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Investigating the acoustics of a sample of open plan and enclosed Kindergarten classrooms in Australia

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ABSTRACT

Open plan classrooms, where several class bases share the same space, have recently re-emerged in Australian primary schools. This study compared the acoustics of four different Kindergarten classrooms: an enclosed classroom with 25 students, a double classroom with 44 students, a linear fully open plan triple classroom with 91 students, and a semi-open plan K-6 classroom with 205 students. Ambient noise levels, intrusive noise levels, occupied background noise levels, and teacher's speech levels were recorded during different activities. Room impulse responses using logarithmic sweeps were also recorded for different teaching scenarios. From these recordings, signal-to-noise ratios, speech transmission index scores, and reverberation times were calculated. The results revealed much higher intrusive noise levels in the two largest open plan classrooms, resulting in signal-to-noise ratios and speech transmission index scores to be well below those recommended in classrooms with students of this age. Additionally, occupied background noise levels in all classrooms were well above recommended levels. These results suggest noise in classrooms needs to be better controlled, and open plan classrooms are unlikely to be appropriate learning environments for young children due to their high intrusive noise levels. The impact of noise on children's learning and teacher's vocal health are discussed.

1. Introduction

Primary school is a child's first experience of formal education, preparing them for higher education and life through literacy, numeracy, and other diverse skills. As the principal modes of communication in the educational setting are speaking and listening, it is important that the acoustic learning environment is conducive from these early stages to enhance future opportunities for these children. On average, children spend 45–60% of their time at school listening and comprehending, so they need to be able to discriminate the speech signal from the vast variety of other irrelevant noises present in the classroom environment [50]. Interfering noises include external noises from outside the classroom (e.g. traffic and construction), intruding noises from adjacent rooms and corridors (e.g. talking and movement), and internal noises from within the classroom (e.g. talking, movement, and air-conditioning unit and appliance noise). High noise levels result in poor signal-to-noise ratios (SNRs), which is a direct measurement of the intensity of the signal (e.g. the teacher's voice) compared to the background noise level. In addition, the use of sound-reflecting building materials creates long reverberation times of both the background noise and the speech signal. The synergistic combination of noise and reverberation results in masking and distortion of the speech signal, reducing speech intelligibility [16,18].

Noise generated by other children is the major noise source found in classrooms [52]. High noise levels adversely affect speech perception [16,18], reading and language comprehension [28,38,49], cognition, concentration, and the psychoeducational and psychosocial achievement of the child [4,16,53]. It is also suggested that poor acoustical conditions and noise places additional demands on children's learning effort. This reduces the resources available for linguistic and cognitive processing and can often result in children 'tuning out' from being overloaded by auditory stimuli [5,38]. Noise levels are reported to be highest in the classrooms of the youngest children [25,33,47,59] which is also the age group most affected [26,32,43,45]. As children's auditory systems are neurologically immature, they have greater perceptual difficulties than adults in discriminating and understanding speech, and cannot use years of previous communicative experience to fill in missing information [58].

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Acute groups of children, including those with hearing impairments who are now more commonly integrated into mainstream classes, are even more affected by poor acoustics [16,33]. Studies in the United Kingdom have shown that on any given day 15% of children in classrooms suffer from hearing impairments, which include not only those who have permanent hearing loss, but also those who have a cold, otitis media (glue ear), an ear infection, or hay fever [44]. Middle-ear related hearing loss in Australia (usually caused by otitis media) affects 50–80% of Aboriginal and Torres Strait Islander school children [42]. This creates feelings of inadequacy for the individual and adversely impacts their classroom performance [37,42]. Children with central auditory processing disorders also find it challenging when listening in the presence of background noise and reverberation [27]. Other acute groups affected by poor acoustics include those for whom English is a second language for [40,41,53], children with sensory hypersensitivity [21], and introverts, who find it difficult to concentrate and relate while doing group work in a noisy environment [14].

Furthermore, it is not only the students who suffer from poor classroom acoustics. While only 5% of the general population experience vocal fatigue, this is experienced by 80% of teachers, putting them at high risk of vocal abuse and pathological voice conditions from the need to constantly raise their voice above a comfortable level to be heard [20,55]. Noise also raises blood pressure, increases stress levels, causes headaches, and results in fatigue (see [5], and [53], for a review). Teachers in classrooms with poor acoustics are more likely to have sick days off work and believe their job contributes to voice and throat problems [33].

These adverse impacts indicate the importance of controlling noise levels for both students and teachers in the educational setting. However, several American studies have shown that classroom acoustic environments rarely have favorable listening conditions [4,29]. While it is generally recommended that unoccupied ambient noise levels should not exceed 35 dBA, unoccupied reverberation times should be less than 0.4 s, and SNRs should be greater than +15 dB [3,16,53], many studies have shown that ambient noise levels reach 60 dBA, SNRs are between −7 to +5 dB, and reverberation times range from 0.4 to 1.2 s [4,16,17]. In occupied classrooms, student generated noise creates the highest noise levels measuring between 50–70 dBA [16,58]. Additionally, it is generally recommended that speech transmission index (STI) scores (which take into account both noise and reverberation times) should be above 0.6 [33,53], though Greenland and Shield [22] suggest that this should be increased to 0.75 for children as young as 6 years. This, however, is rarely achieved [1,22,33]. Particularly of concern is that, despite noise levels already being excessive in traditional enclosed classrooms with 20–30 children, there is a current trend of replacing these enclosed classrooms with new open plan '21st century learning spaces'. These open plan classrooms can result in up to 200 children sharing the same area [56].

Open plan style classrooms are not a new concept for educational institutions. This 'progressive' classroom style was popular during the educational reform of the 1960s and 1970s where traditional didactic teaching was replaced by a more 'child-centered' approach [12]; see also [53]. Additionally, building open plan spaces complemented post-war economic restraints [10]. However, because of noise and visual distraction, it was not long before the open spaces were converted back to enclosed classrooms [53]. Nonetheless, the 21st century has seen a return to the child-centered educational philosophy, hence open plan classrooms have become popular once again, particularly in the United Kingdom and more recently in Australia [21,56]. There are several advantages in adopting an open plan style of classroom. Apart from being architecturally fashionable, these spaces create a more 'home-like' atmosphere and are perceived as being less authoritarian, creating a more secure feeling for the child [34]. They also allow for a range of activities to be carried out and facilitate group work and the child's social development [12]. Additionally, they promote the sharing of skills, ideas, and experiences amongst teachers, and allow for team-teaching which facilitates a more cooperative and supportive atmosphere [12,23]. However, due to large numbers of children sharing the area and being engaged in a range of activities, open plan classrooms result in high levels of fluctuating speech noise. The lack of acoustic privacy (and also lack of visual privacy) is distracting for teachers as well as children, but particularly those with behavioral, intellectual, and physical disabilities (see [53]). The American National Standards Institute [3] strongly discourages the use of open plan classrooms since the high levels of background noise negatively impact the children's learning processes.

Despite this past evidence showing that high levels of noise is a common problem reported in schools with open plan designs, many Australian schools are currently choosing to adopt this classroom layout. Therefore, it is timely that evidence-based research is carried out in these Australian schools (where research is sparse) to assess whether converting to these open plan learning spaces is compromising acoustic privacy, hence potentially hindering educational development.

There have been only a small number of studies in the past that directly compare noise levels in open plan and enclosed classrooms, and they give varying results. In the United States, Finitzo [17] found average noise levels to be significantly higher in open plan classrooms, whereas Airey et al. [2] found that noise levels in open plan classrooms in the United Kingdom were 5 dB lower than in enclosed classrooms. They believed this was because teachers in open plan classrooms spent more time controlling noise and that these classrooms tended to have more sound absorptive materials installed. Other studies in the United States have reported no difference in noise levels between the two classroom designs (e.g. [9,19,31]). However, these three studies did show more fluctuations in noise levels which teachers and students find more annoying than consistent noise at the same average level [15]. Many of these results depend on the definition of an 'open plan classroom', such as how many students and/or class bases share the space, the configuration of the space (e.g. linear, cluster, annular), and whether there are partitions that can be used to separate the spaces (i.e. fully open plan versus semi-open plan). Rather than trying to group together open plan classrooms that are very different, our study presents case studies of four different types of schools found in Sydney, Australia, including an enclosed classroom as a reference point. This way we can compare the different classrooms directly knowing that the same methods for the measurements have been used. This is more reliable than comparing the results across different studies which may have used different experimental procedures. Additionally, the goal of this research was to provide a more comprehensive view of how different types of open plan and traditional enclosed classrooms compare. Previously, many studies have focused on only one aspect of classrooms, such as the objectively measured acoustics. Our more comprehensive approach is achieved by incorporating research on the acoustics of the room with how children perform on a speech perception task conducted live in their classroom, as well as subjective measures on how the teachers and children perceive the listening environment. The current paper reports the results of the classroom acoustic measures. The other aspects will be reported in future papers and related back to the acoustics of the classrooms reported in this paper.

Therefore, the aim of the current study was to compare the classroom acoustic variables (e.g. noise levels, reverberation times, SNRs, STI scores) in open plan and traditional enclosed Australian Kindergarten classrooms using consistent experimental procedures across classroom types. It was hypothesized that, because

Table 1
Building details of the participating classrooms.

	Enclosed classroom	Double classroom	Triple classroom	K-6 classroom
Total number of students in area	25	44	91	205
School's ICSEA	1141	1133	1035	1090
Classroom type	Enclosed classroom with shared concertina wall	Fully open double classroom	Linear, fully open plan classroom	Semi-open plan classroom
Class grades in area	Kindergarten (5-6-year-olds)	Kindergarten (5-6-year-olds)	Kindergarten (5-6-year-olds)	Kindergarten to Year 6 (5-12-year-olds)
Number of class bases in area	1	2	3	5–7 (depending on activity)
Number of students in each class base	25	21–23	30–31	30–50
Room dimensions (m)	8 × 9	15 × 9	37 × 11	27 × 32
Total floor area (m^2)	72	135	407	864
Space per child (m^2)	2.9	3.1	4.5	4.2
Distance between edge of class bases (m)	N/A	2	6	7
Ceiling height (m)	3.0	2.8–4.2	3.3	3.2–6.0
Total room volume (m^3)	216	470	1340	3900

of the lack of acoustic barriers in open plan classrooms, the intrusive noise levels from the adjacent class bases would be higher in the open plan classrooms compared to the traditional enclosed classroom. Additionally, due to the increase in children (i.e. noise sources) present in open plan classrooms, it was hypothesized that background noise levels when all students were engaged in group work activities would also be higher in the open plan classrooms. As a result of these predicted high noise levels, we expected the SNRs and STI scores in the larger open plan classrooms to be well below those recommended for Kindergarten children. Finally, it was predicted that the reverberation times would be longer in the larger classrooms (particularly those without acoustic treatment) due to their increased volume.

2. Schools involved

The study took place in Sydney, Australia in the second half of the school year as part of a comprehensive project investigating the acoustics and listening conditions in open plan and enclosed Kindergarten classrooms. (Note: Kindergarten is the first year of primary school in Australia so the children were five to six years old.) A wide range of potential primary schools were examined before the final selections were made. The number of students in the open plan classrooms that we examined ranged between 40–200 students, divided into class bases of 20–30 children. Therefore, three open plan classrooms across the 40–200 student range were chosen for this study, along with one enclosed classroom with 25 students. Effort was made to choose schools with a similar score on The Index of Community Socio-Educational Advantage (ICSEA) scale. This scale represents a school's level of educational advantage based on family backgrounds. ICSEAs range from 500 to 1300, with a mean of 1000 and standard deviation of 100. Higher ICSEA scores represent more advantaged schools. (More information about ICSEAs can be found on the *My School* website http://www.myschool.edu.au [39].) We used the values calculated for 2013 when the study was conducted. Further details on the participating classrooms are shown in Table 1.

2.1. Enclosed classroom: 25 students

This classroom consisted of 25 Kindergarten students in a classroom with 3 solid brick walls, a closed floor-to-ceiling 4 cm thick concertina wall with pin boards, and a shared storeroom with the adjacent Kindergarten class. The class area was carpeted with

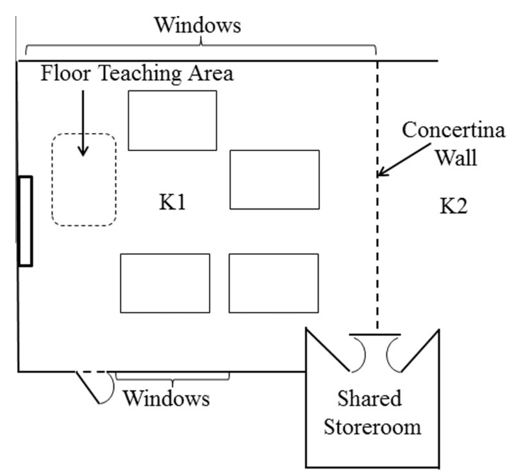

Fig. 1. Floor plan of the enclosed classroom with 25 students.

loop pile carpet and windows were located on both side walls (Fig. 1). The ceiling was rough concrete textured. No acoustic treatment was evident. A survey of 50 primary schools in the region found that 60% of Kindergarten classrooms have a concertina wall between them and an additional 10% have a shared storeroom or door with another class. Only 30% of schools had fully enclosed classrooms with four solid walls. Therefore this classroom with its concertina wall and shared storeroom was more typical of those enclosed classrooms found in the Sydney region, and hence was chosen for the study.

2.2. Double classroom: 44 students

This space originally consisted of two separate classrooms with plasterboard walls, but the wall between had been removed at the start of the year to make it an open plan double classroom for the 44 Kindergarten students. The ceiling was made of plasterboard and was triangular in shape, and the top half of the wall still remained in this area between the two classrooms where the original wall had been. The class area was carpeted with loop pile carpet but the utility area was a hard surface. Windows were located on two walls and pin boards covered the other two walls (Fig. 2). No other acoustic treatment was evident. The acoustic measurements were taken in class K1.

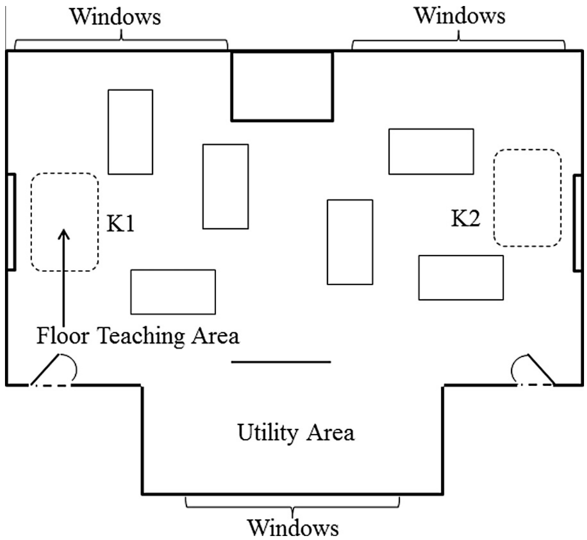

Fig. 2. Floor plan of the double classroom with 44 students.

2.3. Triple classroom: 91 students

This open plan classroom consisted of 91 Kindergarten students grouped linearly into three classes (K1, K2, K3), with no barriers between them. This classroom represented a mid-range student and class base number for an open plan space. The Year 1 and 2 classes were located off an adjacent corridor but had no doors/walls separating the spaces, hence noise from these classes could also be heard. Originally the space had consisted of separate enclosed classrooms with 30 children in each, but these walls had recently been removed to make the area fully open plan. The walls were plasterboard and the class area was carpeted with loop pile carpet, but the corridor floor was a hard surface. The ceiling was acoustically tiled. Windows were located on both the front and back walls and pin boards were on the other two walls (Fig. 3). No other acoustic treatment was evident. The acoustic measurements were taken in class K2.

2.4. K-6 classroom: 205 students

This classroom contained the entire primary school (205 students) in the one area representing one of the biggest types of open plan classrooms. It had been purpose-built to be a '21st century learning' open plan school. The children were separated into class stages with Kindergarten, Year 1, and Year 2 in a semi-open plan layout with dividers between them and only one open wall. Years 3/4 and 5/6 were fully open plan. The Kindergarten class was located in the corner in the acoustically most sheltered location, particularly for their whole class teaching area where the children are grouped together on the floor to listen to their teacher

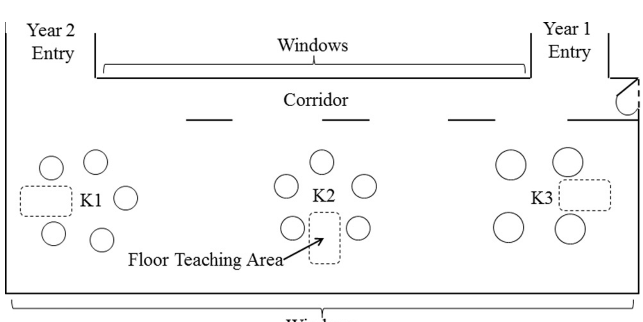

Fig. 3. Floor plan of the triple classroom with 91 students.

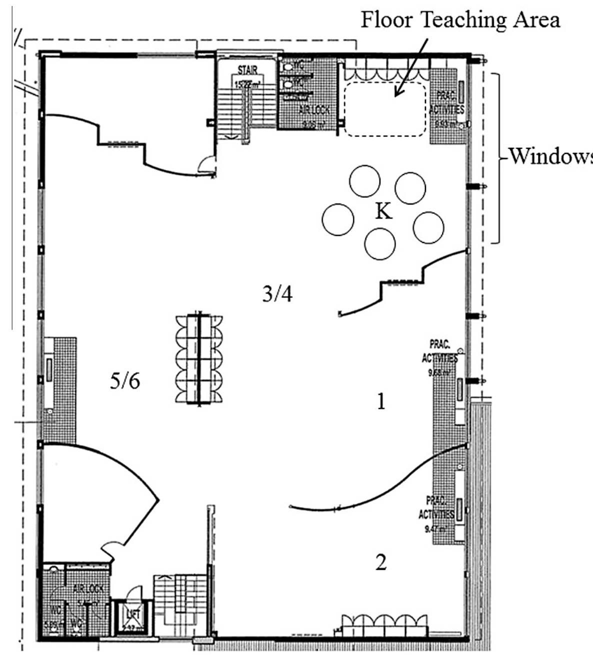

Fig. 4. Floor plan of the K-6 classroom with 205 students.

(see Fig. 4). The ceiling height in this area was the lowest of the room measuring 3.2 m. The entire area was carpeted with loop pile carpet, and 3 cm thick pin boards along the walls and soft furnishings provided some acoustic absorption. The ceiling was acoustically tiled. Windows were located on the external wall.

3. Method

3.1. Classroom activities

Previous research shows that noise levels in classrooms depend on the activity that the students are engaged in [22,52]. For our study we chose two different activities (one representing a quiet activity and the other a noisy activity) to record the noise levels in:

(1) Whole class teaching: This critical listening activity involves the children sitting on the floor in front of their teacher. During this activity only one person is speaking at a time – either the teacher or a child giving an answer.
(2) Group work: This activity involves the children sitting at tables or on the floor working together on tasks. It may also involve children moving around the classroom. During this activity many people are speaking at the same time.

The proportion of time spent in each of these activities from a survey of the Kindergarten teachers at the schools involved is shown in Table 2. These proportions are consistent with those found in previous studies (e.g. [22,58]).

3.2. Equipment

The microphones used for the study included an omnidirectional DPA dual-ear lapel microphone and three ½″ omnidirectional condenser microphones. The condenser microphones were used for both noise recordings as well as Room Impulse Response (RIR) measurements, and were calibrated in diffuse speech-shaped noise using a B&K 2250 sound level meter. The lapel microphone was used for recording the teacher's voice and calibrated as described in Section 3.5. The microphones were

Table 2
Teachers' report of proportion of time spent in various classroom activities.

Classroom	Whole class teaching (%)	Group work (%)	Other (%)
Enclosed	25	45	30
Double	15	75	10
Triple	40	40	20
K-6	15	45	40

Table 3
Recommended ambient, background, and intrusive noise levels, signal-to-noise ratios, speech transmission index scores and reverberation times for Kindergarten classrooms.

Measurement	Recommended value	Reference
Ambient noise	<35 dBA	[8]
Background/intrusive noise	<50 dBA	[11]
SNR	+15 dB	[16]
STI	>0.75 (for 6 year olds)	[22]
Reverberation time	<0.4–0.5 s (unoccupied)	[8]

connected to a RME Quadmic 4-channel microphone preamplifier. A Tannoy VX8 concentrical loudspeaker connected to a Yamaha AX-350 hifi stereo amplifier was used for measuring the RIRs. The computer was a standard PC using RME Hammerfall HDSP 9632 internal soundcard inclusive expansion boards. Adobe Audition software was used for the recordings and MATLAB software was used for the RIR measurements.

3.3. Noise recordings

Noise recordings for four different scenarios were made in the main class base so that levels could be calculated and compared to acoustical guidelines:

(1) Unoccupied ambient noise levels: This recording was taken inside the classroom after school when the classes were completely vacated. It measured the sound levels generated by internal and external noise sources, for example, air conditioning units and road traffic. The recommended ambient noise level for classrooms is <35 dBA as shown in Table 3.
(2) Intrusive noise levels during quiet activities: This recording was taken when the main class base was empty and the other class bases were engaged in whole class teaching.
(3) Intrusive noise levels during noisy activities: This recording was taken when the main class base was empty and the other class bases were engaged in group work.
(4) Occupied background noise levels: This recording was taken when the main class base was occupied and all class bases were engaged in group work. The recommended background noise level (hence intrusive noise level) for classrooms is <50 dBA as shown in Table 3.

For each condition, three omnidirectional condenser microphones on stands at 1 m height were placed around the class area of the main class base. Each recording was 2–10 min in length depending on the activity. Adobe Audition software was used to record the noise levels at each microphone. Each recording was listened to and any artefacts (such as children touching or directly speaking into the microphone) were removed.

3.4. Room impulse responses and reverberation time

RIRs for three different teaching scenarios were measured in the main class base with 30 s long logarithmic sweeps using a Tannoy VX8 loudspeaker and three calibrated omnidirectional

Table 4
Distance of microphones from the loudspeaker for each classroom in each scenario.

Activity	Classroom	Distance of microphone from loudspeaker (m)		
		Mic 1	Mic 2	Mic 3
Whole class teaching	Enclosed	1.0	2.3	2.9
	Double	1.9	2.9	3.8
	Triple	1.3	2.6	3.5
	K-6	2.0	2.0	3.0
	Average	1.55	2.45	3.3
Teacher addressing single table	Enclosed	0.9	1.2	2.1
	Double	0.7	1.4	2.2
	Triple	0.8	1.0	1.5
	K-6	0.8	0.8	0.8
	Average	0.8	1.1	1.65
Teacher addressing all tables	Enclosed	3.5	3.8	4.0
	Double	2.7	3.0	6.0
	Triple	3.2	3.8	4.5
	K-6	2.0	3.9	5.4
	Average	2.85	3.625	4.975

microphones. Based on these measurements, reverberation times and STI scores were calculated and compared to the acoustical guidelines summarized in Table 3. The RIRs were also used to predict the teacher's voice levels inside the classrooms as further described in Section 3.5. RIRs were recorded for the following scenarios:

(1) Whole class teaching: The loudspeaker at a height of 1.2 m (representing teacher sitting on a chair in front of students) was placed at the front of the class. Three microphones at an average height of 0.45 m (representing students sitting on the floor) were placed front to back in front of the loudspeaker.
(2) Teacher addressing single table of students: The loudspeaker at a height of 1.5 m (representing teacher standing in front of students) was placed in front of the table. Three microphones at an average height of 0.7 m (representing students sitting on the chairs) were placed around the table.
(3) Teacher addressing all tables and students: The loudspeaker at a height of 1.5 m (representing teacher standing in front of students) was placed at the front of the class. Three microphones at an average height of 0.7 m (representing students sitting on chairs) were placed around different tables.

Table 4 shows the distance of the microphones from the loudspeaker for each school in each scenario. The distances chosen were those that best represented different positions of children in the class.

The unoccupied reverberation time (T30) was derived from the measured RIRs according to ISO 3382-2 (ISO 3382-2:2008(E) [24]) using the Odeon software. The T30 was first derived in octave bands and then averaged across the bands with center frequencies of 500, 1000, and 2000 Hz. For each scenario, the broadband T30 was finally averaged across the three applied microphone locations. The recommended T30 for classrooms is <0.4–0.5 s as shown in Table 3.

3.5. Calculation of teacher's average speech levels

The teachers of the tested class bases had their speech recorded during whole class teaching. An omnidirectional DPA dual-ear lapel microphone was placed approximately 3 cm from the teacher's mouth and recordings were made using Adobe Audition software. These recordings were then convolved with the measured RIRs for the three teaching scenarios (Section 3.4) to estimate speech levels for each scenario at three listening positions. To remove voice level differences between teachers, speech levels were predicted by using concatenated and equally long speech samples from all teachers as input signal. To provide accurate speech level estimates, the involved equipment and signal processing was calibrated by comparison to a similar recoding performed in an anechoic chamber at the National Acoustic Laboratories, Australian Hearing Hub. Twelve talkers were recorded using the DPA lapel microphone as well as a calibrated B&K 4134 microphone placed 2 m in front of the talkers and attached to a B&K 2610 measurement amplifier. Additionally, the corresponding (anechoic) RIR was measured by replacing the talkers by the same Tannoy VX8 loudspeaker system used in the classroom measurements. Comparing the spectra (and RMS levels) of the direct speech recording at 2 m distance with the corresponding RIR-based simulation allowed the derivation of calibration filters that were then applied to the speech recordings and RIR measurements performed in the different teaching scenarios.

3.6. Calculation of signal-to-noise ratios

The signal-to-noise ratio (SNR) measures the difference between a speaker's speech level (described in Section 3.5) and the noise level. A positive SNR means that the speaker's speech level is higher than the noise level, while a negative SNR means the noise level is higher than the speaker's speech level. Average SNRs were derived for the different teaching scenarios between the teacher's speech level (in dBA) and the noise levels (also in dBA) described in Section 3.3. SNRs were calculated using the average teacher's speech levels at the front, middle, and back of the whole class teaching seating area (as described in Section 3.4) and the average noise levels recorded in the same areas and described in Section 3.3. SNRs were obtained for the three noise conditions that whole class teaching takes place in, i.e. ambient noise, intrusive noise when the other classes are engaged in quiet activities, and intrusive noise when the other classes are engaged in noisy activities. The recommended SNR for 6-year-olds is +15 dB as shown in Table 3. This SNR should be achieved throughout the room [7].

3.7. Calculation of speech transmission index scores

The speech transmission index (STI) provides a guide to how intelligible speech is in a room by measuring the distortion introduced into the speech transmission channel from the source to the receiver, taking into account both reverberation and noise [33]. The STI is represented on a scale from 0 to 1, with 0 indicating that no speech would be understood and 1 indicating that all speech would be understood. STI scores were calculated using the AARAE MATLAB Toolbox [13]. We calculated the STI scores at the front, middle, and back of the whole class teaching seating area using the RIRs without noise (to demonstrate the effect of the room's reverberation alone), and with the three noise conditions described in Section 3.3. STI scores were also calculated using the occupied background noise levels when the teacher was addressing a single table of students and when they were addressing the whole class doing group work at their tables. Recommended STI scores are shown in Table 5 [33]. It is important to note, however, that the STI was developed for adults. Given that children need more favorable listening situations, it is recommended that the STI score should always be >0.75 for 6-year-olds, as shown in Table 3 [22].

Table 5
Speech transmission index rating scale.

STI value	Rating
0.000–0.300	Bad
0.301–0.450	Poor
0.451–0.599	Fair
0.600–0.749	Good
0.750–1.000	Excellent

4. Results

4.1. Noise levels

The average noise levels recorded for the four different scenarios described in Section 3.3 are shown in Fig. 5. As shown in Table 3, the recommended unoccupied noise level is <35 dBA, and the recommended intrusive noise level and occupied background noise level is <50 dBA.

4.1.1. Unoccupied ambient noise levels

None of the classrooms achieved the recommended unoccupied ambient noise limit, however, the double and triple classrooms were only just above it measuring 36.7 dBA and 36.0 dBA respectively. The enclosed classroom measured a level of 41.8 dBA, but of most concern was the K-6 classroom, which had an average ambient noise level of 46.3 dBA. This high ambient noise level is most likely to be due to the heating, ventilation, and air conditioning units used in this classroom.

4.1.2. Intrusive noise levels

Inspection of the intrusive noise levels is where the problem with open plan classrooms becomes most apparent. As shown in Fig. 5, there is a steep rise in both types of intrusive noise levels from the two smaller classrooms to the larger open plan classrooms. As predicted, a statistically significant difference in the intrusive noise levels while the adjacent classes were engaged in quiet activities as determined by one-way ANOVA ($F(3,8) = 52.68$, $p < .0005$, $\eta^2 = .95$) was found between classrooms, with a Tukey post hoc test revealing significantly higher intrusive noise levels for the K-6 and triple classrooms compared to the double and enclosed classrooms ($p_{K\text{-}6\ vs.\ double} < 0.0005$; $p_{K\text{-}6\ vs.\ enclosed} < 0.0005$; $p_{triple\ vs.\ double} = 0.001$; $p_{triple\ vs.\ enclosed} < 0.0005$). A second one-way ANOVA also revealed a significant difference in the intrusive noise levels while the adjacent classes were engaged in noisy activities ($F(3,8) = 31.91$, $p < .0005$, $\eta^2 = .92$) with a Tukey post hoc test again revealing significantly higher intrusive noise levels for the K-6 and triple classrooms compared to the double and enclosed classrooms ($p_{K\text{-}6\ vs.\ double} = 0.002$; $p_{K\text{-}6\ vs.\ enclosed} = 0.001$; $p_{triple\ vs.\ double} = 0.001$;

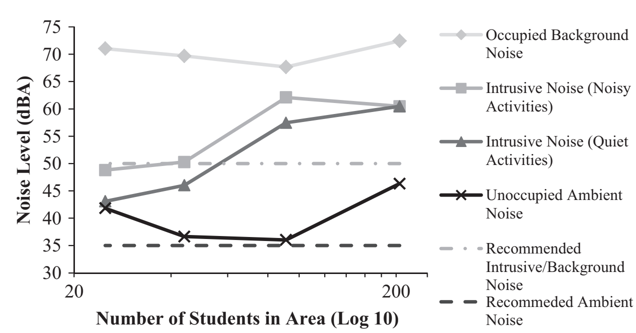

Fig. 5. Average noise levels recorded during different scenarios as a function of how many children are in the classroom area. Note the enclosed classroom had 25 students, the double classroom had 44 students, the triple classroom had 91 students, and the K-6 classroom had 205 students.

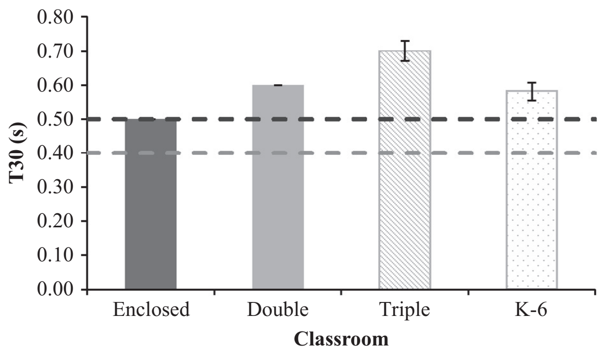

Fig. 6. Average reverberation times for each classroom. Note recommended reverberation time is between 0.4–0.5 s as shown by the dotted lines. Error bars show standard error of the mean where applicable.

$p_{triple\ vs.\ enclosed} < 0.0005$). Fig. 5 shows that while the two smaller schools stayed within the recommended 50 dBA limit for both types of intrusive noise, this was well exceeded by the two larger classrooms. (Note that the average intrusive noise levels during quiet and noisy activities were the same for the K-6 classroom as, due to the large number of class bases in the area, quiet and noisy activities could not be coordinated across the whole school. Therefore this classroom experienced consistent noise levels throughout the day.)

4.1.3. Occupied background noise levels

Interestingly, as shown in Fig. 5, the occupied background noise levels when all children became engaged in group work activities stayed relatively constant across all classrooms, independent of how many children were in the area. The background noise levels were well above recommended levels irrespective of the classroom size, ranging between 67.7–72.4 dBA. These results show that the noise levels when all children are doing group activities can be problematic in each of the classroom types tested.

4.2. Reverberation times

The average unoccupied reverberation times calculated in each classroom are shown in Fig. 6. Only the enclosed classroom achieved a reverberation time within the recommended upper limit for classrooms [8]. The reverberation times for each of the other classrooms were outside of the recommended value of 0.4–0.5 s, but were not unusual compared to those found in previous studies examining classroom acoustics [29]. (Note, however, that due to the directivity of the loudspeaker used in our RIR measurement, our reverberation times may under-predict the reverberation times compared to if they were measured with omnidirectional sound sources, which most standards are based on.)

4.3. Teacher's average speech levels

The average speech levels for the teachers of the classrooms during whole class teaching are summarized in Table 6. These were used to calculate the SNRs given in the next section. These levels are consistent with the findings of Sato and Bradley [51].

4.4. Signal-to-noise ratios

The measured SNRs during whole class teaching are summarized in Fig. 7 for the three relevant noise types listed in Section 3.3. When the ambient noise in the room was the only noise source, the SNRs met the required criteria for all classroom designs except for the largest classroom, which were just below the recommended +15 dB. However, as soon as intrusive noise from other classes was introduced (even just from quiet activities), the SNRs dropped dramatically to well below the recommended level for the two largest open plan classrooms. This problem was further increased when the activities of the other classes changed to noisy group work activities, resulting in SNRs between +0.8 and −6.1 dB for the triple classroom, which is a very poor listening condition. For the double classroom, the SNR for the children sitting closest to the teacher was acceptable when the adjacent class bases were engaged in quiet activities, but fell below the recommended +15 dB for children sitting further away. This effect increased when the adjacent class bases were engaged in noisy activities with SNRs between +13.2 and +6.9 dB at the front and back of the room respectively. However, for the enclosed classroom, the SNRs stayed above +15 dB when the other classes were engaged in quiet activities, and only dropped as far as +12.7 dB (at the back of the room) when the other classes were engaged in noisy activities. This suggests that this was the only classroom design suitable for effective speech communication during critical listening activities such as whole class teaching.

The SNRs when all classes were doing group work activities are shown in Table 7. These SNRs are calculated based on the vocal effort of the teachers during whole class teaching. As seen in Fig. 5, the background noise levels for all classrooms were well above the recommended noise level of 50 dBA. Table 7 shows that if the teacher were to address the students when all classes are engaged in group work activities using the vocal effort they usually employ for whole class teaching, the SNRs would be extremely poor, suggesting little speech would be understood. To achieve SNRs at the recommended level of +15 dB, the teacher needs to raise their voice up to 31 dBA higher, which means they need to speak at a level above 82.7 dBA at 1 m which is equivalent to

Table 6
Teacher's speech levels for each classroom during different activities.

Teaching scenario	Classroom	Teacher's speech level (dBA)						Child's average distance (m)
		Front	Mid	Back	Mean	SD	Range	
Whole class teaching	Enclosed	60.6	60.1	59.0	59.9	0.8	59.0–60.6	2.1
	Double	61.8	57.4	55.5	58.2	3.3	61.8–55.5	2.9
	Triple	62.0	58.2	55.2	58.5	3.5	55.2–62.0	2.5
	K-6	59.7	59.5	58.1	59.1	0.9	59.7–58.1	2.7
Teacher addressing single table	Enclosed	61.3	64.1	59.0	61.5	2.6	59.0–64.1	1.4
	Double	65.2	62.7	60.4	62.8	2.4	65.2–60.4	1.5
	Triple	65.4	62.3	59.7	62.5	2.9	59.7–65.4	1.1
	K-6	62.4	60.9	59.1	60.8	1.7	62.4–59.1	0.8
Teacher addressing all tables	Enclosed	56.2	56.8	52.2	55.1	2.5	52.2–56.8	3.8
	Double	57.5	54.2	53.1	54.9	2.3	57.5–53.1	3.9
	Triple	54.7	51.9	53.4	53.4	1.4	51.9–57.4	3.8
	K-6	60.4	55.2	53.0	56.2	3.8	60.4–53.0	3.8

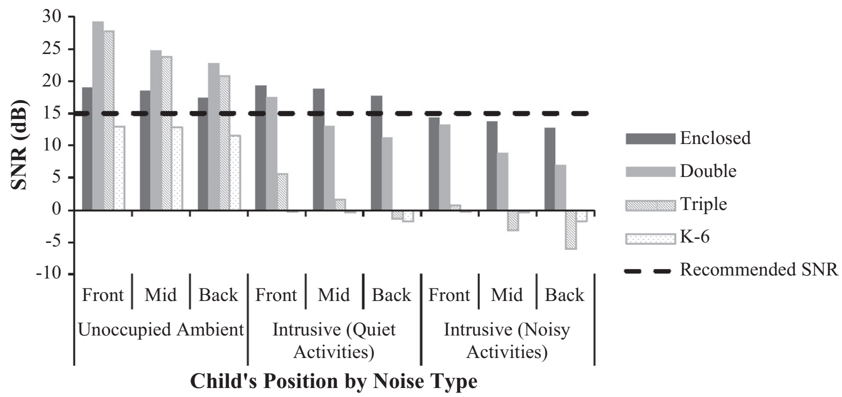

Fig. 7. Signal-to-noise ratios for the child's seating position in different noise types for each classroom during whole class teaching.

Table 7
Teacher's speech parameters when addressing a single table of children and all tables of children engaged in group work for each classroom.

Teacher addressing	Classroom	Average distance from child (m)	Teacher's usual speech level (dBA)	Noise level (dBA)	SNR (dB)	Required speech level for +15 SNR (dBA)	Amount voice needs to be raised by (dBA)
Single table	Enclosed	1.4	61.5	71.0	−9.6	86.0[a]	24.6
	Double	1.6	62.8	69.7	−6.9	84.7[a]	21.9
	Triple	1.1	62.5	67.7	−5.2	82.7[a]	20.2
	K-6	0.8	60.8	72.4	−11.6	87.4[a]	26.6
All tables	Enclosed	3.8	55.1	71.0	−16.0	86.0[a]	31.0
	Double	3.9	54.9	69.7	−14.8	84.7[a]	29.8
	Triple	3.8	53.4	67.7	−14.3	82.7[a]	29.3
	K-6	3.8	56.2	72.4	−16.2	87.4[a]	31.2

[a] Equivalent to shouting [6].

shouting [6]. Constant talking at this level is highly likely to result in vocal health problems. Therefore it is difficult for teachers in any classroom to address a whole table or tables during group work, but only a single student provided they are in very close proximity.

4.5. Speech transmission index scores

STI scores were calculated for the whole class teaching scenario in each classroom for no noise (which demonstrates the effect of room reverberation only) and the three other possible noise types that may be present during this critical listening activity (see Fig. 8). For the enclosed classroom, the STI scores stayed above the recommended score of 0.75 for 6-year-olds for nearly all noise types, and only just slipped below it (but was still in the "good" range) for the middle and back seating positions when the other classes were engaged in noisy activities. Similarly, for the double classroom, the recommended STI was achieved at the front of the class for each noise type, and was still within the "good" range for the mid and back class positions when intrusive noise was present. In contrast, the STI was only at the acceptable level for the two largest open plan classrooms when there was no noise or only ambient noise. For the K-6 classroom, the STI scores were in the "poor" to "fair" range when intrusive noise was present. As soon as intrusive noise was introduced in the triple classroom, even just from quiet activities, only the children sitting at the front remained in the "good" range. When the other classes were engaged in noisy activities, the children seated at the back faced "bad" listening conditions, which is likely to have a major detrimental effect on their learning. The results of both the SNR and STI measurements strongly suggest that the tested open plan classrooms with 90 or more children are not appropriate for speech communication because of their high intrusive noise levels.

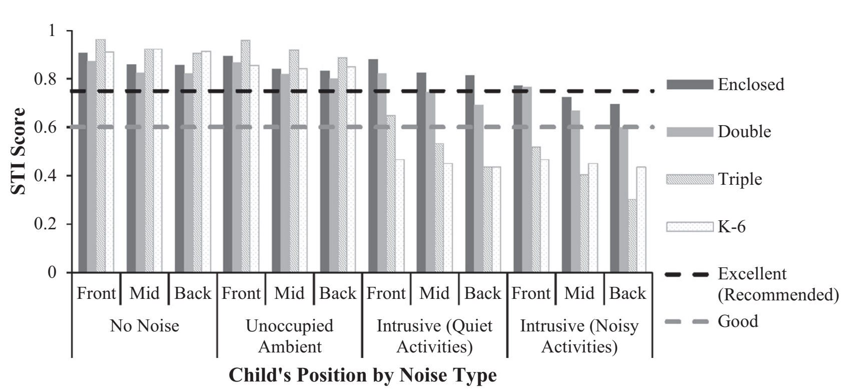

Fig. 8. Speech transmission index scores for the child's seating position in different noise types for each classroom during whole class teaching.

5. Discussion

The aim of this study was to investigate the acoustics of different types of open plan and enclosed Kindergarten classrooms to assess the appropriateness of open plan classrooms as learning spaces for young children.

The first major finding was that the intrusive noise levels (i.e. the noise coming from adjacent classes) in the classrooms with over 90 students (i.e. the triple and K-6 classrooms) were excessive and well above recommended levels, even when the other classes were engaged in only quiet activities. This resulted in SNRs and STI scores that were very poor during whole class teaching (a critical listening activity) which is likely to have a major detrimental impact on children's learning. While the intrusive noise levels were within recommended limits for the double classroom with 44 students, the SNRs and STI scores still slipped below the recommended values for this age group, particularly toward the back of the classroom. The enclosed classroom with 25 students was the only classroom to remain within or close to the recommended values, due to the acoustic barrier between the classes which minimized intrusive noise. Therefore, these results suggest that the enclosed classroom is the best learning environment for effective speech communication among young children.

Although there was a large difference in the intrusive noise levels between the two largest and two smallest classrooms, the second major finding of this study was that the background noise levels when all classes were engaged in group work activities were excessive independent of classroom size. We expected that, because of the greater number of students and high intrusive noise levels in the larger open plan classrooms, the noise levels when all classes were engaged in group work activities would be higher than those in the smaller classrooms as a result of the Lombard effect [57]. This, however, was not the case, with the noise levels in the enclosed classroom also reaching well above those recommended. It is possible that teachers of open plan classrooms make an extra effort to control noise from concern that it will distract the other class bases sharing the area. Therefore the background noise levels may not be as high as they otherwise could be in these classrooms. Although these excessive noise levels were reached mainly during group work rather than during critical listening activities, they are still a concern. This is not only because high noise levels increase stress and are thought to adversely affect both the psychoeducational and psychosocial achievement of the child [4,16,18,51], but also because of the effect they have on the teacher. During these activities it is common for the teacher to move around helping different groups. Therefore, to achieve the recommended +15 dB SNR and be heard, teachers need to raise their voice up to 31 dBA higher than their comfortable teaching voice. This requires teachers to speak at which means they need to speak at a level above 82.7 dBA at 1 m which is equivalent to shouting [6]. This makes talking to more than a single child at a time very difficult. As group activities make up 40–75% of teaching activities (see Table 2), constant talking at this level is likely to result in vocal abuse and pathological voice conditions as well as increase the number of sick days taken due to voice and throat problems [20,55]. Therefore, it is important that teachers try to control the noise levels in all classrooms, and be careful not to raise their voice regularly to get the children's attention. Clapping their hands or using a bell or other signal can be helpful alternatives to get the children's attention in these situations.

As mentioned previously, providing adequate speech perception is not the only reason for ensuring classrooms have good acoustics and minimal noise levels. Noise affects many aspects of children's education such as reading and language comprehension, cognition, attention, concentration, and motivation [16,53]. Consistent exposure to noise also has physiological effects on both the child and teacher including raised blood pressure, increased stress levels, headaches, and fatigue (see [5], and [53], for a review). Therefore, there are many reasons to ensure classroom noise levels are kept to a minimum.

Minimizing noise levels in the classroom is not only important for typically developing children, but is essential for children with special education needs such as those with attention deficits, hearing impairments, auditory processing disorders, language delays, and English as a second language who are more affected by poor acoustics [5,16,27,40]. These children are increasingly being integrated into mainstream classrooms [30]. For example, it is estimated that 83% of children with hearing impairments are now in a regular classroom [48]. It is important to note that the recommended levels in Table 3 are for 5–6-year-old children with typically developing hearing and language skills. Children with special educational needs are thought to require ambient noise levels to be <20 dBA, intrusive and background noise to be <40 dBA, signal-to-noise ratios to be >+20 dB and reverberation times to be <0.3 s [1,7]. The results of our study suggest that these levels are highly unlikely to be achieved in any classroom, let alone in open plan classrooms.

Although little research has been conducted in Australia, the idea that open plan classrooms are not adequate educational spaces has been recognized in other countries. The American National Standards Institute [3] and the Canadian Standard for School Facilities (2001; see [58]) strongly discourages open plan classrooms, stating that any advantage in teaching methodology is defeated by the negative impact on learning caused by their high noise levels. The results of this study support this, suggesting that it may be beneficial for Australia to have recommendations or restrictions for open plan classrooms.

We acknowledge, however, that as teaching methods are favoring a less authoritarian and more child-centered approach, more flexible learning spaces may be desirable [12,34,46,53]. Shield et al. [53] suggests that open plan classes may stay within appropriate noise levels as long as they have:

- A semi-open plan linear style with at least 1.6–2.0 m high partitions with separate quiet rooms that children can use when they need more favorable listening conditions.
- A maximum of three class bases that coordinate activities, especially those involving critical listening, to minimize the effect of intrusive noise [22].
- At least 6.5 m between the edges of the class bases and 4–5 m^2 per child.

It is important to recognize that these classrooms will still compromise on noise, hence speech perception, compared to an enclosed classroom. However, irrespective of design, it is highly recommended that *all* classrooms are acoustically treated to enhance speech perception [54]. This includes:

- Having a maximum ceiling height of 3.5 m and 90% absorption on the ceiling and walls to control reverberation and reduce noise transmission [53,54,58].
- Having carpet to reduce footfall and furniture noise [54].
- Installing heating, ventilation, and air conditioning systems and equipment that have low noise level ratings to reduce ambient noise levels [58]. (The problem with having high ambient noise levels is that speakers need to raise their voice more to be heard above these levels. Therefore, due to the Lombard Effect, this results in higher and higher noise levels with each additional sound source [57]. Minimizing these levels is therefore important for maintaining low noise levels overall.

– Using FM systems for hearing impaired children during critical listening activities [58].)
– Using sound field systems and/or gathering children as close as possible to the teacher. This will help maintain, for all children, higher SNRs, STIs and speech perception, commensurate with those normally enjoyed by children at the front of the class. As a result, this will enhance the children's learning and minimize teacher's vocal strain [35,36]. (Note, however, that amplification systems are not appropriate for open plan classrooms (where the SNR distance effect is even more apparent) because of their disturbance to other classes. This further suggests the shortcomings of this type of learning space.)

It is also important that each classroom is assessed on a case-by-case basis as the acoustics will differ depending on what building materials and fittings are used. Additionally, the age of the students needs to be taken into consideration. While the acoustic conditions may be suitable for older children, it is likely that younger children are still going to struggle in these environments, as are children with special educational needs. Therefore, the findings of both the previous research and our current study suggest that treated enclosed classrooms are likely to be the most suitable learning spaces.

6. Conclusions

The results of our study suggest that open plan classrooms with over 90 students are not appropriate learning environments for young children due to the high intrusive noise levels experienced in these types of spaces. These noise levels are likely to affect not only the children's learning, but also cause vocal health problems for the teachers from the need to constantly raise their voice above a comfortable level to be heard. These findings suggest that while a classroom with four solid fully enclosed walls is likely to be the best learning environment, a single classroom with a concertina wall should provide adequate listening conditions most of the time. This type of classroom also gives the flexibility of opening the concertina wall for the activities the teachers prefer to have a more open plan space for, but then closing it for critical listening activities to minimize intrusive noise and enhance speech perception. Additionally, a double classroom with 44 students in total may also be sufficient for speech communication provided critical listening activities are coordinated between classes and noise is controlled. While this study only provided case studies of four classrooms, the findings are similar to those few studies that have previously been conducted (e.g. [22]). Further investigation is needed, however, to assess exactly what classroom types are suitable learning spaces for children at different ages. It is essential for this research to be conducted in a wide range of open plan and enclosed classrooms to assess which designs are appropriate in order to meet the recommended reverberation times and what the maximum number of students/class bases in an area should be to minimize noise levels and ensure adequate speech perception in the learning environment. Once this research has been conducted it may be beneficial for Australia to implement recommendations or restrictions for open plan classroom design so speech perception is not compromised in the educational setting.

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