The effect of different open plan and enclosed classroom acoustic conditions on speech perception in Kindergarten children^{a)}

Kiri T. Mealings^{b)} and Katherine Demuth

Department of Linguistics, ARC Centre for Cognition and its Disorders, Level 3 Australian Hearing Hub, 16 University Avenue, Macquarie University, Sydney, New South Wales 2109, Australia

Jörg M. Buchholz^{c)} and Harvey Dillon

National Acoustics Laboratories, Australian Hearing Hub, 16 University Avenue, Macquarie University, Sydney, New South Wales 2109, Australia

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Open plan classrooms, where several classes are in the same room, have recently re-emerged in Australian primary schools. This paper explores how the acoustics of four Kindergarten classrooms [an enclosed classroom (25 children), double classroom (44 children), fully open plan triple classroom (91 children), and a semi-open plan K–6 "21st century learning space" (205 children)] affect speech perception. Twenty-two to 23 5–6-year-old children in each classroom participated in an online four-picture choice speech perception test while adjacent classes engaged in quiet versus noisy activities. The noise levels recorded during the test were higher the larger the classroom, except in the noisy condition for the K–6 classroom, possibly due to acoustic treatments. Linear mixed effects models revealed children's performance accuracy and speed decreased as noise level increased. Additionally, children's speech perception abilities decreased the further away they were seated from the loudspeaker in noise levels above 50 dBA. These results suggest that fully open plan classrooms are not appropriate learning environments for critical listening activities with young children due to their high intrusive noise levels which negatively affect speech perception. If open plan classrooms are desired, they need to be acoustically designed to be appropriate for critical listening activities. © 2015 Acoustical Society of America.

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I. INTRODUCTION

Ensuring young children can adequately perceive speech in the classroom is essential for their learning. In Australia, Kindergarten is children's first experience of formal primary school education. In this grade children are introduced to the basic concepts of literacy and numeracy. As children are estimated to spend 45%-60% of their time at school listening, it is vital that they can hear and comprehend their teacher's and classmate's speech amongst the other distracting noises heard in the classroom (Rosenberg et al., 1999). The main noise source present in the classroom is the noise generated by other children (Shield and Dockrell, 2004). High noise levels not only adversely affect children's speech perception (Crandell and Smaldino, 2000; Finitzo-Hieber and Tillman, 1978), but also their reading and language comprehension (Klatte et al., 2010; Maxwell and Evans, 2000; Ronsse and Wang, 2013), cognition, concentration, and their psychoeducational and psychosocial achievement (American Speech-Language-Hearing Association, 2005; Crandell and Smaldino, 2000; Shield *et al.*, 2010). Furthermore, continuous noise exposure places additional demands on children's listening effort which reduces the resources available for linguistic and cognitive processing (Anderson, 2001). As a result, children can "tune out" from the auditory overload (Anderson, 2001; Maxwell and Evans, 2000).

Classes with young children tend to have the highest noise levels (Jamieson et al., 2004; MacKenzie and Airey, 1999; Picard and Bradley, 2001; Wróblewski et al., 2012). Young children are also more affected by noise compared to older children and adults (Johnson, 2000; Leibold and Buss, 2013; Nishi et al., 2010; Nittrouer and Boothroyd, 1990). This is because children's auditory systems are neurologically immature so they cannot discriminate speech or use linguistic knowledge or experience to fill in missing information as adults can (Boothroyd, 1997; Nelson and Soli, 2000; Wilson, 2002). More specifically, children's consonant perception in noise does not become adult-like until the late teenage years (Johnson, 2000). Similarly, it has been shown that sentence recall performance is significantly reduced in young children compared to adults, in particular, when the target sentences are presented in a spatially separated speech background (Cameron and Dillon, 2007). Children with hearing impairment and/or those who have English as a second language (ESL) are even more adversely affected by poor classroom acoustics (MacKenzie and Airey, 1999; Nelson and Soli,

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^{b)}Electronic mail: kiri.mealings@mq.edu.au

^{c)}Also at: the Department of Linguistics, Macquarie University, Sydney, New South Wales 2109, Australia.

2000; Shield *et al.*, 2010) and these children are now often integrated into mainstream classes rather than being in smaller, specialized schools (Konza, 2008). High noise levels also increase annoyance and stress levels for the teachers (Kristiansen *et al.*, 2011).

In the 1970s there was a trend of converting enclosed classrooms into open plan classrooms, where multiple class bases share the same area. These spaces were thought to create a more secure feeling for the child as they are perceived as more "home-like" and less authoritarian (Maclure, 1984). They also allowed for a range of activities to be carried out, facilitating group work and social development (Brogden, 1983). Additionally, they promoted the sharing of skills, ideas, and experiences amongst teachers, and allowed for team-teaching which is thought to facilitate a more cooperative and supportive atmosphere (Brogden, 1983; Hickey and Forbes, 2011). However, these classrooms resulted in high noise levels due to large numbers of children sharing the same area and being engaged in a range of activities, so they were soon abandoned (see Shield et al., 2010, for a review). Now, the American National Standards Institute (2002) strongly discourages the use of open plan classrooms as the high levels of background noise negatively impact children's learning processes. Additionally, studies have shown that smaller class sizes are linked to higher student achievement, and the lower exposure to noise provides a better environment for both students and teachers (Glass and Smith, 1979; Pelegrín-García et al., 2014).

Despite these previous findings, new-style open plan classrooms have recently been emerging in Australia and other countries such as New Zealand, the United States, the United Kingdom, Japan, Norway, Sweden, Portugal, and Denmark, renamed as "21st century learning spaces" which center around group work. These can have up to 200 children sharing the same area (Stevenson, 2011). It is important to note, however, that while these open plan classrooms are primarily designed for group activities, Kindergarten teachers in these classrooms can still spend up to 40% of the time teaching in a traditional didactic-style method (Mealings et al., 2015a), so it is vital that children are able to hear the new concepts that are being taught. Therefore, these newstyle open plan classrooms need to be assessed to see if they are an improvement on the open plan classrooms from the 1970s. As several schools in Australia are currently converting to these layouts, it is timely to conduct some of the first Australian research in these classrooms to assess how the acoustic parameters of these classrooms directly affect children's speech perception accuracy and speed.

Although there is evidence from Europe and the United Kingdom that high noise levels were a common problem in open plan schools, to our knowledge there have been no speech perception studies conducted *live* in open plan classrooms to directly assess how real-life noise *and* the classroom's design affects how well the children can hear their teacher. Most previous research focuses on measuring the acoustic parameters [e.g., noise levels, SNRs, speech transmission index (STI) scores, and reverberation times] of open plan classrooms and comparing these to acoustic standards/ recommendations, rather than directly investigating how

these acoustics affect children's ability to hear the words their teacher is saying. While many studies have investigated speech intelligibility in traditional classrooms (e.g., Astolfi et al., 2012; Finitzo-Hieber and Tillman, 1978; Jamieson et al., 2004; Johnson, 2000; Klatte et al., 2010; Neuman et al., 2010; Vickers et al., 2013; Wróblewski et al., 2012), they usually do so using a virtual environment and/or headphones. Such studies are not representative of natural listening environments, which contain a binaural advantage [see Bradley and Sato (2008)]. Other studies have used simulated classroom noise/multitalker babble which is not representative of the children's/teacher's voices and movement, furniture noise, air-conditioning unit noise and other equipment noises that are present in the classroom (Jamieson et al., 2004). Both Astolfi et al. (2012) and Bradley and Sato (2008) raise the need for speech perception studies to be conducted in live classrooms.

The goal of the present study, therefore, was to investigate the practical implications of the classroom acoustics measured by Mealings et al. (2015a) on the children's ability to hear and understand their teacher. This was achieved via a word discrimination test conducted live in the real classroom environments using the Mealings, Demuth, Dillon, and Buchholz Classroom Speech Perception Test (MDDB CSPT) (Mealings et al., 2015b), which was especially designed for live open plan classroom speech perception studies. In this test, personal response systems (PRSs) were used to simultaneously test all children live in the classroom. This method not only records accuracy, but also response times, which is an important variable for understanding children's ability to process information in noise that many intelligibility tests do not capture. Such a method of testing is expected to provide strong ecological validity, generalizing into real-world learning/speech perception. [More information on the use of PRSs live in the classroom can be found in Mealings et al. (2015b), and Vickers et al. (2013).] Using this type of live test will give a better indication of how well children can hear their teacher in different types of open plan classrooms.

Therefore, the aim of this study was to compare children's speech perception abilities in different open plan and enclosed classrooms when the other class bases were engaged in quiet versus noisy activities. In light of previous findings by Astolfi et al. (2012) and Bradley and Sato (2008), it was hypothesized that the children's speech perception accuracy would be poorer for lower SNR/STI values. In our study, this was determined by two factors: (i) an increase in the noise level from the adjacent class(es) (which we predicted would largely be related to the number of children in the classroom area) and (ii) an increases in the distance the child was seated from the loudspeaker (which simulated the teacher's voice). In addition to measures of speech perception accuracy, we also investigated a new parameter-the children's response times. This gives extra insight into children's ability to process information in the classroom. It was hypothesized that the children's response times would be slower in noisier conditions due to increased cognitive load. Finally, it was also hypothesized that the design of the classroom might be a factor affecting children's speech perception (not just the number of children in

TABLE I. Det	ails of the participating	classrooms (from	Mealings et a	d., 2015a).
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	Enclosed classroom	Double classroom	Triple classroom	K-6 classroom
Total number of children 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	Kindergarten	Kindergarten	Kindergarten to year 6
	(5-6-year-olds)	(5-6-year-olds)	(5–6-year-olds)	(5-12-year-olds)
Number of class bases in area	1	2	3	5-7 (depending on activity)
Number of children 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

the classroom area). Therefore, we predicted that the children in the purpose-built, "21st century" semi-open plan K–6 classroom would perform better than those in the untreated, fully open plan triple classroom despite the K–6 classroom having over twice the number of children.

II. METHOD

A. Schools involved

The study took place in Sydney, Australia in the second half of the school year. The same schools that were involved in the classroom acoustic measures study by Mealings et al. (2015a) were involved in this study. As described in Mealings et al. (2015a), a wide range of potential primary schools were examined before the final classrooms were selected. As the number of children in the open plan classrooms we examined ranged between 40 and 200 children (divided into class bases of 20-30 children), we chose three open plan classrooms across the 40-200 child range as well as one enclosed classroom with 25 children. A subset of Kindergarten children (i.e., 5-6-year-olds in their first year of primary school) in each classroom participated in the speech perception test. When selecting the schools, effort was made to choose those with similar scores on The Index of Community Socio-Educational Advantage (ICSEA) scale which represents a school's level of educational advantage based on family backgrounds. ICSEA scores range from 500 ot 1300 (M = 1000; SD = 100) where higher scores represent more advantaged schools. [More information about the ICSEA can be found at My School (2013).] We used the school's ICSEA scores calculated for 2013 when the studies were conducted. Below are the descriptions of each of the classrooms involved in the study as found in Mealings et al. (2015a). Further details on the participating classrooms are shown in Table I. More details on the room acoustics can also be found in Mealings et al. (2015a).

1. Enclosed classroom: 25 children

This classroom consisted of 25 Kindergarten children in a classroom with three solid brick walls, a closed floor-toceiling 4 cm thick concertina (i.e., operable) wall with pin boards, and a shared storeroom with the adjacent Kindergarten class. The class area was carpeted with 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. The average unoccupied reverberation time (T30) of this classroom was 0.50 s,¹ which is within the recommended time of 0.4-0.5 s (Australia/New Zealand Standard, 2000).

2. Double classroom: 44 children

This space originally consisted of two separate classrooms with plasterboard walls, but the wall between had



FIG. 1. Floor plan of the enclosed classroom with 25 children.



FIG. 2. Floor plan of the double classroom with 44 children.

been removed at the start of the year to make it an open double classroom for the 44 Kindergarten children. 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 average unoccupied reverberation time (T30) of this classroom was 0.60 s, which is above the recommended time of 0.4–0.5 s (Australia/New Zealand Standard, 2000).

3. Triple classroom: 91 children

This open plan classroom consisted of 91 Kindergarten children grouped linearly into three classes (K1, K2, K3), with no barriers between them. This classroom represented a mid-range number of children and class bases 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 average unoccupied reverberation time (T30) of this classroom was 0.70 s, which is above the recommended time of 0.4-0.5 s (Australia/New Zealand Standard, 2000).

4. K-6 classroom: 205 children

This classroom contained the entire primary school (205 children) in the one area representing one of the biggest types of open plan classrooms found in Sydney. It had been



FIG. 3. Floor plan of the triple classroom with 91 children.

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 in the fully open plan area. The Kindergarten class was located in the corner in the acoustically most sheltered location, particularly for their whole class teaching area where the children were grouped together on the floor to listen to their teacher (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. The average unoccupied reverberation time (T30) of this classroom was 0.58 s, which is above the recommended time of 0.4-0.5 s (Australia/New Zealand Standard, 2000), but lower than the reverberation times of the double and triple classrooms.

B. Participants

Twenty-four Kindergarten children from each school were randomly selected to participate in the classroom



FIG. 4. Floor plan of the K-6 classroom with 205 children.

TABLE II.	Demographic	information	for parti	cipating	children.
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Classroom	Number of children in area	Number of participants	Number of males/females	Age range and mean	Number who have ESL	Number who have attended preschool
Enclosed	25	23	13M; 10F	5;3-6;7 M = 6:0	12	23
Double	44	23	12M; 11F	5;7-6;9 M = 6:3	0	20
Triple	91	22	9M; 13F	5;5-6;6 M = 5:9	11 (+4 multilingual)	19
K6	205	23	12M; 11F	5;0-6;5 M = 5;10	4 (+6 multilingual)	21

speech perception test. No children were reported by their parents to have otitis media, or intellectual or behavioural disabilities in the enclosed, triple, and K-6 classrooms. One child in the double classroom was reported to have a sensory processing disorder, but as their performance did not deviate from their peers, they were included in the analysis. For both the double and K-6 classrooms, one child was absent on the day of testing so only 23 children were included in the study. For the triple classroom, two children who participated in the study were excluded as they did not finish the test. For the enclosed classroom, one child only scored 8% in the quiet condition so was excluded from the analysis as they failed to demonstrate an ability to understand and complete the test. Table II shows the demographics of the participating children. The remaining Kindergarten children in each of the classrooms made up the class(es) to provide the intrusive noise.

C. Stimuli

The MDDB CSPT word lists were used for the study (Mealings et al., 2015b). This test was chosen as it was developed especially to be conducted live in real classroom environments, efficiently testing a whole class of children simultaneously through the use of PRSs. Additionally, this test was developed in Australia, so the words are appropriate for an Australian context and the stimuli are presented in an Australian accent. This test is based on the Chear Auditory Perception Test (Marriage and Moore, 2003). The test consists of 6 lists of 4 minimally contrastive monosyllabic words, with Lists O1, O2, and O3 having onset consonant contrasts and Lists C1, C2, and C3 having coda consonant contrasts (Table III). Phonemically, the types of contrasts are balanced between list pairs with Lists O1 and C1 contrasting voiceless stops and fricatives, Lists O2 and C2 contrasting voiced stops and nasals, and Lists O3 and C3 contrasting voiceless stops, fricatives, affricates, and clusters. Each

TABLE III. MDDB CSPT word lists.

List O1	List O2	List O3	List C1	List C2	List C3
_Art	_Eat	<u>T</u> alk	K_	Bee_	Beat
<u>T</u> art	Beat	Fork	Ca <u>pe</u>	Bea <u>d</u>	Bee <u>s</u>
Cart	Meat	Chalk	Ca <u>ke</u>	Beam	Beach
Heart	Neat	Stalk	Ca <u>se</u>	Bean	Beast

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word is pictorially represented and appears in one of six five-syllable carrier sentences (one sentence for each list, e.g., *Sally likes the...*).

The test uses audio recordings of the 24 sentences by an adult Australian-English female speaker using teacher-like speech. These recordings were made in an anechoic chamber using a DPA headset microphone and the intensities were normalized so that each sentence had the same average root mean square value. [For more information on how the test was developed, see Mealings *et al.* (2015b).]

D. Listening conditions

The aim of the experiment was to assess how intrusive classroom noise impacts children's listening abilities. There were two listening conditions; one when the other classes were engaged in quiet activities (e.g., whole class teaching or quiet individual work) and the other when they were engaged in noisy activities (e.g., group work with movement). The study was run in the afternoon after the lunch break and the teachers of the other classes were instructed to choose typical quiet and noisy activities for their classes to engage in. To counterbalance possible learning effects, the participants were split into two groups. Group 1 completed the experiment in quiet then in noise, whereas group 2 completed it in noise and then in quiet. The noise from each activity was recorded using an omnidirectional condenser microphone (calibrated in diffuse speech-shaped noise using a BandK 2250 sound level meter) connected to a USB sound card and Toshiba Satellite U940 Ultrabook running Audacity software. This allowed us to calculate the average noise levels for each activity offline. These noise files were then segmented and the speech signal of the stimuli and any other artefacts were removed from the final noise file so the average noise levels for each activity could be calculated.

E. Procedure

Participants were each assigned a seating position in one of six rows of four children in front of a Smart Board with males/females and ESL children evenly distributed front to back. The distance of the children from the loudspeaker ranged from 1 to 3 m. The visual stimuli were projected onto a Smart Board via a Toshiba Tecra Notebook and the audio was played through a Genelec 8020B (active studio monitor) loudspeaker positioned at the front of the classroom under the center of the Smart Board. The audio volume was adjusted so that the average sound level presentation was 60 dBA at 2m [which represents a teacher's average speech level (Sato and Bradley, 2008)] as measured by a calibrated Dick Smith Electronics Q1362 sound level meter. The test began with all participants completing a familiarization phase of the target words, pictures, and their PRS. When the children were ready the testing phase began. The children saw the four pictures of a particular list appear on the screen, accompanied by the audio sentence that contained one of the words of that list. They were instructed to select the picture they heard via the colour-coded buttons on their PRS. The List order was pseudo-randomised (e.g., 1, 4, 6, 3, 5, 2) and the lists were rotated through four times. Pseudorandomisation was used rather than having all four words of a list presented consecutively to make it harder for children to use a process of elimination. This procedure was repeated for all 24 stimuli (pseudo-randomized) in both conditions. A maximum of 15 s (from the start of each stimulus display) was allowed for the children to record their response. Group 1 completed the test in the quiet condition first while Group 2 left the testing area. Groups 1 and 2 then completed the testing phase in the noisy condition together (to ensure the noise level was the same for both groups tested) before Group 1 left Group 2 to do the test in the quiet condition. Having two Groups complete the test in different orders helps minimise learning effects. The responses were then collated and analyzed for both performance accuracy and speed using the TurningPoint software.

III. RESULTS

A. Noise levels

The noise levels were recorded during the test in each classroom as described in Sec. II D. Figure 5 shows a comparison of the levels recorded for each school while the other classes were engaged in quiet versus noisy activities. It is recommended that classroom noise levels should be kept below 50 dBA (Berg *et al.*, 1996). This was only achieved for the two smaller classrooms in the quiet condition. (Unfortunately the open-door shared store room in the enclosed classrooms, resulting in above recommended noise levels during its noisiest periods.) The noise levels generally



FIG. 5. Average recorded noise levels for each classroom while adjacent classes were engaged in quiet activities and noisy activities.

increased as class size increased, however, the noise levels in the K–6 classroom did not reach the high level of noise that the triple classroom did during the noisy condition. Notice also that the noise levels were consistent for the K–6 classroom across conditions. As with the other schools, we asked the surrounding classes at this school to engage in quiet activities and then noisy activities so we could measure the difference between the two conditions. However, due to the large number of class bases in the area, it was not possible to coordinate this across the whole classroom. Hence the recorded noise levels were the same for both conditions in the speech perception test demonstrating that the noise levels in this classroom stay fairly constant in contrast to the changing noise levels in the other three classrooms.

B. Overall speech perception scores

1. Linear mixed effects model results

A linear mixed effects analysis was conducted using IBM SPSS Statistics software (version 21) to assess what factors may contribute to the children's speech perception scores. The fixed factors of classroom type (which included factors such as room volume, design, number of children, reverberation time, ICSEA, etc.), noise level, test order (i.e., quiet/noise condition order), gender, ESL, time in preschool (using the square root of total hours), and distance from the loudspeaker (using log base 2) were entered into the model with participant as the random factor. This model was used to predict the change in score relative to that in the enclosed classroom. As predicted, noise level and distance from the loudspeaker were significant factors in the model [F(1,87) = 70.92, p < 0.0005; F(1,79166) = 30.47, p < 0.0005, respectively]. As shown in Table IV, if all other predictor variables were held constant, every increase in noise by 10 dBA resulted in scores being 14.3% lower, which was approximately the difference in noise levels between the quiet and noisy condition in the classrooms. Similarly, if all other predictor variables were held constant, scores were estimated to decrease by 12.8% for each doubling of distance the child was seated away from the loudspeaker (i.e., 1, 2, 4 m, etc.). Further analysis of these two factors for each classroom can be found below. Interestingly, classroom type was also a significant factor [F(3,99) = 5.24,p = 0.002]. The scores of the K–6 classroom were estimated

TABLE IV.	Estimates of	fixed	effects	for	speech	perceptio	n scores.
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Parameter	Estimate	SE	df	t	р
Intercept	163.58	10.46	146	15.64	0.000 ^a
K-6 classroom	8.17	3.65	113	2.24	0.027 ^a
Triple classroom	-1.25	3.72	127	-0.34	0.737
Double classroom	-4.80	3.54	79	-1.36	0.179
Enclosed classroom	0.00	0.00			
Noise level	-1.43	0.17	87	-8.42	0.000 ^a
Distance	-12.81	2.32	79	-5.52	0.000 ^a
Test order	-3.94	2.27	79	-1.73	0.088
Gender	-0.10	2.30	79	-0.04	0.967
ESL	-1.66	2.84	79	-0.59	0.560
Preschool	0.03	0.05	79	0.69	0.495

 $^{\rm a}p < 0.05$.

to be 8.2% higher than the enclosed classroom, 13.0% higher than the double classroom, and 9.4% higher than the triple classroom, when all other predictor variables, including noise level, were held constant. Test order, gender, and time in preschool were not significant factors in the model [F(1,79) = 2.99, p = 0.088; F(1,79) = 0.00, p = 0.967; F(1,79) = 0.47, p = 0.495, respectively]. Additionally, ESL was not a significant factor in the model <math>[F(1,79) = 0.34, p = 0.560] despite previous research suggesting these children are more affected by noise (Nelson and Soli, 2000). [Note, however, that Astolfi *et al.* (2012) who conducted a similar speech perception study in Italy also did not find a significant difference between children who had Italian as their first language with those who did not.]

2. Speech perception scores by classroom type

Figure 6 shows the children's average percentage of correct responses by classroom type for both the quiet and noisy conditions. Paired t-tests were conducted to compare the children's performance for each classroom in the two conditions. Performance was significantly better while adjacent classes were engaged in quiet compared to noisy activities for the enclosed classroom [t(22) = 5.34, p < 0.0005, d = 1.31],the double classroom [t(22) = 5.16, p < 0.0005, d = 1.26], and the triple classroom [t(21) = 7.70, p < 0.0005, d = 1.43] as expected following the trend of the noise levels shown in Fig. 5. Note, however, that there was no difference in performance for the K-6 classroom between the two conditions. As mentioned previously, there was no difference in noise levels for the two conditions in this classroom as quiet versus noisy activities were unable to be coordinated across classes because of its size. Noise levels therefore tended to stay at a consistent level (and reliability of the test is shown by the children having similar group mean scores both times they participated in the test). As the K-6 classroom does not have the two noise conditions like the other classrooms, we report the average results from the two conditions to compare with



FIG. 6. Children's average percentage of correct responses for each classroom while adjacent classes were engaged in quiet activities and noisy activities. Note that the K–6 classroom did not have different quiet/noise conditions as activities could not be coordinated across all classes. Error bars show standard error of the mean. The dashed lines indicate pairs of classrooms which significantly differed in average scores, and the asterisks indicate classrooms for which the average score in the noisy condition was different from the average score in the quiet condition, both with p < 0.05.

the other classrooms for the remaining analyses, as shown by the different shading in Figs. 6 and 7, and 9.

A significant difference in speech perception scores was found between classrooms in the quiet condition as determined by one-way analysis of variance (ANOVA) $[F(3,87) = 6.48, p = 0.001, \eta^2 = 0.18]$ with a Tukey *post hoc* test revealing significantly better performance by children in the enclosed classroom compared to the triple and K–6 classroom ($p_{enclosed vs triple} = 0.004, p_{enclosed vs K-6} = 0.003$). A second one-way ANOVA also revealed a statistically significant difference between classrooms in the noisy condition [F(3,87) = 8.76, $p < 0.0005, \eta^2 = 0.23$] with a Tukey *post hoc* test revealing significantly poorer performance by children in the triple classroom (which had the highest noise levels) compared to the other classrooms ($p_{enclosed vs triple} = 0.001, p_{double vs triple}$ = 0.009, $p_{K-6 vs triple} < 0.0005$; see Fig. 6).

C. Performance by seating position for each classroom

Figure 7 shows the children's speech perception scores as a function of how far they were seated away from the loudspeaker simulating the teacher's voice. A correlation analysis was conducted for each classroom to assess how the children's scores changed for each doubling of distance the children were seated away from the loudspeaker (i.e., the change from 1 m to 2 m to 4 m, etc.). For the enclosed and double classrooms, no correlation between children's performance and seating distance was found for the quiet condition, with children performing consistently well front to back (which were also the conditions that reported noise levels within the 50 dBA recommended limit). For the noisy condition, however, both classrooms reported a moderate negative correlation $(r_{\text{enclosed}} = -0.59, R^2_{\text{enclosed}} = 0.35, p_{\text{enclosed}} = 0.003;$ $r_{\text{double}} = -0.54, R^2_{\text{double}} = 0.29, p_{\text{double}} = 0.012$). (Note that we excluded two outliers in the noise condition for the double classroom for this analysis as the unusually low scores clearly did not fit the linear trend when plotted, i.e., it is likely that these two children did not attend to the whole test.) On average, scores at the front were 80% compared to 53% at the back for the enclosed classroom and 79% at the front compared to 52% at the back for the double classroom. For the triple classroom, a moderate negative correlation was found between children's performance and seating distance in the quiet condition (r = -0.63, $R^2 = 0.40$, p = 0.002). On average, scores at the front were 82% compared to 56% at the back. When the other classes changed to noisy activities, this relationship increased to a strong negative correlation (r = -0.80, $R^2 = 0.65$, p < 0.0005). In this condition, children's scores decreased by 30% per doubling of distance from the loudspeaker, with average scores at the front being 72% compared to only 25% at the back. Overall (as there was no difference in noise levels for the two conditions) the K-6 classroom reported a weak-to-moderate negative correlation (r = -0.49, $R^2 = 0.24$, p = 0.001). On average, scores at the front were 83% compared to 55% at the back. These results show the detrimental effect of reduced SNRs on speech perception as a result of being seated further away from the teacher, especially in high noise levels.

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FIG. 7. Children's speech perception scores as a function of how far they were seated away from the loudspeaker (using log base 2 for the line of best fit) while the others classes were engaged in quiet activities and noisy activities for each classroom. Note that the K–6 classroom did not have different quiet/noise conditions as activities could not be coordinated across all classes.

To compare the measured children's speech perception scores to corresponding STI scores, the noise recordings of the quiet and noisy conditions that were taken during the speech test were used in a STI calculation together with the room impulse responses (RIRs) previously measured in the same four classrooms (see Mealings *et al.*, 2015a). Thereby, target speech levels were predicted by convolving the (calibrated) RIRs with the speech-test material, which was presented at a sound pressure level of 60 dBA at a distance of 2 m. Since RIRs were only available at three different distances per class room, only speech scores were considered for children that were sitting at a similar distance (within 10 cm) to the measured RIRs. As a consequence, 52 out of the total of 182 speech perception scores were considered in this analysis and plotted in Fig. 8.

A sigmoidal function was used to fit the data by minimizing the RMS error between measured and predicted scores using MATLAB. This function was given by

$$y = \frac{a}{1 + e^{-c(x-d)}} + b,$$
 (1)

where a = 67, c = 6.1, d = 0.4, x = STI score, y the predicted children's speech perception score, and



FIG. 8. Children's speech perception scores as a function of predicted STI scores together with a fitted sigmoidal function.

 $b = 25 - \frac{a}{1 + e^{cd}} = 19.6.$ (2)

Equation (2) ensured that for an STI value of zero the chance level of 25% was reached. The RMS error between measured and predicted scores was 13% and the function is shown in Fig. 8. There is a reasonable fit between the sigmoidal function and the data, especially considering that the data were collected with young children live in the classrooms.

D. Response times

In addition to decreased performance accuracy, we also predicted that there would be a decrease in the speed of the children's response (measured from the onset of the stimulus display) in noisier conditions. Therefore, a linear mixed effects analysis was conducted using IBM SPSS Statistics software (version 21) to assess this as well as investigate what other factors may affect the children's response times. The fixed factors of classroom type (which included factors such as room volume, number of children, reverberation



FIG. 9. Children's average response times for each classroom while the others classes were engaged in quiet activities and noisy activities. Note that the K–6 classroom did not have different quiet/noise conditions as activities could not be coordinated across all classes. Error bars show standard error of the mean. The dashed lines indicate pairs of classrooms which significantly differed in average response times, and the asterisks indicate classrooms for which the average response time in the noisy condition was different from the average response time in the quiet condition, both with p < 0.05.

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time, ICSEA, etc.), noise level, test order (i.e., quiet/noise condition order), gender, ESL, time in preschool (using the square root of total hours), and distance from the loudspeaker (using log base 2) were entered into the model, with participant as the random factor. This model was used to predict the change in response time relative to that in the enclosed classroom. As predicted, noise level was a significant factor in the model [F(1,87) = 70.92, p = 0.003]. As shown in Table V, if all other predictor variables were held constant, every increase in noise by 10 dBA resulted in response times being 364 ms longer. Distance was also a significant factor in the model [F(1,79) = 18.62, p < 0.0005]. If all other predictor variables were held constant, response times were estimated to increase by 844 ms for each doubling of distance the child was seated away from the loudspeaker (i.e., 1 m, 2 m, 4 m, etc.). Classroom type, test order, gender, ESL, and time in preschool were not significant factors in the model [F(3,94) = 1.84, p = 0.048; F(1,79) = 0.01,p = 0.925; F(1,79) = 0.97, p = 0.328;F(1,79) = 1.03, p = 0.314; F(1,79) = 2.31, p = 0.133, respectively].

Figure 9 presents children's average response times for each classroom while adjacent classes were engaged in quiet activities and noisy activities. Note in particular the slow response times by the children in the triple classroom in the noisy condition.

IV. DISCUSSION

Open plan style classrooms have recently been reemerging as "21st century learning spaces." The main issue with open plan classrooms is the intrusive noise coming from the other classes sharing the space. This is particularly problematic when one class is trying to engage in critical listening activities; while the teacher can tell their own class to be quiet, they have no control over the noise levels of the other classes. As school is a vital time for children to learn new concepts and words, they need to be able to hear clearly what their teacher is saying. Therefore, the aim of this study was to assess and compare Kindergarten children's speech perception *accuracy* and *speed* live in different types of open plan and enclosed classrooms when the other class bases were engaged in quiet versus noisy activities.

TABLE V. Estimates of fixed effects for response times.

Parameter	Estimate	SE	df	t	р
Intercept	2.94	0.78	160	3.78	0.000 ^a
K-6 classroom	0.12	0.30	103	0.41	0.682
Triple classroom	0.44	0.30	114	1.48	0.143
Double classroom	0.58	0.30	79	1.93	0.057
Enclosed classroom	0.00	0.00			
Noise level	0.04	0.01	87	3.06	0.003 ^a
Distance	0.84	0.20	79	4.32	0.000 ^a
Test order	0.02	0.19	79	0.10	0.925
Gender	-0.19	0.19	79	-0.98	0.328
ESL	0.24	0.24	79	1.01	0.314
Preschool	0.01	0.00	79	1.512	0.133

 $^{\rm a}p < 0.05.$

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Measurements of the noise levels during the test revealed acceptable listening conditions only in the enclosed and double classrooms while the other classes were engaged in quiet activities (although it is likely that they would have remained acceptable in the enclosed classroom during noisy activities if the shared store room door was closed). The noise levels in the triple classroom, however, were problematic especially when the other classes were engaged in noisy activities. The noise levels were also high in the K–6 classroom, but did not reach the high levels found in the triple classroom despite the K–6 classroom having over twice the number of children.

The speech perception test revealed, as expected, that higher noise levels significantly decrease children's speech perception accuracy and speed of response. The children's speech perception accuracy and speed also decreased the further away the child was seated from the loudspeaker (simulating the teacher's voice), but only when the noise level was over the recommended 50 dBA (Berg et al., 1996). In quiet conditions, the children in the two smaller classrooms performed consistently well front to back. However, in the larger classrooms, the children seated at the back were at a disadvantage as the noise levels during the "quiet" condition were still high. Most concerning, however, was the triple classroom which had particularly high noise levels when the other classes were engaged in noisy activities. This resulted in very poor speech perception scores for the children seated at the back. The distance effect in the K-6 classroom, however, was less severe and more similar to the smaller classrooms during the noisy condition.

It was also found that the K-6 classroom had consistent intrusive noise levels throughout the day, rather than the changing quiet and noisy periods that the other three classrooms had depending on what activities the adjacent classes were engaged in. Interestingly, the children in this classroom also had significantly better speech perception scores overall compared to the children in the other three classrooms, if noise levels were to be held constant across all the classrooms. It is unlikely that socio-economic status contributed to this difference in performance as this school had the second lowest ICSEA of the schools tested. It is possible that the children in this classroom have learned to work in the consistent noise levels and are less distracted both auditorily and visually because it is consistent rather than dynamic or impulsive. This possible explanation needs to be considered with caution, however, as mixed results have been found regarding the age at which children are able to habituate to noise (e.g., Anderson, 2001; Barnett et al., 1982; Maxwell and Evans, 2000; Shield et al., 2010). This issue therefore needs further investigation.

The most likely explanation for these better scores is that the design of the K–6 classroom aided the children's speech perception—this classroom was newly purpose-built as a "21st century open plan learning space." The Kindergarten class was located in the corner with a semiopen plan style (i.e., only one open wall), so the extra barriers may have helped remove some of the visual distraction as well as providing some acoustic shielding. It was also equipped with pin boards and other furnishings for absorption which helped reduce reverberation and hence the effect of noise as the two combine synergistically to mask speech (Crandell and Smaldino, 2000; Klatte *et al.*, 2010). This contrasts with the double and triple classrooms where they had just knocked down the original wall/s between the existing classrooms and no proper acoustic modifications were put in place to help reduce reverberation and noise. The K–6 classroom also had the greatest spatial separation between classes. This means that the speech coming from the children in other classes was likely to be less intelligible/ distracting.

These results suggest that the new architectural style of the "21 century learning spaces" are an improvement on the open plan classrooms that simply add classrooms together by removing walls. This is shown by the higher scores and quicker response times by the children in the K-6 classroom compared to those in the triple classroom, despite it having over twice the number of children. However, this classroom still needs to reduce noise levels to be within the recommended 50 dBA maximum to eliminate the distance effect, and add acoustic absorption to bring the reverberation time within 0.4-0.5 s (Australia/New Zealand Standard, 2000). It is also important to note that although classroom type was a significant factor in the speech perception scores linear mixed effects model (with the children in the K-6 classroom having better performance than children in the other classrooms if noise was held constant), noise was also a significant factor. Additionally, the children in the K-6 classroom still had lower scores than the children in the enclosed classroom during the quiet condition. Therefore, the children in the K-6 classroom would still perform better in a quieter environment even though they still performed fairly well in this noisy open plan setting.

These results suggest that if open plan classrooms are desired, they should be acoustically built as *flexible* learning spaces. That is, they should have operable walls that can stay open for group work and other activities that benefit from an open plan space, but can be closed for critical listening activities. This will create an acceptable environment like the enclosed classrooms tested, and we expect it will still be acceptable even if the other classes are engaged in noisy activities provided there are no other sound transmission channels like the open-door shared store room.

The results of this study clearly demonstrate the benefit of having acoustic barriers (i.e., enclosed walls) between classes to minimize the transmission of intrusive noise from adjacent classes and enhance speech perception. This is especially important for younger children as their auditory systems are neurologically immature and world knowledge and experience cannot as effectively be used to fill in the missing pieces with top-down information (Boothroyd, 1997; Wilson, 2002). The results of the study generally support those found by Pelegrín-García et al. (2014) who conclude that "no acceptable acoustic conditions can be achieved for more than approximately 40 students without exposing the teacher to talk uncomfortably or the students to experience noticeably degraded speech intelligibility." This is shown by the poor speech perception accuracy and speed by the children in the triple classroom, even when the other classes were engaged in only quiet activities. However, number of children is not the only factor that needs to be considered when designing classrooms. Although the noise levels in the K–6 "21st century learning space" with 205 children were still too high, they were not as high as those in the triple classroom, and the children's performance on the speech perception test was actually better. This suggests that purpose-built semi-open plan classrooms may be able to provide tolerable listening environments for more than 40 children if they are appropriately designed (which future research needs to determine). Is it important to note, however, that they will still compromise acoustic privacy compared to an enclosed classroom and children may still find it hard to concentrate in these environments.

Overall, the results suggest that when there is noise coming from other classes in open plan classrooms, the children engaged in active listening are likely to misunderstand their teacher. Even if they initially hear their teacher, the presence of noise results in slower processing of the sentence, which means they are more likely to miss the following information while they try to understand and integrate what has previously been said. The distance effect further emphasizes the importance of controlling noise levels and gathering children close to the teacher during critical listening tasks. One limitation of this study it that it used a loudspeaker with constant gain, whereas talkers tend to increase their speech level as function of the distance to the listener and the effect of the room (Pelegrín-García et al., 2011). The advantage of this is an increased SNR (hence increased speech intelligibility), however, it is likely to result in the teacher speaking above a comfortable level which may contribute to vocal health problems (Gotaas and Starr, 1993; Smith et al., 1997). Using sound field amplification systems in classrooms are one way of decreasing the distance effect without requiring teachers to speak louder. Note, however, that amplification systems are not appropriate for open plan classrooms because of their disturbance to other classes. This further suggests the shortcomings of this type of learning space as it is in these classrooms that speech perception is even more affected by the child's distance from the teacher because of the high intrusive noise levels.

Minimizing noise levels in the classroom is not only important for typically developing children, but is essential for children with special educational needs such as those with attention deficits, hearing impairment, language delays, auditory processing disorders and ESL (Anderson, 2001). These children are increasingly being integrated into mainstream schools (Konza, 2008). For example, it is estimated that 83% of children with hearing impairment are now in a regular classroom (Punch and Hyde, 2010). These children are even more affected by poor acoustics, so it is vitally important to ensure the listening environment for these children is good (Crandell and Smaldino, 2000; MacKenzie and Airey, 1999). Future research is needed to investigate how the acoustics of open plan classes may affect these populations. This will assist people in making informed decisions when choosing the most appropriate schools for these children to attend. The results of our study suggest that favourable listening conditions for young typically developing children are unlikely to be achieved in fully open plan classrooms, so we would expect that they are even more problematic for children with special educational needs. Minimizing noise levels is also important for the teachers as high noise levels raises blood pressure, increases stress levels, causes headaches, results in fatigue, increases annoyance, and puts 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 (Airey et al., 1998; Anderson, 2001; Evans and Lepore, 1993; Gotaas and Starr, 1993; Kristiansen et al., 2011; Leão et al., 2015; Shield et al., 2010; Smith et al., 1997). As this study only involved four classrooms, it is important that future research is conducted in a wide range of open plan and enclosed schools. This will help provide a better understanding of what noise levels, reverberation times, and classroom sizes/designs are needed to provide adequate speech perception in the classroom for all children at their different ages. Acoustic modelling can then be used for designing new classrooms or determining the treatment needed for existing classrooms so they achieve these acceptable conditions. Once this research has been conducted it may be beneficial for Australia and other countries to implement recommendations or restrictions for classroom acoustic conditions and classroom design so speech perception is not compromised in the educational setting.

V. CONCLUSIONS

The results of this study revealed acceptable listening conditions for the enclosed and double classrooms, but only when the adjacent class was engaged in quiet activities. For the two larger open plan classrooms, the noise levels were excessive irrespective of the activity of the other classes. Higher noise levels resulted in decreased speech perception accuracy and speed, especially for the children seated towards the back of the class when the noise level was over the recommended 50 dBA limit (Berg et al., 1996). Interestingly, however, the noise levels and children's speech perception scores were better in the K-6 "21st century learning space" compared to those in the untreated converted triple classroom, despite it having over twice the number of children. This demonstrates that the new-style open plan classrooms are an improvement on the open plan classrooms that simply add rooms together by removing walls. However, it is important to note that the statistical model still suggested children would perform better in a quieter environment.

Overall, the findings of this study provide further evidence for the importance of having optimal listening conditions in Kindergarten classrooms to enhance children's access to new concepts. The results suggest that classrooms that are unable to control the ingress of noise from nearby classes do not provide appropriate learning environments for critical listening activities with young children due to the adverse effects of this noise on children's speech perception.

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¹Note a Tannoy V8 loudspeaker was used for measuring the room impulse responses which were used to calculate the T30s for the classrooms (see Mealings *et al.*, 2015a). Hence, the directivity of this loudspeaker may have resulted in a slight underestimation of the T30 when compared to measurements with an omni-directional sound source which most standards are based on. However, the directivity of the applied loudspeaker better resembled the directivity of a teacher's voice and thus, provided more realistic predictions of the STI which is why it was used.

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