Proceedings of the International Symposium on Room Acoustics, ISRA 2010

29-31 August 2010, Melbourne, Australia

Classroom Acoustics and Green Schools

Dr. Kenneth P. Roy

Sean D. Browne, MS

Armstrong World Industries, R&D, Lancaster, Pennsylvania, USA

PACS: 43.55.HY

ABSTRACT

Schools are designed and built specifically for the purpose of educating students. Teachers ‘teach’ and students ‘learn’ primarily on the basis of verbal and visual cues – obviously, a primary design goal must be the acoustic performance of classrooms for speech intelligibility. Standard metrics for speech intelligibility such as Articulation Index (AI) [1], Speech Intelligibility Index (SII)[2], Speech Transmission Index (STI)[3], etc. are good general indicators, but must be used carefully as they only represent speech intelligibility for young adults with both normal hearing and language recognition. Often times the key listeners in grades K-12 will be young children, 2nd language listeners, etc., such that the normal metrics do not apply. Acoustic requirements are today included in various green rating systems for schools including the United States Green Building Council (USGBC) LEED® for Schools [4], and the Green Building Council Australia (GBCA) Green Star – Education [5]. Acoustics are usually addressed using both the maximum acceptable room reverberation time (RT), and the maximum acceptable background noise (N). In essence, this is prescribing the speech intelligibility in terms of sound clarity and signal-to-noise (S/N) ratio. An experienced architectural designer may also wish to consider other fundamental factors such as direct-to-reflected (D/R) ratio, and sound clarity (C_{50})[6]. Sound clarity is determined by architectural design factors including classroom size, shape, and surface treatments, and it will not change unless the architecture is changed. Background noise on the other hand, is based primarily on the factors of exterior (environmental) noise intrusion, and the interior HVAC noise. The acoustic design objective for classrooms must involve designing for speech clarity with architecture, and protecting the speech clarity by ensuring good mechanical design to limit the background noise. Various classroom architectural layouts were designed and evaluated using EASE [7] modelling software to investigate speech clarity. An actual classroom mock-up of one of these models was also investigated as a comparison to the modelling outcomes.

GREEN SCHOOL RATING SYSTEMS

Both the USGBC LEED® for Schools and the GBCA Green Star – Education, list requirements for the allowable reverberation time and background noise in classrooms for grades K-12. These requirements for the maximum acceptable reverberation time are shown in Table 1 for each of the rating systems.

Table 1. Allowable classroom reverberation time (seconds)

	< 283 m^3	< 566m^3	> 566 m^3
LEED2009	0.6 s	0.7 s	< 1.5 s
	Teaching Spaces - Primary schools		
Green Star	0.4 s to 0.5 s*		

The LEED requirements are based on ANSI S12.60 Pt 2 for permanent school buildings [8], and listed by classroom size. LEED requirements listed in the green shaded areas are prerequisites which must be achieved to receive any level of certification. Green Star requirements listed in the yellow shaded area are based on the AS/NZS 2107:2000 Table 1 [9] requirements and achieving the lower value will provide 1 additional credit point. The * indicates that the lower level (0.4 sec) must be achieved for classrooms intended for students with disabilities, otherwise 0.5 sec is acceptable (without optional credit).

The background noise requirements are likewise shown in Table 2 for each of the rating systems.

Table 2. Allowable classroom background noise level (dBA)

	Prerequisite	Optional Credits	
	(required)	**1**	**2**
LEED2009	< 45 dBA	40 dBA	
Green Star	-	45 dBA	35 dBA

The LEED requirement listed in the green shaded area is a prerequisite which must be achieved to receive any level of certification. The LEED requirement listed in the yellow shaded area is available for 1 optional credit point. Green Star requirements listed in the yellow shaded area are based on the AS/NZS 2107:2000 Table 1 requirement, and achieving the lower value (in combination with the lower RT in Table 1) will provide 1 additional credit point.

SPEECH INTELLIGIBILITY METRICS

Standard metrics for speech intelligibility such as Articulation Index (AI), Speech Intelligibility Index (SII), Speech Transmission Index (STI), etc. are based on speech perception studies performed with young adults having both normal hearing and language recognition. Often times the key listeners in grades K-12 will be young children, 2nd language listeners, students with disabilities, etc., such that the normal metrics may not apply so well when it comes to predicting subjective perception from the objective measurements.

Rather than focusing solely on such speech perception metrics, it may be more insightful to also consider objective measurements such as D/R, C_{50}, RT, and S/N as these can be physically measured and are not susceptible to the issues related to typical listeners in grades K-12 as discussed in the previous paragraph.

The D/R is a measure of the direct sound to the reflected sound incident at the student's ear. Obviously, the greater this ratio (more direct) the better, since any reflected sound will take on the signature (characteristics) of the reflecting surfaces. If the D/R is – 10 dB, then the reflected sound is about twice as loud as the direct sound and the speech quality will start to be degraded beyond that level. The D/R will be somewhat related to the RT since more reverberant sound also means more reverberation (longer time). This ratio can be easily calculated in architectural acoustic modelling software such as EASE.

The C_{50} is a measure of the direct plus early reflected sound (first 50 msec) to the late reflected sound, and so is also loosely related to the D/R and RT. This metric is good for the evaluation of speech sounds that are enhanced by strong early reflections, especially as we intend to look at the effects of reflectors installed in the ceiling plane close to the teacher location. Values of C_{50} greater than 3 dB are considered favourable. This metric can be easily calculated in architectural acoustic modelling software such as EASE.

In the end, the speech intelligibility will be dependent on the sound quality as perceived by the listener. The sound quality will be dependent on both the sound clarity which is determined by the architectural design, and on the signal-to-noise ratio which for a given space (and talker) will be dependant on the intruding noise.

ARCHITECTURAL/ACOUSTIC SIMULATIONS

Architectural models for normal classrooms (< $283m^3$) were developed within the EASE software, and these were evaluated for acoustic performance using a female teacher talking in a 'raised' voice level. The usual speech intelligibility metrics were calculated to compare the effect of a room with normal acoustical suspended ceilings, against the same room but with added ceiling reflector panels above the teacher location.

In Figures 1 and 2 are shown a typical rectangular classroom with two different orientations of the teacher relative to the students. The level of the direct sound is indicated on the figures, and the level of the reverberant sound for this particular room was 55 dBA. Obviously, the D/R ratio is much more advantageous for the students oriented as in Figure 2.

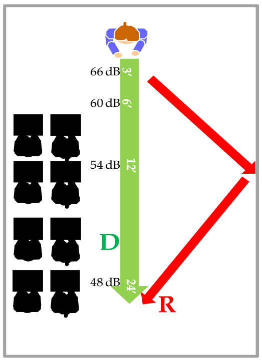


Figure 1. Classroom oriented in the long dimension, D/R at back of room = 48/55 = -7 dBA.

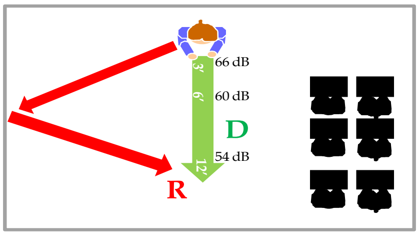


Figure 2. Same classroom, oriented in the short dimension, D/R at back of room = 54/55 = -1 dBA.

The classroom configured according to Figure 1 was then evaluated with the addition of a reflective ceiling element located above the teacher as shown in Figure 3.

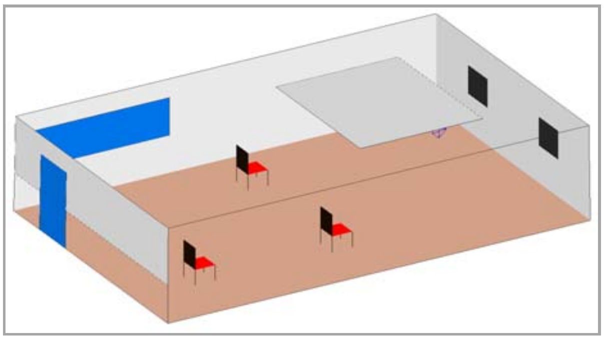


Figure 3. Same classroom as from Figure 1, but with 2.4 m x 3.7 m, dry wall (DW) reflector panel installed in ceiling

Table 3. Speech Intelligibility metrics for 3 classrooms.

	Rm A	Rm B	Rm C	Noise (dBA)
STI	0.59	0.62	0.61	45
	0.62	-	-	40
	0.65	0.68	0.66	35
C50 (1kHz, 2kHz)	2.9, 3.7	3.9, 5.0	3.8, 4.4	dB
RT (1kHz, 2kHz)	0.6, 0.6	0.4, 0.4	0.5, 0.5	sec

In Table 3 are presented the various speech intelligibility metrics for 3 different classrooms of the same size and shape, but with different surface treatments.

Rm A is a classroom finished in the usual way: ceiling is a standard NRC 0.55 acoustical tile, walls are DW, floor is vinyl tile. This room does not meet the RT requirements of LEED 2009 - unoccupied RT of 0.6 sec at 500 Hz, 1 kHz, 2 kHz, or Green Star which is an RT of 0.5 sec, respectively.

Rm B is a classroom finished as follows: ceiling is an NRC 0.70 acoustical tile, walls are DW with acoustical treatment on parts of 2 adjacent walls, floor is commercial carpet. This room meets the RT requirements for both LEED 2009 and Green Star.

Rm C is a classroom finished as was Rm 2, but with a DW reflector above the teacher as shown in Figure 3.

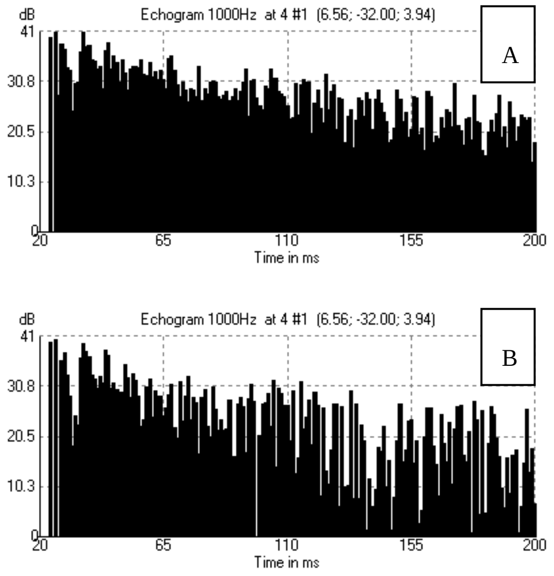
The calculated STI is slightly lower for Rm A then either of the other two rooms and all behave the same with higher background noise levels. The STI does not change significantly with the use of the ceiling reflector panel compared to the fully absorptive ceiling for this case.

The calculated C_{50} is noticeably lower for Rm A then for either of the other two rooms. The C_{50} is actually lower with the ceiling reflector panel compared to the fully absorptive ceiling. This was not expected, but can be explained because the RT is actually higher in Rm C than in Rm B. This happened because when the reflector panel replaced the absorptive ceiling tile, no additional absorptive material was added, so the RT went up accordingly, and C_{50} is related to RT.

As it turns out, neither the STI nor the C_{50} show any significant sensitivity to the addition of the ceiling reflector panel above the teacher location as experienced by the students at the back of the room. This however is only one design case.

ACOUSTIC SIMULATIONS

The EASE models also calculated the room impulse response for a source at the teacher location, and a receiver at the student location in the back of the room. These are presented in Figure 4a, b, c for the three rooms Rm A, Rm B, and Rm C, as defined above.



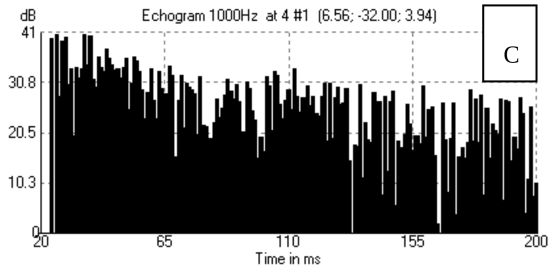


Figure 4. Room Impulse Response for Rm A, Rm B, Rm C.

Looking at Figures 4B and 4C, the difference between these two rooms is the addition of the reflective ceiling panel in 4C, and this seems to indicate a higher density of reflections in the first 50 msecs for 4C. This would mean that the reflector actually does work by sending more early reflections to the rear seating areas, even thought this is not indicated by the STI or the C_{50} metrics.

Next we wanted to do some simple laboratory testing to further investigate this effect.

LABORATORY MOCK-UP TESTS

A classroom mock-up (7.3 m x 11.6 m x 3 m) was constructed and furnished with an acoustical suspended ceiling, partial acoustical wall treatment (on 2 adjacent walls), and a commercial grade carpet. This mock-up met both the LEED 2009 and Green Star requirements for classroom mid-frequency RT at approximately 0.4 seconds. This mock-up is pictured in Figure 5.

Figure 5. Actual classroom to match size and shape of model Shown in Figure 1.

The mock-up classroom was set up with a loudspeaker at a typical teacher location at the front of the room, and the sound level was monitored from the front student seat, to the back student seat location. This measurement layout is shown in Figure 6.

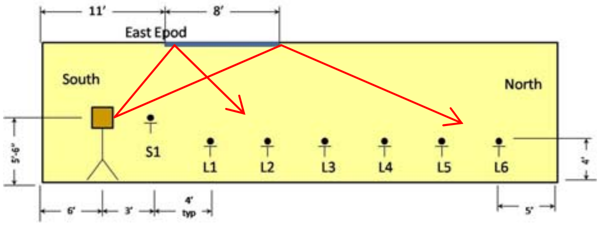


Figure 6. Sound source and microphone locations from front of room to back of room. Location of ceiling reflector (when used) is constructed of 2.4 m x 3.7 m drywall (DW) panels.

The reflective ceiling elements were fabricated from 600 mm x 600 mm DW panels and installed in place of the acoustical ceiling tile to form a 2.4 m x 3.7 m reflector section. This section was located relative to the teacher so as to specifically cover from the middle to back of the classroom. In

Figure 7 is presented the measured sound level in dBA for both cases with and without the reflective element in the ceiling plane.

Since the reflector was designed to provide added early reflections to the back ½ of the room, we expected to see a rise in sound level starting midway back, and that is exactly what we see in Figure 7.

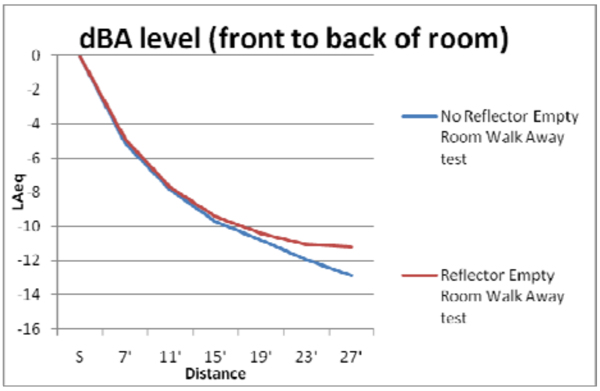


Figure 7. Overall sound level (dBA) difference from front to back of the classroom with and without the Reflective Ceiling Panel installed.

Since speech is the primary concern, the sound level difference with and without the ceiling reflector element is shown for the 1 kHz and 2 kHz frequency bands respectively in Figures 8 and 9.

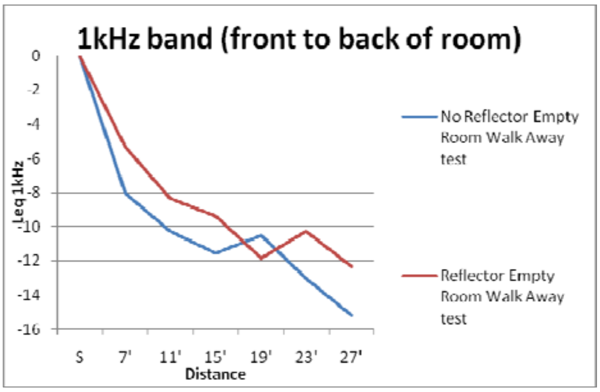


Figure 8. 1/3 OB @ 1 kHz difference from front to back of the classroom with and without the Reflective Ceiling Panel installed.

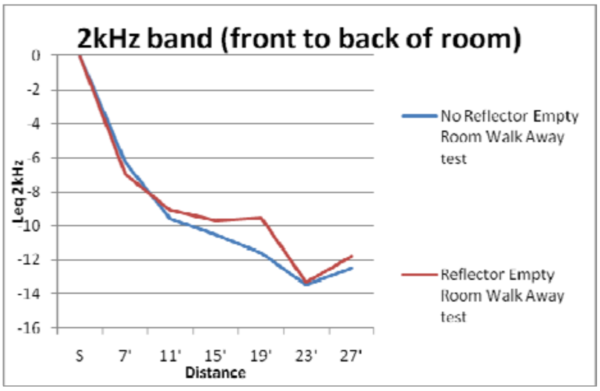


Figure 9. 1/3 OB @ 2 kHz difference from front to back of the classroom with and without the Reflective Ceiling Panel installed.

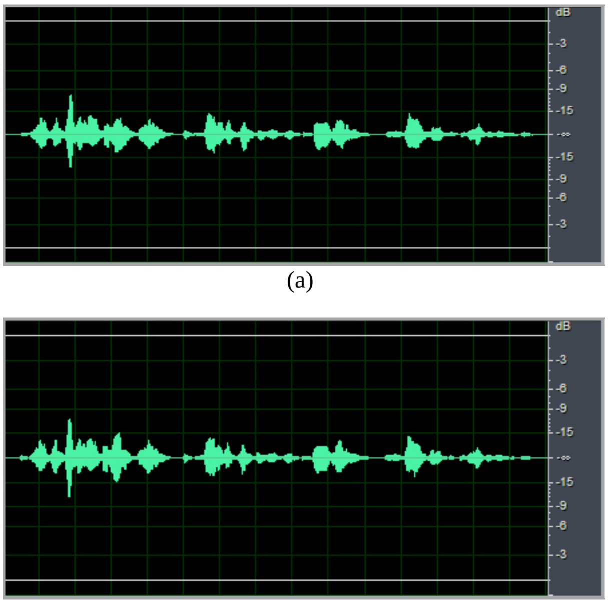
As can be seen from these data, the ceiling reflector is effective in sending more early reflections to the back of the room as designed. These reflections show a 1 to 2 dB increase in overall sound level for the back of the room. Whether this is significant and can be perceived by the students is the next question that we will consider.

LABORATORY LISTENER TESTS

A CD was recorded with several tracks of dry sound using a number of both male and female talkers having conversations in an anechoic chamber. These tracks of running discourse were played back in the mock-up classroom and recorded at a student location in the rear of the room. Recordings were made both with a fully sound absorptive ceiling and with an added reflective element above the speaker locations shown in Figure 6. These room recordings were then presented to a panel of listeners as a double blind A-B-X [10] comparison test (using headphones, see Figure 10) to look for a discernable difference between the two room configurations.

A range of adult participants were unable to perceive a significant difference between audio samples (Figure 11) for the absorptive ceiling (Rm B) versus the reflective panel (Rm C).

Figure 10. Listener making A-B-X comparison of running discourse recordings.



(a)

(b)

Figure 11. Audio waveform of a listening test sample (a) is from fully sound absorptive ceiling case and (b) is from reflective element case

This testing was conducted using 4 different audio comparisons (2 different female voices & 2 different male voices) which were presented to 12 different participants. For each comparison the participant was able to listen the recorded audio clip with the fully absorptive ceiling (“A”), then with the added reflective element (“B”), and finally the unknown clip (“X”) which could be either “A” or “B”. This process was repeated 10 times for each of the 4 audio comparisons. None of the participants were able to correctly identify the different audio clips (average = 45%).

CONCLUSIONS

The addition of a reflective ceiling element to an otherwise sound absorbing suspended ceiling can effectively provide early reflected sound to students at the back of a classroom. This effect was shown from room impulse responses calculated in a room modelled using an architectural/acoustic simulation software (EASE), and can also be seen and measured in a real room (mock-up space).

For the particular cases researched in this study, the actual increase in sound level was not very great, being only 1 to 2 dB in the speech frequency range. But this effect can be measured and heard by a qualified listener. The question is whether this will be of value to a ‘typical’ student in grades K-12.

Standard speech intelligibility metrics such as STI and C_{50} were not very useful in comparing the before/after effects of the reflective element in the ceiling plane for these particular cases. The C_{50} was affected by the change in RT since the substitution of the reflector was not offset by the addition of make-up absorption, which means that more energy was also added after the 50 msec cut-off due to reverberation.

Obviously more research should be performed to better understand and verify the effectiveness of ceiling reflectors in classrooms. This should include studies of both the room architectural design including both size and location of reflectors, and an assessment of methods for verification of performance improvement using existing or new metrics if need be.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the valuable test data provided by our colleague Kenneth Good, Jr., specifically as relates to the field acoustic measurements taken in the classroom mock-up.

REFERENCES

1 ANSI S3.5 (1969), “Methods for the Calculation of the Articulation Index”, American National Standards Institute. http://webstore.ansi.org/

2 ANSI S3.5 (1979), “Methods for the Calculation of the Speech Intelligibility Index”, American National Standards Institute. http://webstore.ansi.org/

3 Speech Transmision Index, STI, http://www.embeddedacoustics.com/index.php/speech-transmission-index

4 USGBC, “LEED 2009 for Schools – New Construction and Major Renovations”, http://www.usgbc.org/DisplayPage.aspx?CMSPageID=1971

5 Green Building Council, Australia, Green Star - Education, http://www.gbca.org.au/green-star/rating-tools/green-star-education-v1/1762.htm

6 John Bradley, et al, “A Just Noticeable Difference in C_{50} for Speech”, Applied Acoustics, Vol 58, Issue 2, pgs 99-108, http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V1S-3W6F6R0-1&_user=10&_coverDate=10%2F31%2F1999&_rdoc=1&_fmt=high&_orig=search&_sort=d&_docanchor=&view=c&_acct=C000050221&_version=1&_urlVersion=0&_userid=10&md5=f53375154a6fcd549ce09c134081e680

7 ADA Acoustic Design Ahnert, EASE room acoustical simulation software, http://www.ada-acousticdesign.de/set_en/setsoft1.html

8 ANSI/ASA S12.60-2010/Part 1, “Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools, Part 1: Permanent schools”, American National Standards Institute. http://asastore.aip.org/shop.do?pID=594

9 AS/NZS 2107:2000, Acoustics - Recommended design sound levels and reverberation times for building interiors. http://infostore.saiglobal.com/store/Details.aspx?ProductID=363589

10 ABX, Blind Listening Tests for Audio Files, http://www.hydrogenaudio.org/forums/index.php?showtopic=16295 http://www.kikeg.arrakis.es/winabx/