10 Years of Classroom Acoustical Design

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• **The Beginning** -- It all started with a workshop organized by Anabel Cohen (EDRA 1983) “Perspectives on Acoustics in environmental Design”, where four of us (Anabel Cohen, Angelo Campanella, Lyn Marshall & Cristin Nuttall-Grant) conducted a panel on that subject, followed by our 1987 paper in the *Journal on Architectural and Planning Research*. This included my diagram of acoustical and noise control design, but more importantly the results of quantitative intelligibility research by John Bradley.
Ten years of classroom acoustical design

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ABSTRACT: Bradley found [JASA 80(3) 837-845] with word score tests that S/N and room reverberation time (RT) affect speech intelligibility. He found that U50 [JASA 80(3) 846-854] was maximum for rooms having RT<0.6 sec and quieter than 35dBA. We applied this to teleconferencing rooms [JASA 111(5) 2411(A)], and classrooms for distance learning [JASA 107(5) 2861(A)]. Design strategies to economically reduce classroom RT and HVAC noise and achieve RT values between 0.5 and 0.7 seconds, and NC values less than 30 were developed: Absorption is provided by acoustical ceiling tiles of NRC>0.6. Carpets help. Chalk and cork boards provide some wall absorption, while in-use posters and book storage add more later. Central air handling systems promote NC-25 HVAC design. Noisy supply (VAV) air boxes are placed in the corridor ceiling. The transmitting manifold is lined. A flexible duct link to diffusers provides more noise attenuation at no added cost. Larger supply air diffusers satisfy NC-25. Common ceiling return air plenums compromise noise isolation between classrooms. High CAC ceiling tiles and return air openings near the room center provide NIC>40 vs recommended NIC50. Sketches and some cost estimates are provided.

[1] Rationale:

Much has been said about the status of education and its facilities in the United States today. It is not a matter of money or is it a matter of technology. Some say that the student products leave something to be desired. It may be more the case that in recent generations, the emphasis has shifted from technical quality to diverse experiences, that a student with more “worldly” knowledge was thought to be of greater value to society than one with only a detailed technical knowledge in a specific area. It is also the common desire of parents, school boards and even students that the school “look good” to the community and to outside observers. This paper attempts to demonstrate that acoustically efficient classrooms for intense learning are now practical and cost effective.

Acoustical Design of Occupied Spaces

1. Identify Occupied Spaces
2. List All Nearby Sound Sources
3. Provide Designs **for All Spaces & Sources

- Auditorium - Speech Sound Treatment, Echo Supression, P.A. System
- Paging - Loudspeaker Placement & Equalization
- Conference Room - Reverberation Control (NRC)
- Open-Plan Office - Ceiling (NRC), Screens (NIC), Masking Sound
- Remote - Wall Noise Insulation (STC)
- Remote - Floor (STC & IIC, INR)
- Nearby - Absorption (NRC), Barrier (STC)
- Equipment - Noise Barrier (STC, NIC)
- Exhaust Silencer
- Transportation - Barrier, Re-Orient Site
- Service (HVAC) - Cooling Tower Barrier, Recirculation
- Fixed - Functional (Product)
- Production Area - Acoustic Treatment

Acronyms:
- NRC: Noise Reduction Coefficient
- STC: Sound Transmission Class
- NIC: Noise Isolation Class
- IIC: Impact Insulation Class
- INR: Impact Noise Rating
- HVAC: Heating/Ventilating/Air-Conditioning Equipment
Figure 3. Best-fit curves from multiple regression analysis of measured values of speech intelligibility vs. signal-to-noise ratio for reverberation times of 0.5 (top), 1.0 (middle) and 1.5 s (bottom). Reprinted from Bradley (1986a, p. 851) with permission of the American Institute of Physics, Journal of the Acoustical Society of America.
Figure 4. Equal speech intelligibility contours in a 300 m$^3$ room based on calculated U-50 (useful/detrimental sound ratio) values. Reprinted from Bradley (1986a, p. 853) with permission of the American Institute of Physics. Journal of the Acoustical Society of America.
For “No Child Left Behind” We must improve new classrooms. Much has also been said about the excess costs that accrue from “special” acoustical treatment. It is true that elegant materials are available, but they are unnecessary extremes. Proper acoustical treatments are not special, but rather generic, and can be chosen on the basis of sound acoustical reasoning. The cost increase is minimal, on the order of about one percent of the school construction budget. Put another way, the school is built by the community it serves to teach that community’s youth. The classroom is the location where up to perhaps 90% of intense learning occurs. It logically follows that perhaps 90% of the construction budget should be devoted to classrooms (and their support). It means in the least that a major part of the architect’s efforts, and the construction budget, should be aimed at fulfilling that requirement.

By “intense learning”, it is meant that the critical and often difficult portions of the teaching and learning process require an intimate coupling of the students’ and teacher’s minds must occur before learning can occur. That teaching occurs is no guarantee that learning also occurs. Yet learning is (or should be) the goal of our school buildings (else why need they be built?). This mind coupling, in young naïve persons requires use of all their senses. Proper light, ventilation, air quality and temperature have been traditionally provided without question for decades. It is now time that proper acoustical conditions be also provided. The ground work for rooms with optimum speech intelligibility has long been laid. It remains for the architectural design process to have firm footing in achieving the same speech intelligibility for academic learning spaces.

It is chosen here to define classrooms as “learning spaces” and not teaching spaces. One can teach, but learning may not occur for a variety of reasons. Rather, our objective must be that the design creates optimal learning spaces! In architectural design words describing the form and function of room elements need be numerous and tedious to achieve the desired result.

As the practical ideal, I propose that in a classroom, “Everybody shall understand and be able to talk to everybody else”. Some pictures will be used here to depict the many cost-effective ways to design a proper learning space with generic materials whose cost can be minimized.

Good Speech sound is “early” sound, reflected sound that arrives within 20 milliseconds of direct sound.

Good classroom design may include a central reflector; 50% width and length, 25% area, often drywall laid in the grid in place of acoustical tile; and economical boost to classroom performance.

In Summary, Classrooms require a maximum of direct and early sound.

They also need to be quiet.

How did our classrooms become noisy? Previous to about 1950, natural convection and low velocity ventilation was common. Teachers and students alike were informed on “elecution”, the projection of one’s voice into a large room (“Raise your head; speak to the last row”, etc.). For some years after 1950, when air conditioning (cooling) fans were needed, fan motor power was usually under the control of the user. Fan motors could be turned off by any room occupant for critical lectures and dialogues.

HVAC Today: Ventilation systems are automated. The control of them is only at remote sites with an energy + ‘uniformity’ agenda with no attention to room noise except where commercial interests are at stake (theaters, board rooms, auditoria, etc.).
“Leave No Child Behind”

School design:

• Demand for classroom space greater than ever!
• School administrations are hesitant to believe that room acoustics must be optimum for proper learning conditions. Teaching may occur, but teachers will always concur that learning will not always occur until hearing is optimum.
• School Administrators and architectural designers may not have a good understanding of speech sound and its distribution in the classroom.
Room Design for Group Intelligibility

- The spoken word is the necessary medium of exchange in classrooms.
- Ideal is that “Everyone can understand, and can talk to, everybody else”
- Learning requires this!
Good Early Sound

Large Room Treatment includes a lowered & tilted ceiling, and absorption placed to absorb useless reflections.

Less than 20 milliseconds (22 feet) delay = “Early Sound”.

Sound Absorbing Materials

Lower Reflecting Ceiling

10' + 25' - 30' = 5' = 4 ms = “early”

Talker = Audience

The ceiling central reflector is 50% width and length; 25% area providing fully 75% of the ceiling area for sound absorbers. Less than 20 milliseconds (22 feet) delay = “early Sound”.

Central Reflector

Sound Absorber

8/16/2009
Summary; Key Room Acoustics Elements for Speech

- Maximum Early Speech Sound
  - (delay < 20 ms)
- Quiet Surroundings (our next topic).
  - Less than NC-30;
  - NC-25 for Large Rooms
- Teleconferencing works well in such rooms!
  - ("distance learning")
Word Discrimination Requires Quiet:

In small meeting rooms (classrooms), results are best for background noise not more than NC-25 and the reverberation time not more than 1/2 second. As both are diminished, improvement occurs, but not for values any smaller than these.

There is a reluctance of the design and budgeting community to accept these requirements. We must evolve cost-effective ways to achieve NC25 & 1/2s.
How Our Rooms Became “Noisy”

• Before 1950, HVAC Room Background Noise was not a problem in classrooms. Heating was by convection. HVAC then was rare.
  • Cooling was by open windows. Fans were transient.
  • Room surfaces, especially ceilings, were hard. Persons were taught to speak loudly (“Elecution”).
HVAC noise Today

- Expert Noise Control Software is now available to Mechanical Engineers. ASHRAE has promulgated the quiet conference and class room guidelines, as low as NC-25 (30 dBA).
- There is a reluctance for architects and administrators (building owners) to adopt the quiet concept on the basis that “it’s too costly”.
- ANSI 12.60 is now available for widespread use.
Examples of good Acoustical design:

[14] A Good Modest Classroom Design has central air conditioning where the mechanical systems are remote from the classroom, to easily achieve NC-25. Adequate sound absorption is provided by an acoustical tile ceiling. The central part of the ceiling is made sound reflective to increase early sound, especially for the rear seats. Where an open plenum is demanded by architectural and economy considerations, the ceiling tile must be of a high CAC rating, typically CAC 40 or more. The return air openings must not be near a wall common to other classrooms, offices or mechanical activities. Sound absorbers, typically R-19 fiberglass, should be placed over and four feet either side of the common wall.

[15] Where HVAC design requires VAV boxes, they must be placed outside the classroom over the corridor where their radiation (“breakout”) noise is of no consequence. A good and economical addendum is flexible ducting that should be used as the branches from the local manifold to the supply diffusers. (Flexible ducts have significant sound breakout action, the actual attenuation action, that is allowable here since the plenum is absorptive. The high CAC tiles are an adequate sound barrier).

[16] Portable and temporary classroom suffer from the de facto use of local HVAC mechanical units, often the dominant source of excess noise. I propose a switch be re-introduced that allows disabling the circulating fan and mechanical pump at critical times under the full control of the teacher. This should be mandatory for all portable classrooms and for any classroom that contains noisy mechanical systems.

[17] In Summary, Proper design for a room where the spoken word is necessary to learning shall have a preponderance of direct + early sound over reverberant sound, and a noise level of less than NC-30.

[18] Our 1986 design for distance learning is where the requirements for low noise and minimal reverberation was first discovered and these improvements applied.

[19] In 1995, an architect was enthused to design special wall absorption treatment to meet the requirement of minimal reverberation.

[20] On the same project (pictures follow) we provided a design for a plenum silencer for a VAV using oval duct as the plenum body, to accommodate the noisy VAV (placed over the corridor) discharge that was selected by the project mechanical engineer.

[21] This is the finished product; a 50-seat lecture room, declared to have “awesome acoustics” easy on the voice of the lecturer, who was intelligible to all.

[22] The central reflector a was larger than prescribed for aesthetic continuity. Acoustical tile was applied on the bottom of the entire wide perimeter soffit. Acoustical panels were added to all feasible wall surfaces.

[23] The background noise level was NC-23.

[24] The RT60 was 0.7 seconds.
EXAMPLE 1:

- Reflective Ceiling Center
  - “First bounce” Early Sound Reaches Everyone!
- Supply & Return Air from Remote Fans.
- Flex Duct in Branch Feeds.
QUIET HVAC Arrangement

- Airflow Control boxes emit noise. They must be placed in corridors.
- Lined duct or attenuator into classroom. Flexible duct to diffusers.
“Any fan producing more than 35 dBA at any rear seat in the classroom shall be provided with a switch that shall allow the teacher to immediately turn this fan off. This fan switch shall be located within reach of the teacher’s desk.”

(Add to Mechanical Specifications of portable & temporary classrooms)
SUMMARY

Room Design for Group Intelligibility:

• The spoken word is the necessary medium of exchange in all classrooms.
• Ideal is that “Everyone can understand, and can talk to, everybody else”.
• This is achieved by a dominance of Direct + Early sound over Reverberant sound;
1986 Electronic Classroom
(Ball State University t-com center)

This is the “Electronics Classroom” envisioned by MSKTD and the Ball State University Staff in 1986. Its main feature is that it allows integrated teaching of classical subjects, those supported by all A/V functions and the teaching of A/V techniques of the broadest coverage. It is being constructed in ’86–’87.
Wall Absorber design submitted to architects

Acoustical Wall Absorber Configuration Detail
TELECONFERENCE ROOM WALLS (AS NEEDED)
OSU FISHER EXECUTIVE EDUCATION
VAV Box Discharge Sound Attenuator

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SOUND TRAP (ATTENUATOR) FOR T-COM ROOMS IN FISHER BUILDINGS (SEE LIST) 11 JAN 96 AJC
Classroom Photos (Front).

- Fisher 265
- 50 Seats.
- Faculty Acceptance
- Less Stress
- More Exchanges
- “Awesome Acoustics”
- (NC-23, RT=.7 sec)
Classroom Photos (Rear)

• Central Reflector.
• Acoustical Panels.
• VAV in corridors.
• Attenuator between that and classroom.
• Flex feed to Diffusers.
Room 265 Background Noise

Octave Band SPL ---> dB re 20 uPa

Octave Band Center Frequency ---> Hz

- Front. 34 dBA
- Rear. 32 dBA
- NC-25
Room 265 Reverberation Time

Reverberation Time (RT60) -> Seconds

Octave Band Center Frequency --> Hz

- Avg. Front & Rear
- Target
- Predicted @ Design
A 250 seat “Undergraduate auditorium”, to be used also for distance learning (suspended microphones are evident), was the initial cause for me to be hired for this entire project. It has a composite ceiling where acoustical tile is in broad strips fore and aft, with narrower drywall strips added to aesthetically meet the need for early sound.

The walls and rear walls have acoustical panels. The result was an RT60(500) of 0.79 seconds and a background noise level of NC-23 (29 dBA).

More Conventional Classrooms should have the ceiling treatment required, but the walls beg to be simple, so wall panels are usually shunned. However, the in-use décor always includes chalk boards, cork pin-up boards, cabinets, and ultimately posters. This classroom was recently commissioned (2003, Pickerington, OH New High School). It already has some wall objects that will absorb and scatter sound. This was found to have an NC-26 background, and a reverberation time of about 0.6 seconds. The sound decay curve was concave, indicating a shorter 20 dB decay and a loner full-decay time, implying an early decay on an absorbent axis (vertical) and a slower decay on lesser absorbent (horizontal) directions.

Future HVAC Systems should have our best efforts applied to PRODUCE the quietest systems with reasonable costs. Systems with remote mechanical equipment, often “central air” systems should be encouraged, though novel arrangements are often possible. Where VAV boxes are demanded by the architect, all efforts should be made to get them out of the classroom ceiling; and where they are perforce placed there, to have them operate at low noise radiation settings (possible now down to NC-25), and where unit ventilators are mandated, demand that a switch be provided for the teacher to switch it off at her will.

Future Classroom Interiors should have a 25% area central ceiling reflector, and acoustical tile about the rest of the ceiling acoustical panels. Where adjacent activities exist, the common wall should achieve NIC 50, and the plenum should be carefully treated with high CAC tile, ceiling return air openings remote from common walls and R-19 fiberglass laid over an area which is at the common wall and 4 feet either side of it.

With regard to costs of these measures (the last tangible cause of reluctance on the part of administrators): An example is the salary earned (and local taxes paid) by all students that learned in a classroom during its useful life (40 years). 20 students times 40 years = 800 students. If their salary (assume $40,000/year) is improved by 1%, they will eventually benefit the community by 800x40000x1%=$320,000.oo EACH year. The tax benefit to the community is perhaps ½% of this, which will cumulatively accrue to $5,000 in 15 years, which approximates the increased initial cost of construction. But this accrues further, doubling in the next eight years, and accruing faster from them on. Over the 40 year life, this meager 1% increase will have accumulated to over $320,000! Figure your local taxes on that!

Our next steps are: Require one of these mechanical solutions and the ceiling & wall treatments to be considered on each school project.

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ASA @ San Diego 19 November, 2004.
250 Seat Auditorium - Front.

NC-23, 29 dBA
250 Seat Auditorium - Rear.
250 Seat Auditorium - Side.
NC-26, 33 dBA

8/16/2009
Classroom Reverberation Time

Reverberation Time (RT60) – Seconds

Octave Band Center Frequency --> Hz

20 dB decay
Target
Full Decay
The Future of HVAC

- We should make it our business to PRODUCE quiet designs; NC-25.
  - Central air.
  - VAV in corridor.
- Operate VAV boxes at Low “Radiation” Settings (NC-25).
The Future of Class Room Interiors

- The ceiling center should be reflective for “first bounce” Early Sound to reach the most persons.

- Sound Absorption for Short RT(60),

  \[ RT = 0.1(1+\log V) \]
Payback!

For a 20 student classroom, 40 year life. These 800 students would earn $40,000 / Y, but may earn 1% more if they learned more due to good classroom acoustics. 1% increase yields $400 / Y / student. They will pay local taxes on this, say 1/2% (average between income tax and real estate tax). In only fifteen (15) years, this totals $5,000 more taxes from students that graduated from that room. This will double in only 8 more years!
Cost Benefit of Improved Classroom Acoustics

- Increased wages per annum
- Accumulated taxes collected.

ONE CLASSROOM

PAYBACK

BENEFIT

Annual Earnings Increase

Cumulative Increased Taxes Collected

TIME ---> YEARS

$0 $50,000 $100,000 $150,000 $200,000 $250,000 $300,000 $350,000 $400,000

$0 $5,000 $10,000 $15,000 $20,000 $25,000 $30,000 $35,000 $40,000

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Next Steps

• In the past, we have applied these requirements on a project if asked.

• In the future, we should require sound absorption \textit{and} one of these HVAC solutions at the outset, refining costs and construction material choice \textit{---------}

• “to fit the project and the budget”.