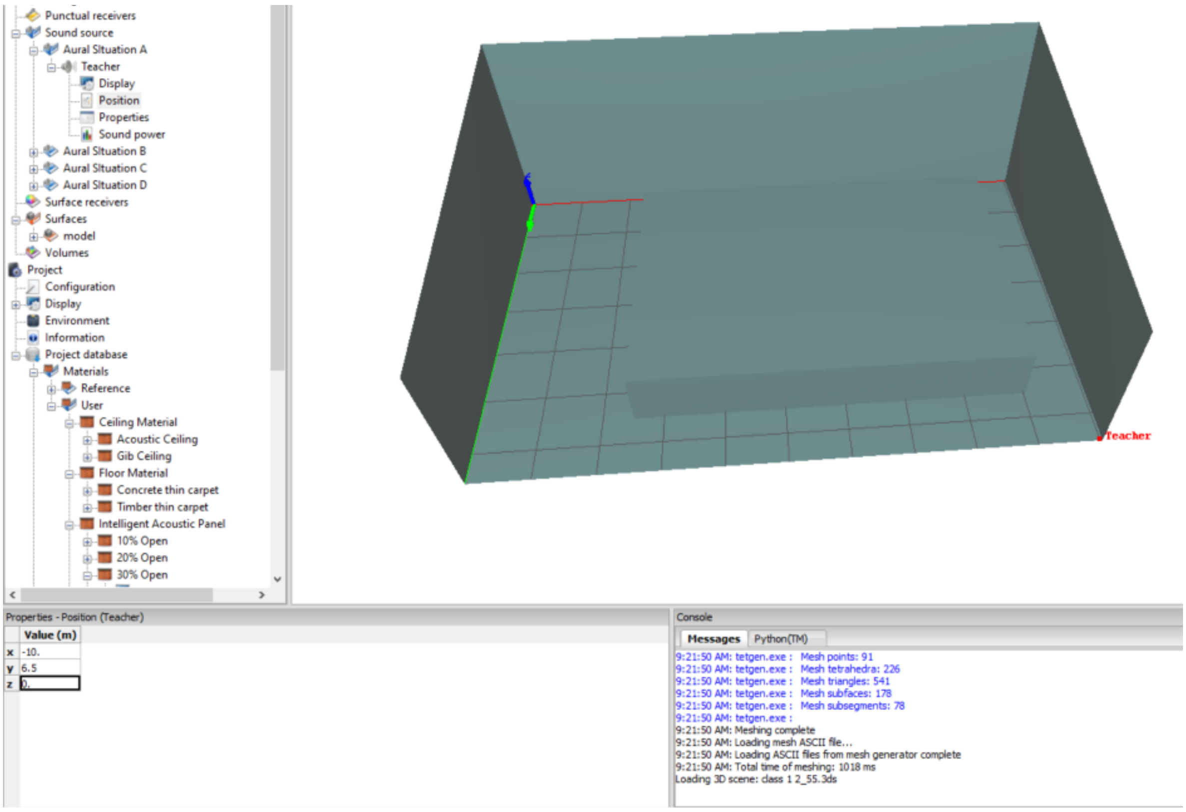


Figure 7.1. Checking dimensions of the model (as seen in the bottom left corner, the precise position of the mark 'teacher'

Generate a meshing and visually activate the meshing to check your dimensions. Now surfaces can be applied to groups. For the classroom example, 'seating area' group was created last, as it could easily include the rest of the surfaces which had not yet been assigned. Now the surface materials can be applied to the surface groups, and this can be saved as a template for your basic and all-encompassing environment. Copies of the template can be made, and upon opening each separate copy, one aural situation can be enabled per template and space positions applied.

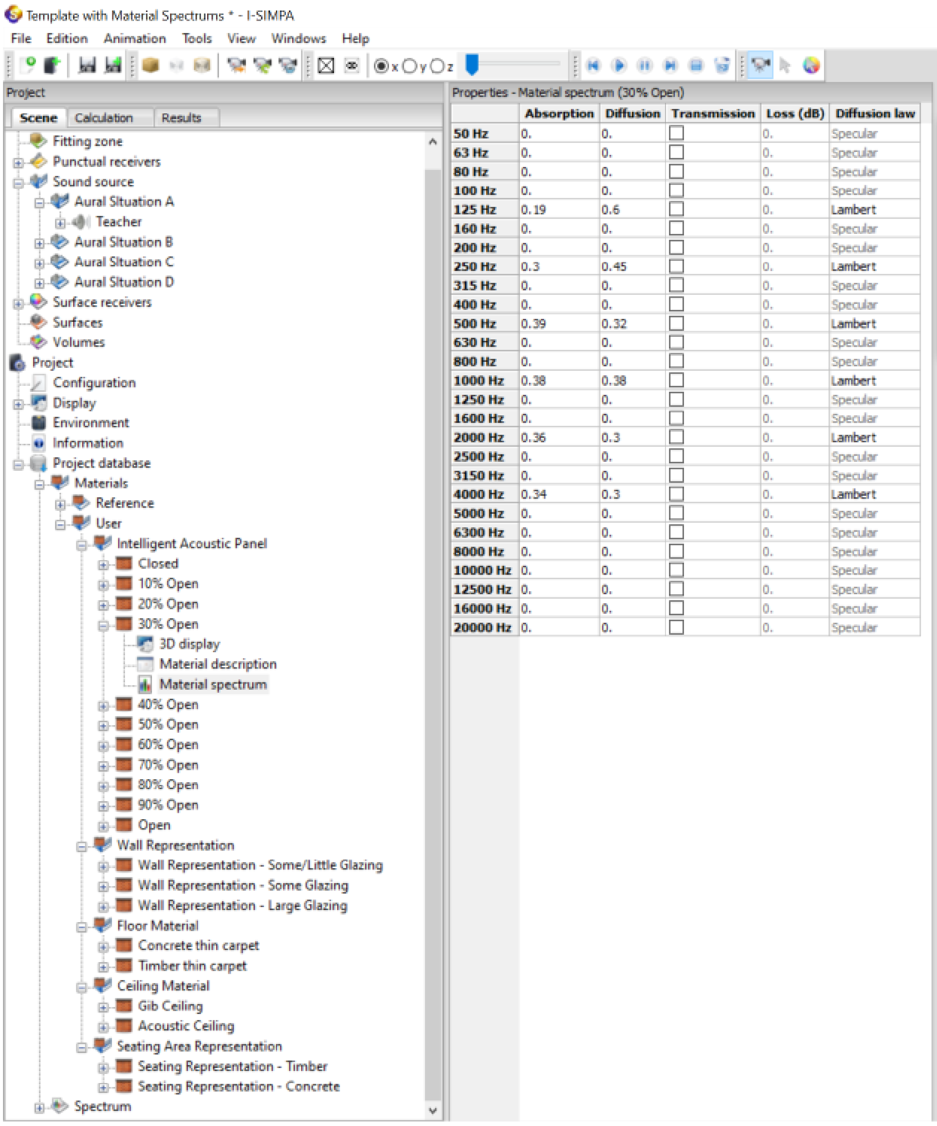


Figure 7.2. Template in I-Simpa with user-loaded material spectrums, selected calculation spectrum, surface groups, aural situation sound sources and sound levels (not position or directivity)

The easiest way to use the templates is to then adjust the wall properties in increments, re-calculating and saving each calculation results report with a clear label, within the same I-Simpa environment file. So, when it comes to analysis, each file can be opened and the various results reports easily accessed.

Spreadsheet - SPPS\2020-08-16_16h52m05s\acoustic_param.gabe

Acoustic parameters

	Sound level (dB)	Sound level (dBA)	C-50 (dB)	C-80 (dB)	D-50 (%)	Ts (ms)	RT-15 (s)	RT-30 (s)	RT-60 (s)	EDT (s)	ST (dB)
125 Hz	36.427	36.427	5.5012	10.0017	78.018	37.4756	0.482	0.504	0.536	0.460	2.7120
250 Hz	39.344	39.344	5.7152	10.3125	78.851	36.5983	0.465	0.481	0.505	0.448	2.5992
500 Hz	42.3103	42.310	6.3949	11.2895	81.343	34.2217	0.418	0.420	0.400	0.412	2.3130
1000 Hz	46.1781	46.178	4.6511	8.8875	74.478	41.0328	0.520	0.520	0.497	0.511	3.3087
2000 Hz	47.594	47.594	7.8307	13.3634	85.852	30.0525	0.355	0.356	0.339	0.353	1.4542
4000 Hz	51.6503	51.650	5.6518	10.2300	78.607	36.8284	0.460	0.461	0.451	0.451	2.6982
Global	54.396	54.396	5.9302	10.5560	79.665	35.8891	0.456	0.466	0.467	0.439	2.4913
Average			5.9575	10.6808	79.525	36.0349	0.450	0.457	0.455	0.439	2.5142

Figure 7.3. Example of I-Simpa output spreadsheet

Appendix 5. Additional data for simulation measurement

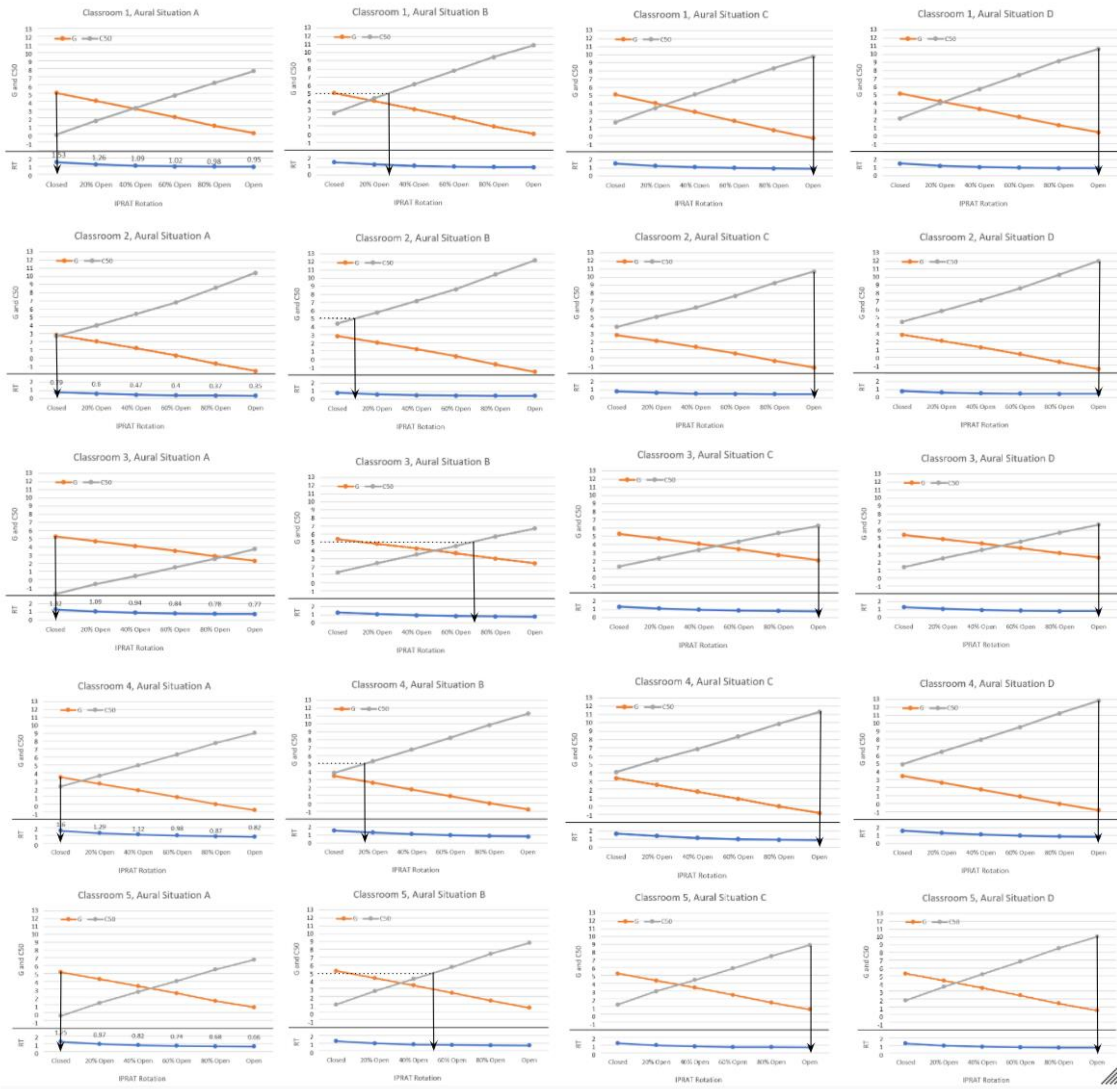


Figure 7.4. Deriving optimal IPRAT rotations

Table 7.4. All simulation means for each classroom environment

Classroom	Aural Situation	RT difference	C50 difference	G difference
1	A	-0.03	0.06	0.07
1	B	-0.33	2.46	-1.28
1	C	-0.64	8.23	-5.33
1	D	-0.60	8.65	-4.71
2	A	-0.63	0.71	-0.08
2	B	-0.74	1.24	-0.41
2	C	-0.95	7.48	-4.06
2	D	-0.96	8.16	-4.31
3	A	-0.21	-0.02	0.03
3	B	-0.55	3.81	-1.96
3	C	-0.76	5.11	-3.21
3	D	-0.74	5.43	-2.81

4	A	-0.03	0.97	-0.02
4	B	-0.28	1.61	-0.67
4	C	-0.83	7.64	-4.13
4	D	-0.81	8.34	-4.26
5	A	-0.13	-0.04	0.07
5	B	-0.70	4.09	-2.82
5	C	-0.69	7.56	-4.54
5	D	-0.67	8.25	-4.69

Appendix 6. Statistical test assumption checking for simulation data

In manuscript 3, a multiple regression was run to explain RT improvement from the classroom and aural situations. Beforehand, the researchers needed to check the standard assumptions for regression stand true: normality, independence of residuals, linearity, multicollinearity, normality of residuals and homoscedasticity. Our dependant variable (RT improvement) satisfies the requirement of being continuous, and there are 2 independent variables which are categorical (Classroom and Aural Situation). Firstly, the researchers have already demonstrated the data for RT improvement is normally distributed. Second, a Durbin Watson test was performed with 1.439 returned (less than 1.5), proving no autocorrelation between observations. Third, a scatterplot was created to check for linearity, confirmed with a generally linear trendline.

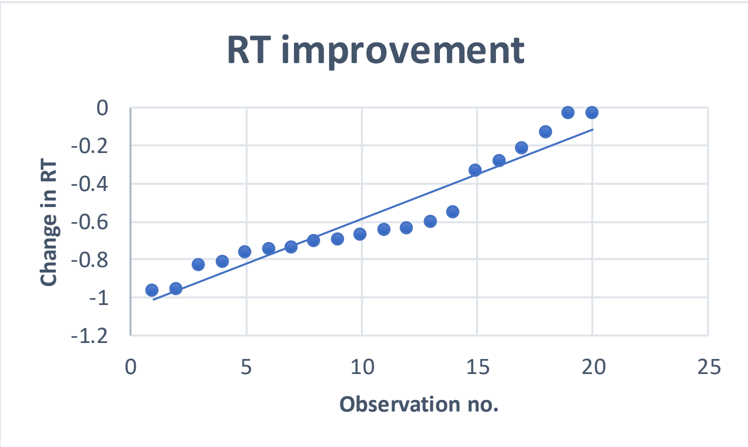


Figure 7.5. SPSS linearity of data check

Next, multicollinearity was tested for in SPSS. With VIF statistic=1 for both variables (so <3.0), no variables were multicollinear. The normality of residuals was confirmed using linear regression on SPSS, from the scatter plot. The normality of residuals was tested due to the small sample size, and was confirmed using linear regression on SPSS, shown on the scatter plot.

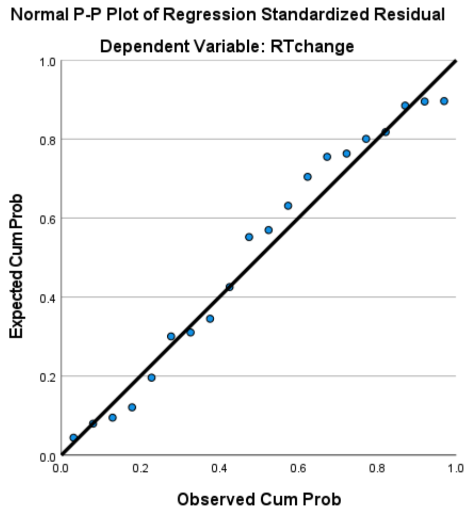


Figure 7.6. SPSS normality of residuals data check

Lastly, a linear regression test in SPSS was used to confirm the homoscedasticity of the data. The data contains no significant outliers, highly influential points, or high leverage points.

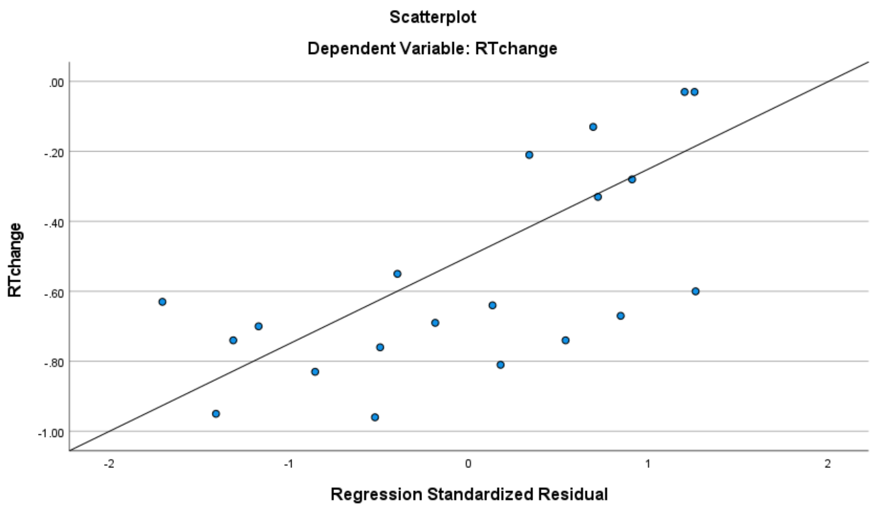
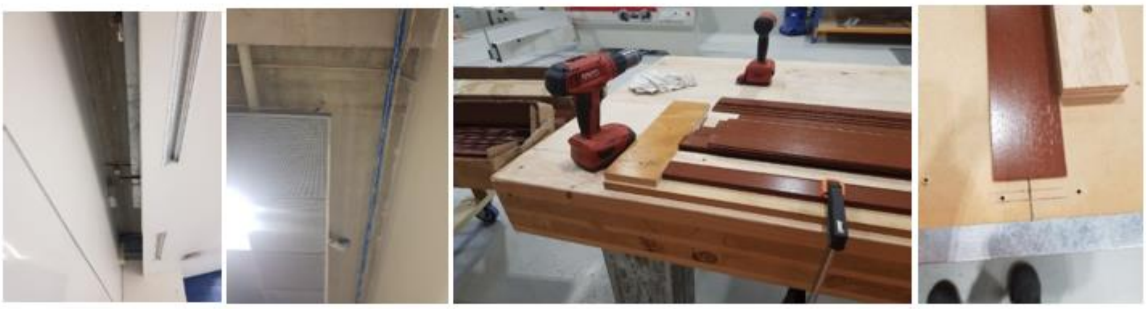


Figure 7.7. SPSS homoscedasticity of data check

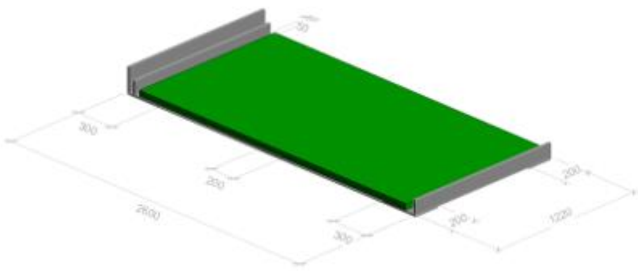
With the assumptions checked, the multiple regression analysis was run for classroom and aural situations. These variables statistically significantly explained RT improvement, $F(2, 17) = 10.9$, $p < .0005$, $R2 = .562$. Individually, the classroom variable was not a significant predictor for RT improvement, however, the aural situation was $p < .001$.

Appendix 7. Additional details on constructing the prototype

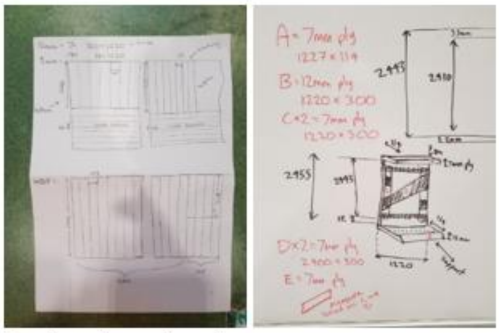


Classroom ceiling space

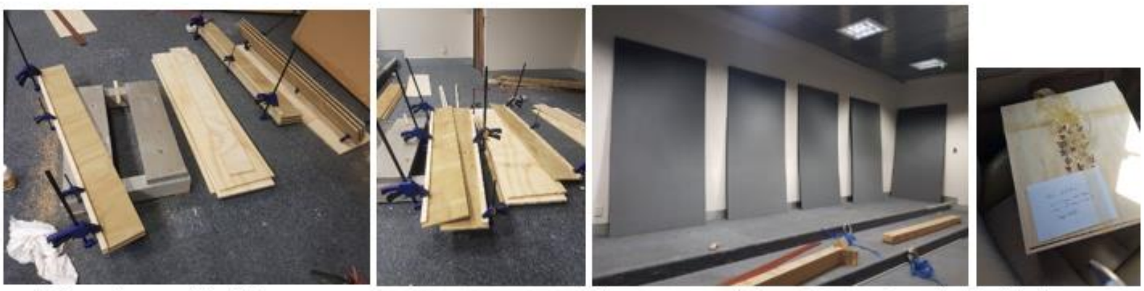
Preparing slats



Planning plywood backing on CAD



Construction planning on paper



Building plywood baking

Classroom with soft panels only

Gift for Autex

Attaching slats to panels

Finished panels

Figure 7.8. Photos from the construction process

Appendix 8. Pre-prototype measurement of two under-performing apps

In this section, the use of two measurement apps is detailed, which eventually didn't work well enough when the prototype was installed, so they were replaced with other measurement apps.

Two Android applications were initially identified for RT measurement and were used in conjunction to confirm the validation of the individual applications. The first application is Reverberation Time Pro (Nachhallzeit), developed by Prof. Dr. Wolfgang Kröber and released in February 2017. This application measures the drop in sound pressure level after a sound is created loud enough to trigger the measurement, e.g., by popping a paper bag. The RT is displayed, and the graphical display bars will be green if there was sufficient sound data for that frequency for the statistical analysis within the app. Only measurements with all sound frequencies satisfied will be used for the data collection. It is recommended that 3-5 RT measurements are taken with this app, and an average is found. The second application is APM Tool Lite by Suonoevita, last updated in December 2020 (Suonoevita | en | SeV) This application works similarly to the previous one, measuring an RT at each octave band and calculating an average of 3 measurements.

Figure 7.9. Left: Screenshots from Reverberation Time Pro (Nachhallzeit) (Krober). Right: Screenshot from APM Tool Lite (Suonoevita)

The accuracy of Nachhallzeit has been studied by comparing its measurements with a professional RT setup, and a standard deviation of 0.08 seconds was found, validating the use of this app for accurate measurements (J.A., Vílchez Gómez, & Rubio García, 2016). Another study comparing 3 RT applications found the APM tool to be the more accurate, and Nachhallzeit a close second (Bengtsson & Sandefeldt, 2019).

Before the prototype was constructed and set up, the RT was measured. 8 measurement receiver locations were defined in the space, to include and accurately average the RT measurement in all areas of the classroom (Figure 0.10). The RT was measured 3 times at each receiver location, using 3 different sound source locations. These RT measurements were taken before the prototype was installed. The average for each measurement location is shown in Table 0.5.

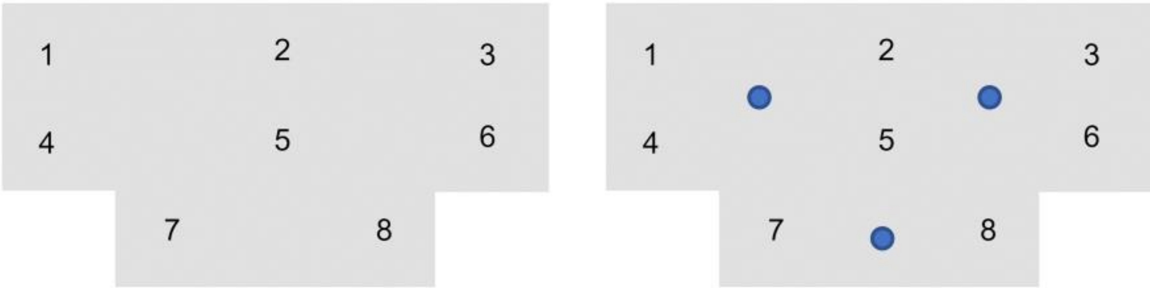


Figure 7.10. Left: RT receiver locations. Right: Sound source locations

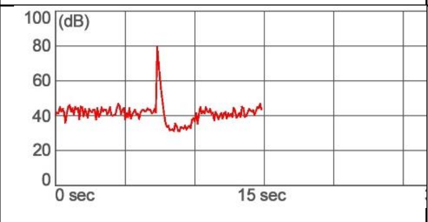
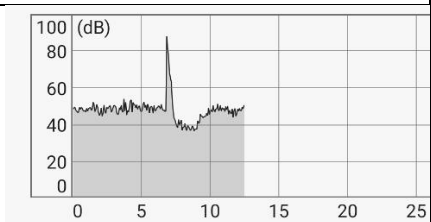
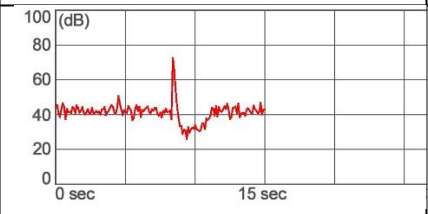
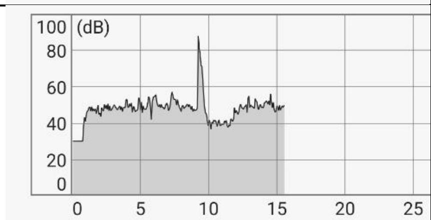
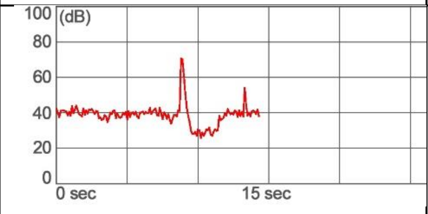
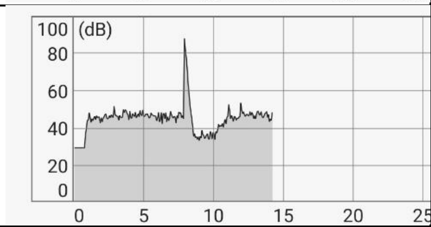
Table 7.5. Pre-prototype RT measurements on 2 apps

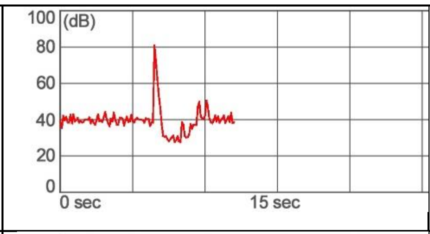
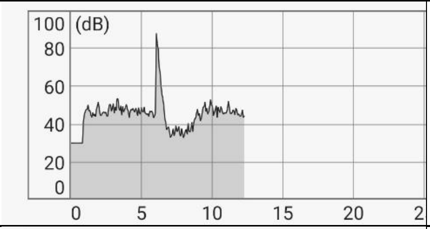
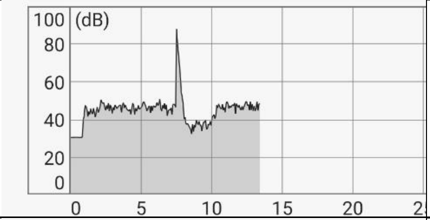
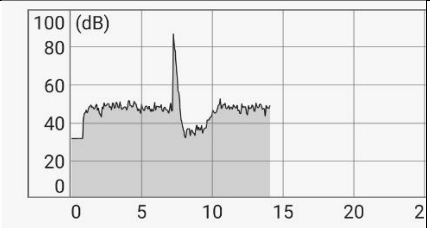
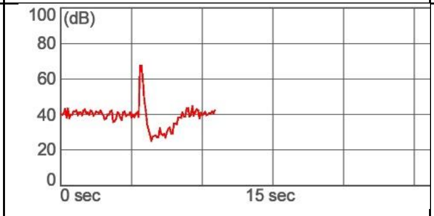
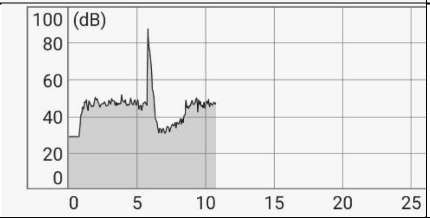
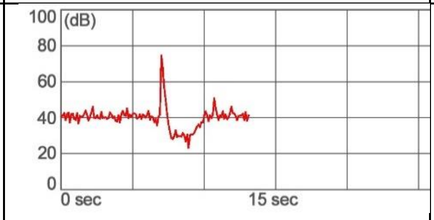
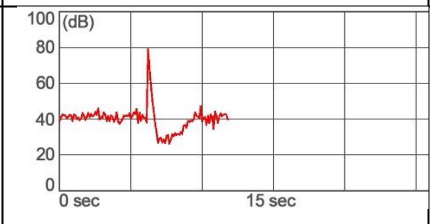
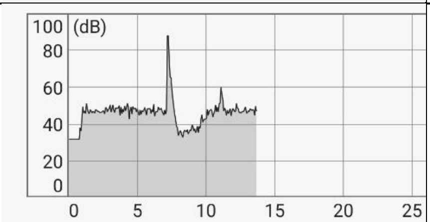
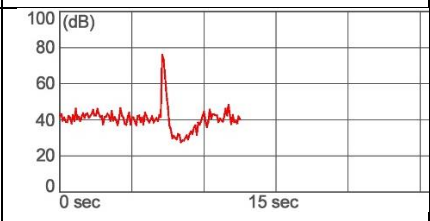
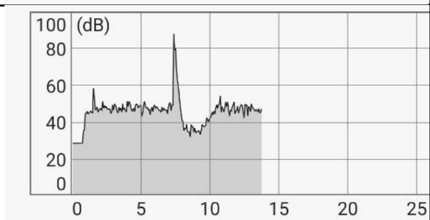
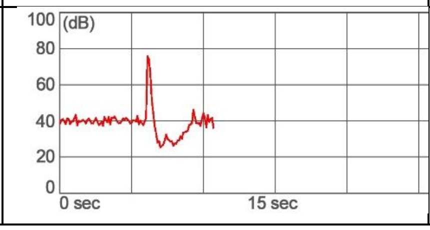
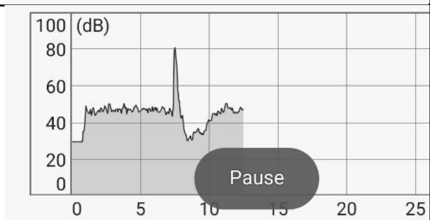
Location	RT measurement average of 3 measurements from RT Pro	RT measurement 2 average of 3 measurements from APM tool
1	0.9	0.83
2	0.87	0.93
3	0.88	0.99
4	0.8	0.83
5	0.83	0.82
6	0.79	0.81
7	0.83	0.91
8	0.91	0.83
Average	**0.85**	**0.87**

In the end, the 2 apps used here did not give complete readings once the prototype was installed. Thus, 3 new apps were found. Nevertheless, the initial data for pre-prototype measurement for these 2 apps is interesting to note.

Appendix 9. Additional data for case study measurement

Table 7.6. Raw data for deriving RT from SPL apps

		App 1	Ave	App 2	Ave
All Closed	1a		44.8		48.5
	1b		40.0		49.4
	2a		42.0		45.5

	2c		43.6		48.1
All Open	1a		40.3		44.6
	1b		42.2		49.2
	2a		39.7		46.7
	2c		41.1		46.4
All half to left	1a		36.1		47.4
	1b		38.9		47.2
	2a		39.7		46.6

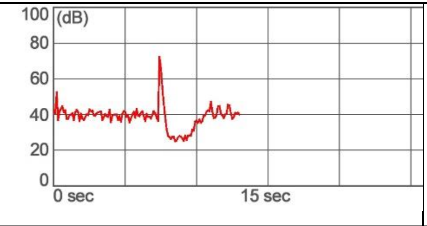
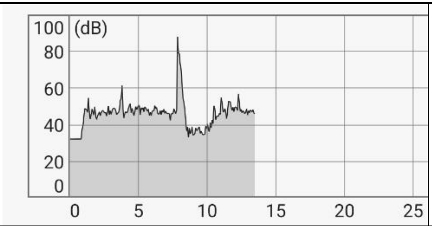
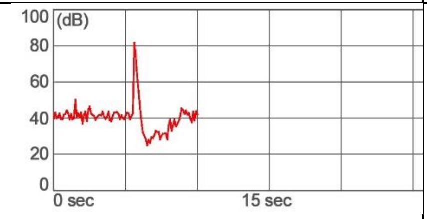
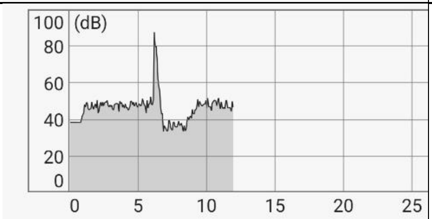
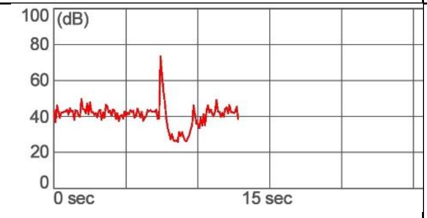
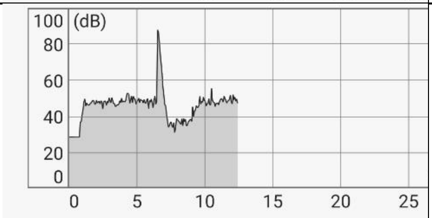
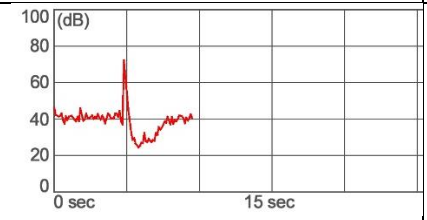
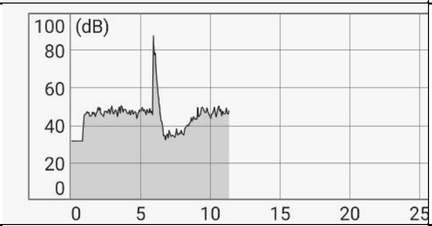
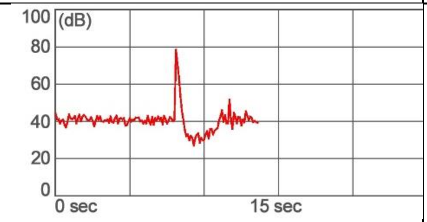
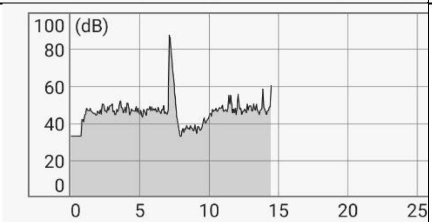
	2c		40.3		46.1
All facing to center	1a		43.4		46.0
	1b		43.5		49.5
	2a		41.3		46.2
	2c		38.7		46.7

Table 7.7. Deriving the equations relating RT and IPRAT coverage

	Equation				
coverage	**m**	**c**	**when x=100, RT=**	**when x=0, RT=**	**Variance=**
0.0%	0	0.935	0.935	0.935	0
8.4%	0.000456	0.79124	0.83679	0.79124	0.04555
16.8%	0.000911	0.64748	0.73858	0.64748	0.0911
25.2%	0.001367	0.50372	0.64037	0.50372	0.13665
33.6%	0.001822	0.35996	0.54216	0.35996	0.1822
42.0%	0.002733	0.2162	0.4895	0.2162	0.2733

Appendix 10. Case study statistical test results

Table 7.8. Shapiro-Wilk results showing normality of each IPRAT state data set with and without outliers

		Shapiro-Wilk – With Outliers			Shapiro-Wilk – Without Outliers		
	IPRAT	Statistic	df	Statistic	df	Sig.	Statistic
RT	No IPRAT	.921	6	.510	Not affected by outliers		

Soft panels only	.887	4	.369	Not affected by outliers		
IPRAT Open	.908	20	.058	.955	20	.449
IPRAT Centered	.954	20	.427	Not affected by outliers		
IPRAT 50%	.965	20	.648	.932	20	.169
IPRAT Closed	.919	20	.095	Not affected by outliers		

Table 7.9. The results from the Games-Howell multiple comparisons test

			95% Confidence Interval	
(I) IPRAT	(J) IPRAT	Sig.	Lower Bound	Upper Bound
IPRAT Open	IPRAT Centered	1.000	-.0369	.0395
	IPRAT 50%	.098	-.0712	.0043
	IPRAT Closed	*.039*	*-.1257*	*-.0026*
IPRAT Centered	IPRAT 50%	.069	-.0715	.0020
	IPRAT Closed	*.032*	*-.1266*	*-.0044*
IPRAT 50%	IPRAT Closed	.521	-.0915	.0301

Appendix 11. Ethical considerations

There was not a requirement to gain ethics approval for the simulations, as there were no participants and no physical spaces used. Ethical consideration was however obtained for the Case Study by AUTEC. The ethical consideration for the case study included gaining permission from AUT Estates to set up and use the prototype in a classroom. A more extensive research plan including making sounds and measuring audio data in a live classroom was also originally approved, however, this was not needed in the end as the Covid-19 epidemic caused a shift in the research methods.

Appendix 12. Program for panel surface area requirement

```
# Megan Burfoot, 29/07/2019, INITIAL CONSULTATION

# This code calculates the m2 of acoustic device a space would need
# depending on its unique features of that space

import numpy as np

# Store input numbers
print("This code calculates how many square meters of acoustic device your"
      " space will require to satisfy the whole RT range within your space")
vol = float(input('Enter Volume (m3): '))
sa = float(input('Enter Surface Area (m2): '))
rt = float(input('RT with no occupancy: '))
rto = float(input('RT with full occupancy: '))
q = float(input('Enter level of quality/accuracy you would like: 1 = Regular, 2 = High
Quality, 3 = Ultra High Quality ___'))

# Define graph gradient and thus RT range for quality
if q == 1:
      x = 1
elif q == 2:
      x = 1.2
else:
      x = 1.4
```

```
# Calculate Absorption coefficient of Space
cso = round(.161 * vol / (sa * rto), 2)
cs = round(.161 * vol / (sa * rt), 2)

# Calculate RT max and RT min. These equations could change based on
# what RT's I think are required in classrooms
rtmn = round((np.log10(vol) * .2 / x - .07), 2)

if vol == 50 or vol < 50:
    rtmx = round((np.log10(vol) * .38 * x - .07), 2)
else:
    rtmx = round((np.log10(vol) * .36 * x - .07), 2)

# Calculate Maximum Needed Device Surface Area
sdomx = round(((.161 * vol / rtmn) - cso * sa )/(0.95 - cso), 2)
sdomn = round(((.161 * vol / rtmx) - cso * sa )/(0.05 - cso), 2)
sdmx = round(((.161 * vol / rtmn) - cs * sa )/(0.95 - cs), 2)
sdmn = round(((.161 * vol / rtmx) - cs * sa )/(0.05 - cs), 2)

sd = max(sdomx, sdomn, sdmx, sdmn)
sw = round(sa - sd, 2)

# Print calculation results
print("The calculated absorption coefficient of your space is ",cs,
      " with no occupance and ",cso," at full occupancy.")

print("Your minmum RT required is: ", rtmn,"\n"
      "Your maximum RT required is: ", rtmx)

print("SA required to achieve minumum RT during full occupancy is: ",sdomx,"\n"
      "SA required to achieve maxumum RT during full occupancy is: ",sdomn,"\n"
      "SA required to achieve minumum RT during no occupancy is: ",sdmx,"\n"
      "SA required to achieve maximum RT during no occupancy is: ",sdmn)

print("Therefore, your space requires ",sd," m2 of acoustic device."
      "The left over SA in the space is ",sw," m2.")

# Large loop to find quality options
for x in [1, 1.2, 1.4]:

    # Calculate RT max and RT min. These equations could change based on
    # what RT's I think are required in classrooms
    rtmn = round((np.log10(vol) * .2 / x - .07), 2)

    if vol == 50 or vol < 50:
        rtmx = round((np.log10(vol) * .38 * x - .07), 2)
    else:
        rtmx = round((np.log10(vol) * .36 * x - .07), 2)

    # Calculate Maximum Needed Device Surface Area
    sdomx = round(((.161 * vol / rtmn) - cso * sa )/(0.95 - cso), 2)
    sdomn = round(((.161 * vol / rtmx) - cso * sa )/(0.05 - cso), 2)
    sdmx = round(((.161 * vol / rtmn) - cs * sa )/(0.95 - cs), 2)
    sdmn = round(((.161 * vol / rtmx) - cs * sa )/(0.05 - cs), 2)

    sd = max(sdomx, sdomn, sdmx, sdmn)

    if x == 1:
        q1 = sd
    elif x == 2:
        q2 = sd
    else:
        q3 = sd


if q == 1:
      print("FYI: sa required for other levels of quality/accuracy:",
      "High Quality = ",q2," m2.","\n",
      "Ultra High Quality = ",q3," m2.")

elif q == 2:
      print("FYI: sa required for other levels of quality/accuracy:",
      "Regular = ",q1," m2.","\n",
      "Ultra High Quality = ",q3," m2.")

else:
      print("FYI: sa required for other levels of quality/accuracy:",
      "Regular = ",q1," m2.","\n",
      "High Quality= ",q2," m2.")
```