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Global case studies of acoustics in classrooms

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Abstract

Classroom acoustic standards and guidelines are being discussed around the world now that the design community is becoming well aware of the need for good acoustic performance in schools, and especially in grades K-12. Teachers teach and the students learn primarily by hearing and seeing the teachers work. School designers are aware that 3 aspects of the building design are important in providing an effective acoustic environment, these being 1) a high level of speech clarity, 2) adequate signal-to-noise ratio above the ambient mechanical/electrical/plumbing noise, and 3) sufficient blocking of activity noise from adjacent spaces. Speech clarity is addressed by the architectural design, noise by the ambient noise level from building systems, and activity noise intrusion by the barriers provided in the wall/ceiling systems. Schools in both North and South America and in China and India have been evaluated to date. Evidence based design studies have been conducted, and those results including measurement data and audio/video samples are being presented. In each case, an architectural intervention was conducted between the before/after evaluations that include both objective measures of performance and subjective perceptions by the students and staff. Good design is both noticed and valued by both the students and the teaching staff.

Keywords: classroom, speech clarity, intelligibility, ambient noise

Global case studies of acoustics in classrooms

1 Introduction

In recognition of the need for good acoustics in the school environment, most countries currently have some level of acoustic criteria for the design and construction of K-12 schools. These criteria may be found in Government Regulations, in the National Building Codes and Standards, in Green Rating System such as the USGBC, or in individual school system design specifications. Unfortunately in most cases the criteria are not mandatory which means that they are treated loosely as recommendations, and that of course usually results in non-compliance with the intent of the criteria. Field studies were conducted in several countries to determine if in fact these acoustic criteria were being met, and Evidence Based Design (EBD) case studies were conducted to determine if it were possible with a simple architectural intervention, such as with the installation of an average suspended acoustical ceiling, to bring these classrooms into compliance. Additionally, we wanted to know about the student's and teacher's perceptions of the acoustic environment in their classrooms, such as, would they notice and value the difference in interior environmental quality (IEQ) between a standard classroom and one that has a good acoustic environment?

1.1 Acoustic design criteria

Review of the current range of international criteria generally shows that a maximum reverberation time of 1.2 to 0.4 seconds is specified in large to small sized classrooms, and a maximum ambient noise level of 45 to 35 dBA for normal classrooms. Most national criteria will have at least a criteria for the maximum ambient noise in dBA, and most (but not all) will also have a maximum criteria for reverberation time in seconds.

It is important to note that the clarity of speech transmitted from the talker to the listener is only dependent on the architecture, and so, it is incumbent on the architects and designers to ensure that the reverberation time does not exceed the criterion value. Three factors relating to architecture will determine the speech clarity and those are 1) size of room, 2) shape of room, and 3) surface treatment in the room. Once built, the only factor that can be easily modified to improve the speech clarity is the choice of surface treatments (thus the application of a suspended acoustic ceiling in the EBD case studies).

Once the architecture has been designed to achieve adequate speech clarity, it is important to ensure that the speech will be heard above the ambient noise from both the mechanical systems within the classroom, and from the combined activity noise and environmental noise intruding from outside the classroom, this is the Signal-to-Noise ratio (S/N). Taken together, this means that we need to design for a reverberation time significantly less than the maximum criteria, in combination with an ambient noise less than the maximum dBA to ensure adequate speech intelligibility. Especially in the primary and middle school classrooms, a higher S/N is necessary due to young students learning the language, 2nd language students, children with temporary hearing loss due to illness, etc., which means a need for even lower ambient noise.

1.2 Objective and subjective evaluations

Objective measurements of reverberation time and ambient noise will tell us if the design criteria have been met or not, and this is a simple pass-fail test. But we are just as interested in the student/teacher perceptions of the acoustic comfort in both the standard and enhanced classrooms because this tells us the "value" of good vs. poor design. These studies conducted in 4 countries all demonstrated that proper architectural design will affect the acoustic environment, and that acoustic outcomes are both noticeable and important to the occupants' learning outcomes.

2 Evidence based design

2.1 School in South America

The test school was the Sagrados Corazones de Alameda, in Santiago, Chile, which is a K-12 grade school with 52 classrooms. The teachers had been complaining about the vocal effort and resulting strain needed to teach in their classrooms, and were considering the purchase of microphone/speaker systems to alleviate this problem. A site visit by my colleague, Micaelina Campos, found that the rooms were finished in all hard surfaces with a high ceiling, and that transportation noise was a significant noise intrusion issue. It was decided to choose 2 representative classrooms to develop an EBD case study for before/after evaluation of an acoustic design intervention which included both added room sound absorption and improved window acoustic treatment. Adding a sound system did not seem to be a good approach.

2.1.1 Classroom objective measures, and teacher subjective perception

A total of 4 classrooms of similar size and design were selected for study. Two of these classrooms were designated as "control" and two others were designated as "before/after" classroom which will have the acoustic modifications installed. The acoustic intervention consisted of the addition of an NRC 0.70 ceiling tile in suspended grid, a band of NRC 0.50 tile at top of walls, both front and rear walls at 1 row height, and an added pane of glass with air gap on each window. The standard and enhanced classroom is shown in Figure 1 along with the objective measurements of the reverberation time and ambient noise.

Reverberation time was reduced from 2.6 sec to 0.6 sec by the addition of the acoustic ceiling and band of tile at top of front and back walls, plus due to a loss in total room volume because of the suspended ceiling. A reverberation time of 0.6 seconds is known to provide significantly higher speech clarity whereas 2.6 second is more appropriate for symphony music. The ambient noise in the classroom was reduced from 66 dBA to 38dBA which is well within most noise criterion. Approximately 6 dB of this reduction can be attributed to the added absorption from the ceiling and wall band absorption, and the remaining 22 dB can be attributed to the added pane of window glass and sealing of leakage in the window.

The teacher's subjective perception of the acoustic comfort was improved by 80% over the standard classroom due to fewer headaches and less vocal strain. This was also borne out by the schools records which showed a reduction in teacher absences due to those same issues from 57% in 1997, down to only 35% in 2000.

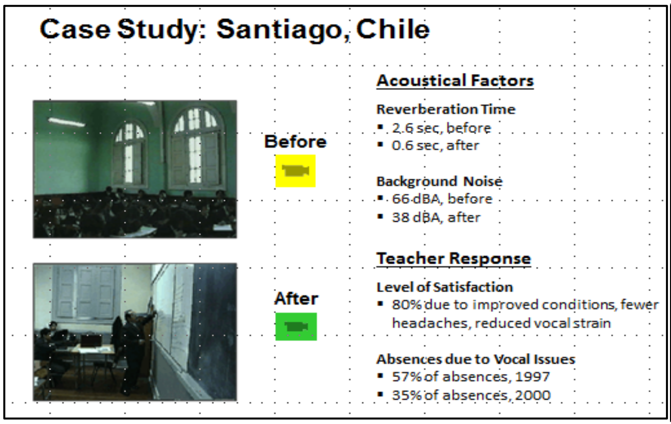


Figure 1. Standard (before) and enhanced (after)

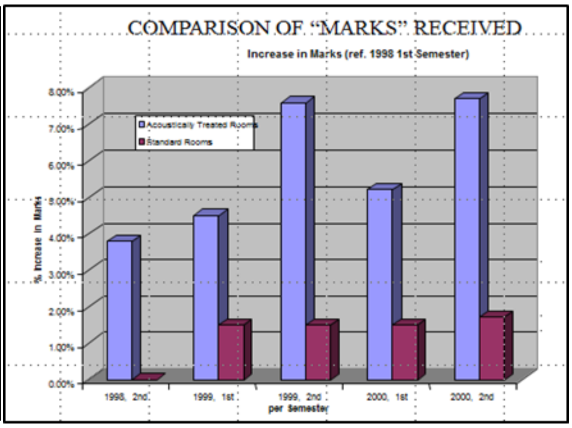


Figure 2. Student's grade improvements

2.1.2 Student's grade performance

The student's grades were tracked from 1998 to 2000 in both the standard and enhanced classrooms and the improvement in grades are shown for both cases in Figure 2. On average, the students in the enhanced classrooms scored approximately 5.8% higher than before the acoustic enhancement, while the students in the standard classrooms scored approximately 1.2% higher without any changes to the rooms.

2.2 School in North America

The test school was the Lamberton School in Philadelphia, USA, which was built in 1949 and is a K-12 grade school in a quiet residential area, Figure 3. A site visit with my colleagues Ken Good Jr., and Sean Browne, found that this classroom was finished in all hard surfaces with the exception of the ceiling which had a thin layer of spray applied fiberglass insulation on plaster. It was decided to use this classroom as an EBD case study for before/after evaluation with an acoustic design intervention consisting of adding sound absorption by installing a suspended ceiling. Due to location, transportation noise was not an issue, and the heating system was a hot water based unit with low noise emissions.

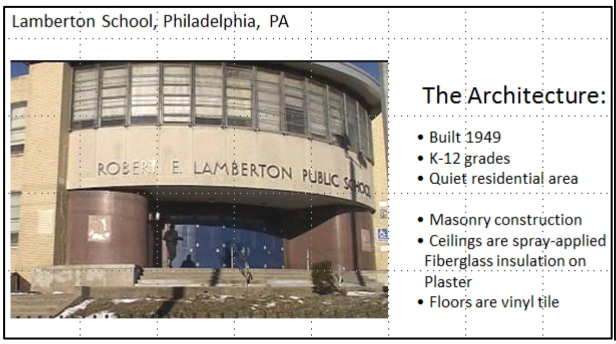


Figure 3. Lamberton School

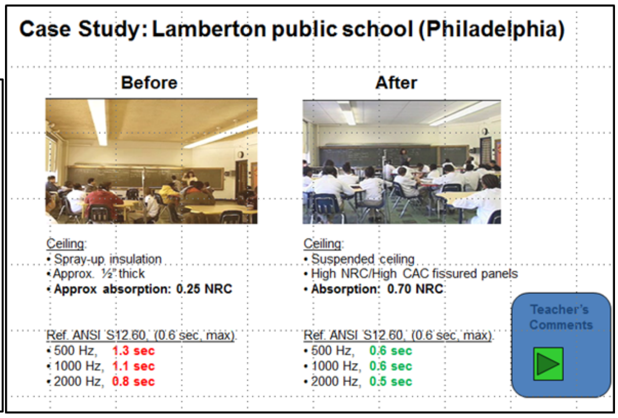


Figure 4. Standard (before) and enhanced (after)

2.2.1 Classroom objective measures and teacher perception

The acoustic intervention consisted of the addition of an NRC 0.70 ceiling tile in suspended grid with a drop to just above the lighting fixtures such that they need not be moved. The standard and enhanced classroom is shown in Figure 4 along with the objective measurements of the reverberation time.

Reverberation time was reduced from an average of 1.1 sec, which did not meet the criterion according to the American National Standard S12.60 Part 1[1], for each of the noted frequency bands, down to 0.6 sec such that it was now in compliance for all bands.

The teacher interview noted that after the intervention:

- She did not hear as much extraneous activity noise from papers, pens, chairs
- She could hear the students better when they answered back to her
- She did not have to do as much repeating of a question to students
- She said “I was able to do more teaching in the same amount of time”

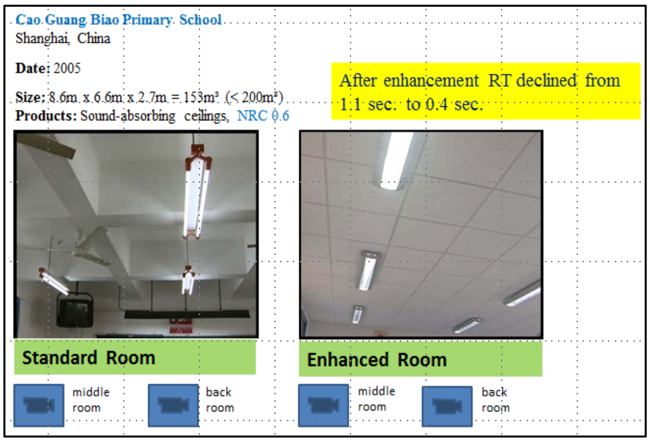
2.3 Schools in China

With the assistance of my colleagues Lily Huan, (Jerry) Li Jia, and our Shanghai team, we surveyed many schools in China over the course of about 10 years mostly in support of the Green Campus work group based at Tongji University in Shanghai. Results from a few of these field trials are being presented. Typical Chinese classrooms are of masonry construction with windows on both exterior and corridor walls, and most do not have heating/cooling systems. Ambient noise levels generally come from adjacent activity noise (classrooms, corridors, courtyard, etc.) and ceiling mounted air fans.

2.3.1 Cao Guang Biao Primary School, Shanghai, China

A typical classroom in grade 4 was chosen for architectural enhancement along with an adjacent classroom of similar size and design as a control. The architectural changes included installing a suspended ceiling with NRC 0.60 tiles, upgrading the lighting fixtures, upgrading the windows, and installing a vinyl floor tile. The classroom which was upgraded is shown in Figure 5 along with the measured reverberation time both before (standard) and after enhancement (enhanced). The measured reverberation time dropped from 1.1 sec to 0.4 sec with the addition of the suspended acoustical ceiling which both added sound absorption to the hard space, and slightly reduced the volume of the room.

Student’s grades where monitored for one year after the architectural intervention and compared to the previous year’s grades for each of the classrooms looking for relative improvements due to the architectural intervention. The improvement in grades is shown in Figure 6 for both students in the standard classroom and for those in the enhanced classroom. The change in overall grades for the standard classroom with the high (1.1 sec) reverberation time is approximately +2% over the duration, whereas the change is closer to +14% in the enhanced classroom with the reverberation time meeting the Chinese design standard of 0.8 sec max. It should also be noted that there is a substantial difference in the enhanced classroom between the scores for mathematics (+3.5%) and English language (+25%), which is not seen in the standard classroom (+1%, +2% respectively).



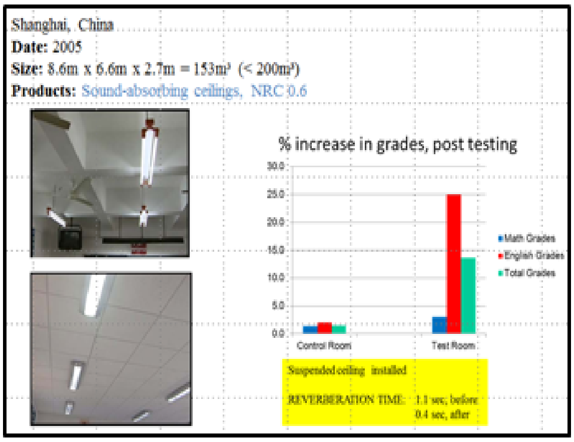


Figure 5. Standard (before) and enhanced (after) **Figure 6. Student's grade improvements**

Since the English language is either a second or third language for the Chinese early middle grade students, it makes sense that high quality speech clarity as indicated by a reverberation time of 0.4 seconds compared to the standard classroom with reverberation time of 1.1 sec should make a big difference. And so it does. However, this does not carry over to the mathematics grades in the same way. We should note that mathematics is as much a visual learning process as an aural learning process and that the teacher writes the mathematic on the board and speaks in the student's native language. Even so, the students in the enhanced classroom showed an improvement in the mathematics scores of +3.5 % compared to +1% in the standard classroom.

Listening to the A/V recording of the occupied classroom demonstrates that much of the activity noise within the classroom from papers, pens, chairs is significantly reduced in the enhanced classroom due to the lower reverberation within the space, which also helps to improved S/N in addition to the improved speech clarity.

2.3.2 Ten school Green Campus WG study, China

A large scale study was developed to survey the range of classroom styles and acoustic treatment options for K-12 classrooms across China. A total of 10 schools were chosen in 8 cities as indicated in Tables 1 and 2. Two or more classrooms were chosen in each school for evaluation first as the standard design, and then as an enhanced design with the installation of an acoustical ceiling. A suspended acoustical ceiling is the least expensive approach to adding sound absorptive treatment into a classroom space. Acoustic ceiling tiles with sound absorption ratings of NRC 0.50 to 0.70 were installed to investigate the range of available solutions.
The Chinese building design code GB50118-2010[2] for sound insulation in buildings lists the maximum acceptable reverberation time (RT) in seconds for schools as 0.8 to 1.0 seconds

depending on classroom volume. A two-step process was followed in the 10 school study: first, verify the current performance in all standard (pre) classrooms, and second, if the requirement is not met, then determine what ceiling tile options could be installed in the enhanced (post) classroom to meet this requirement. Reverberation time results are shown in Table 1.

No.	Schools	Product NRC	Volume (m³)	Unoccupied RT(sec), 500Hz -1000Hz			
				GB 50118 Maximum	Standard	Enhanced	Reduced by
1	Shanghai P.	0.6	174	0.8	0.84	0.45	46%
2	Yuyao P.	0.6	195	0.8	1.39	0.56	60%
3	Fuzhou P.	0.6	192	0.8	1.55	0.54	65%
4	Beijing M.	0.7	191	0.8	1.57	0.51	68%
5	Chengdu P.	0.6	262	1	1.55	0.58	64%
6	Liaoyang P.	0.6	211	1	1.1	0.5	55%
7	Shanghai M.	0.6	238	1	2.07	0.67	68%
8	Zhuhai M.	0.5	345	1	1.3	0.68	48%
9	Zhuhai H.	0.6	292	1	1.18	0.61	48%
10	Guangzhou M.	0.7	268	1	1.16	0.45	58%

Table 1. RT comparison for standard & enhanced classrooms, and GB 50118

The measured reverberation times are presented in the “pink” column of Table 1 and listed as the “Standard” classroom. The requirements of Chinese standard GB 50118 [2] are presented in the adjacent “yellow” column and listed as “maximum”. None of the classrooms of either volume as currently designed and built meet the maximum allowable reverberation time per the standard. However, when a suspended acoustical ceiling of NRC .50 to .70 rating was installed, all of the enhanced classrooms met the GB standard for RT with a range of 0.45 to 0.68 seconds as presented in the “green” column. A ceiling with NRC 0.60 will likely be satisfactory for most applications.

The Chinese building design code intends that the background noise be evaluated in an unoccupied classroom during the school day, with all doors and windows closed, and all appliances in an ‘off’ condition. Unfortunately this was not possible in most schools due to the continuous occupancy, and so only school #10 was so measured. Table 2 presents a summary of the measured background noise levels in the 10 schools relative to the requirements of GB 50118 (yellow column 3, max. dBA = 45). All of the standard classrooms, with the exception of school #10, had background noise levels below 45 dBA when all doors and windows are closed and no mechanical equipment is in operation within the classroom. We know that there is significant adjacent activity noise from students during school hours as evidenced by an increase in background noise of 8 to 20 dB in school #10 during school hours compared to all the other schools just after school hours. The presence of adjacent activity noise during school hours as a major noise source was also identified in the student perception surveys. Note that all background noise levels exceeding 45 dBA are shown in ‘red’. Of the 5 classroom measurements conducted with the fans ‘on’, 4 out of those 5 measurements exceeded 45 dBA noise level in the standard classroom, whereas with the installation of an acoustical ceiling, only 2 out of 5 of those classrooms exceeded 45 dBA. When the windows/doors are open, all of the measured classrooms exceeded 45 dBA, and some exposures were as high as 50-60 dBA.

No.	Schools	Indoor background noise, dBA[1]						
		GB 50118 Maximum	Doors/Windows closed Fans off[2]		Doors/Windows closed Fans on[2]		Doors/Windows open Fans off[2]	
			Standard	Enhanced	Standard	Enhanced	Standard	Enhanced
1	Shanghai P.	45	30.9	27.7	45.6	40.8	49.7	47.8
2	Yuyao P.	45	33.4	32.4	46.4	44.6	61.8	58.7
3	Fuzhou P.	45	40.0	35.5	53.3	46.4	57.1	53.0
4	Beijing M.	45	32.0	27.7	40.1	38.8	-	-
5	Chengdu P.	45	33.0	32.2	45.8	45.9[3]	-	-
6	Liaoyang P.	45	21.3	19.1	-	-	-	-
7	Shanghai M.	45	42.0	38.9	-	-	50.5	47.1
8	Zhuhai M.	45	29.5	27.2	-	-	-	-
9	Zhuhai H.	45	33.0	30.4	-	-	-	-
10[1]	Guangzhou M.	45	50.4	47.0	-	50.5	-	60.9

Note [1] : Noise measurements (with exception of No. 10 made during school hours) were taken immediately after school hours.
Note [2] : Noise measurements in Standard & Enhanced rooms taken consecutively & therefore dependent on exterior noise profile.
Note [3] : The exterior noise for Enhanced classroom was 3.3dBA higher than for the controlled classroom measurements.

Table 2. Ambient noise comparison for standard & enhanced classrooms, and GB 50118

Typical Chinese primary and middle school students have never experienced an acoustically designed classroom, so student perception surveys were conducted first in the standard classroom, and again after installation of a suspended acoustical ceiling in the enhanced classroom. In this way we were able to register both their concerns with the standard classroom, and the shift in perception after experiencing the acoustic enhancement. The first survey was conducted by paper survey forms the week before the architectural intervention, which was installed over the weekend, and the second survey was conducted on the following Thursday or Friday.

Since the post survey (enhanced) provides comparative information relative to the pre survey (standard) only those results are shown here. The same students (N= 259) who previously occupied the standard classrooms were again interviewed in the same classrooms but after those had been modified by the installation of a suspended acoustical ceiling. These students were allowed to experience the enhanced classroom for about a week so that they would have a feel for the acoustic environment in the newly renovated classrooms, but still had a memory of what it had been like in the previous standard classroom environment. The first question asked of them was which classroom did they prefer, and the answer to that question is presented in Figure 7. Typical questions addressed the issues of student preference relative to concentration, intelligibility, and background noise levels in the enhanced classrooms after installation of the acoustical ceilings compared to that of the standard classrooms to which they were accustomed to learning in. These results are presented in Figure 8, and a significant percentage of the students, 92%, believe that it is easier/as easy to concentrate in the enhanced classrooms. Likewise, a significant percentage of the students, 92%, believe that the teacher can be heard more clearly/as clearly in the enhanced classrooms. And, about 86 % of the students believe that the background noise levels in the enhanced classrooms are lower/as low compared to the standard classrooms.

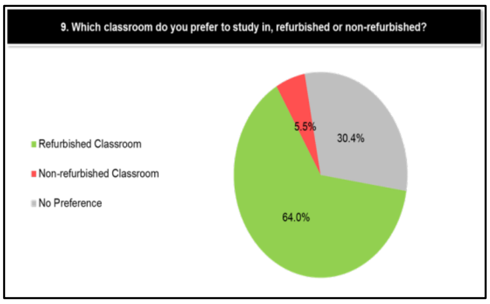


Figure 7. Classroom preference

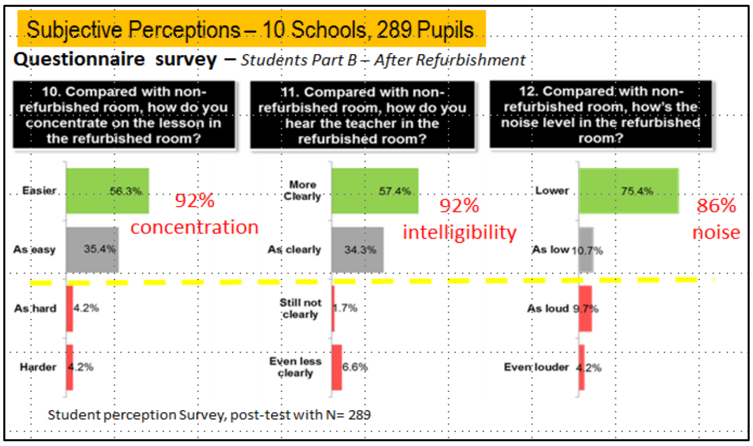


Figure 8. Perception of the improvement in acoustic comfort

In summary: although the students did not initially realize that the acoustic environment in the standard classrooms was less than optimal, once having experience a good acoustic environment, most students would prefer to study in an enhanced classroom that meets the requirements of GB 50118-2010 for reverberation time.

2.4 School in India

The test school was the Billabong High School in Santacruz, Mumbai, India. The standard classroom was finished in all hard surfaces, and the acoustic design intervention consisted of adding sound absorption by installing a suspended ceiling with NRC 0.60 tiles. The standard and enhanced classroom is shown in Figure 9 along with the reduction in reverberation time from 1.1 sec (standard) to 0.6 sec (enhanced) where the India criteria is 0.75 sec max.

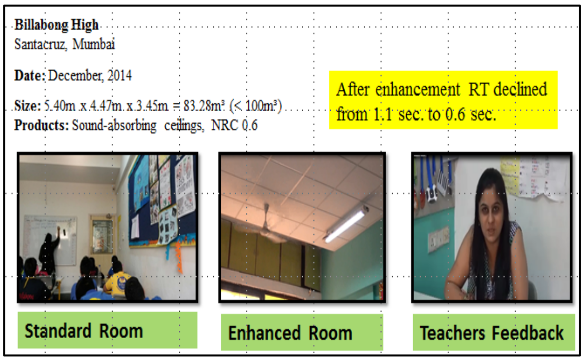


Figure 9. Classroom before and after comfort

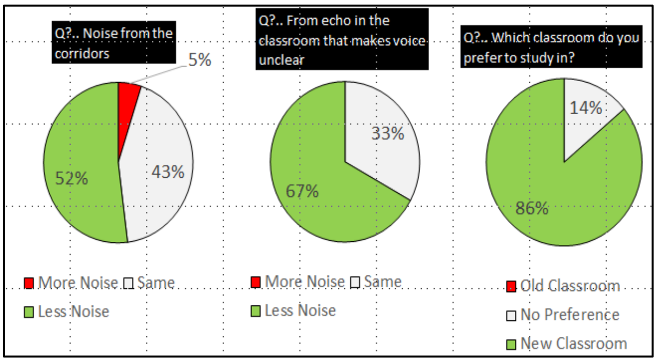


Figure 10. Perception of the improvement in acoustic

The students also noticed the reduction in both noise and reverberation, and solidly preferred the enhanced classroom as shown in Figure 10.

3 Conclusions

The learning provided by the combined objective and subjective surveys conducted in many schools spanning 3 continents have been very instructive in what could and should be done in the future to provide a better learning environment in the K-12 schools.

- Although many countries have pertinent acoustic performance criteria for classrooms, these are mostly not mandatory, and so, the reverberation time (RT) criteria were not met in any of the tested standard classrooms. These must be made mandatory.
- The simple installation of a suspended acoustical ceiling with NRC 0.60 rated tile will meet the RT design criteria for speech clarity in most normal classrooms with RT requirement of 0.75 to 1.0 sec, and a tile with NRC 0.70 will meet the RT of 0.6 to 0.7 sec.
- The background noise (dBA) in unoccupied classrooms during school hours seldom met the criteria of 45 dBA max., in large part due to window and door leakage of adjacent student activity noise.
- The simple installation of a suspended acoustical ceiling with NRC 0.60 to 0.70 rated tile will provide approximately 5to 6 dB in noise reduction within the classroom, and together with improved classroom door and window seals will help meet the 45 dBA max.

- Students are not initially aware of the poor speech clarity and reduced concentration in standard classrooms since they have never experienced a well-designed (acoustic) classroom.
- Both the students and teachers had a strong preference for the acoustically enhanced classrooms compared to the standard classrooms once they had experience the difference that good acoustic design can deliver in terms of improved speech clarity, comprehension, lower vocal effort, less fatigue, less repetition, etc.

Acknowledgments

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References

[1] ANSI/ASA S12.60-2010/Part 1 American National Standard – Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools, Part 1: Permanent Schools (American National Standards Institute, New York).

[2] GB 50118-2010, Code for design of sound insulation of civil buildings, Beijing, China.