Acoustical Standards for Classroom Design
Comparison of International Standards and Low Frequency Criteria

Jack B. Evans, P.E.,

JEAcoustics
Engineered Vibration Acoustic & Noise Solutions

1705 West Koenig Lane
Austin, Texas, 78756 USA

Info<at>JEAcoustics.com

Abstract

Many countries have acoustical standards or regulations for educational facility design and construction. They are based on speaking and hearing abilities of teachers and learners. Criteria are often stipulated for reverberation decay time, sound isolation and allowable background noise. The standards may use single number A-weighted overall level descriptors (dBA), or octave band spectrum criteria (NC, RC, NR, etc.). A-weighted overall level criteria control mid- to high frequencies better than lower frequencies. Very few, if any countries specify low frequency noise standards, although limitations are implicit in spectrum criteria curves, such as (North American) Noise Criteria (NC) or Room Criteria (RC) or (European) Noise Rating (NR). Many educators focus on mid- to high-frequency effects on speech intelligibility, but low frequency noise (LFN) may cause some (upward) masking of speech with reduction of intelligibility. In addition, LFN may affect student attitudes, behavior, performance and/or fatigue. This paper compares acoustical criteria from several countries with respect to spectrum. Frequency spans of reverberation, sound isolation and background noise are contrasted with hearing and speech characteristics of children and adult learners. Principal findings of some LFN research by others are introduced, such as annoyance, speech intelligibility and fatigue. While this paper does not present a quantitative measure or model for low frequency noise versus learning, it investigates links between acoustical environment and learner success potential. Tabular comparisons of acoustical criteria and graphic charts of representative criteria will be presented. General recommendations are made, based on findings inferred from review and comparison of standards.

SUMMARY

Many countries have established acoustical standards or regulations for teaching facilities. Some are voluntary, others are mandatory, but all require the cooperation of the owner (national or local educational system), the architectural and engineering designers, the builders, and the facility operators. Acoustical criteria for classrooms in some countries have evolved as extrapolations of normal building acoustics standards or regulations, but in recent years many other countries have modified or established criteria to accommodate the special needs of children. Numerous behavioral studies have shown that children are more adversely affected than adults by noise and reverberation, and physiological data indicate that children's central auditory pathways are maturing well into adolescence.[1] Newer standards are based on results of physiological, speech perception and other studies of young students.

CHILDREN'S LISTENING AND LEARNING ISSUES

In a review of works by Elliott, Eisenberg, Wightman and others, Dr. Peggy Nelson highlighted theories for adult/child differences. Issues affecting children include: 1) inefficient listening strategy, 2) inability to put together missing pieces, 3) immature weighting of acoustic information, increased susceptibility to distractors, and 5) decreased ability to segregate signals from noise. Other research (Flavell, Evans (no relation to the author), Maxwell, French, Steinberg, Plomp, etc., summarized in ANSI S12.60, Appendix A, has focused on speech intelligibility as a function of reverberation and correlations with signal-to-noise ratio (SNR). The essence being how loud speech is relative to the background noise. Intelligibility increases as the speech level is increased, the background noise is decreased, or a combination. Speech perception research has shown that individuals with hearing impairment, speech and language disorders and limited language proficiency require improved SNR.[2] Children fall into this group. Nelson listed four primary sources of noise in classrooms.[3] : 1) building services and utilities, including HVAC, 2) exterior noise transmitted through the classroom building envelope, 3) interior noise transmitted through partitions, floors, ceilings, ventilation ducts, etc., and 4) noise generated within the classroom by occupants and classroom equipment. Many other studies can be found on classroom acoustics and characteristics of learners.

For practical reasons, research studies tend to focus on specific parameters (to simplify research, variables are limited). Speech perception may consider distance between speaker and listener or background noise or reverberation, etc., but usually in terms of A-weighted sound. Since A-weighting is based on normal hearing characteristics for humans at moderate sound levels, it would seem to be ideal, but the single-number descriptor does not provide much information about spectral or tonal characteristics. Speech intelligibility can also be affected by broadband noise, including lower frequencies, by temporal changes, i.e. off/on or time-varying level, by tonal noise and by information bearing content. The single-number A-weighted descriptor can represent many different sound spectra. In other words, not all sounds of a given A-weighted level are equal. Therefore, hidden variables relating to spectrum differences may influence some results, without researchers acknowledging or accounting for those differences. The aggregate results, however, of many studies tend to converge on similar findings. An in-depth review and comparison by Crandell and Smaldino, of many studies comparing speech recognition for normal and hearing impaired children[4], discussed several acoustical variables in classrooms with respect to noise effects on academic and teacher performance, including background noise, SNR, speaker-to-listener distance and reverberation time. The combined effects of noise and reverberation being greater than the sum of the independent effects were documented in addition to other effects. Except for upward masking, the effects of low frequency noise (LFN) were largely ignored.

Continuous lower frequency noises, such as air conditioning system components can effectively mask speech (creating speech interference) because of the "upward spread of masking," referring to the increased masking effect on signals at higher frequencies that the noise. Continuous noise sources more effectively mask speech than off / on, interrupted noises[5]. Two of the four most common primary noise sources in classrooms, identified by Nelson, above, are continuous building system noise, which is often low frequency dominant, and intrusive noises from the exterior, which might include low frequency noise of traffic, aircraft or stationary outdoor mechanical equipment. For these reasons LFN should be specifically considered in design for new classrooms or facility renovations.

Avoidance of teacher stress and fatigue is another reason to limit background noise and reverberation. Remarking on different studies by Smith and Knecht, Nelson discusses teachers that must speak at elevated volumes report vocal strain and health concerns. ."Smearing" of speech signals by reverberation aggravates those problems. Improved SNR can be achieved with quieter voice levels when the background noise is more moderate[6]. Effective use of acoustically absorptive building materials, therefore, can improve speech clarity, while it also reduces background noise incrementally, by room effect. Of course, the room effect may also attenuate teacher voice noise, as well, but where the teacher-to-student distance is less than the distance from mechanical, HVAC or exterior intrusive noise, the student listener benefits.

The documented differences between children and adult learners provide a substantial basis for the acoustical standards and regulations that exist. Most acoustical criteria for background noise are A-weighted. Sound transmission criteria are STC, R'w, or similar curve-fit descriptors that are limited to frequencies between 125-4000 Hz. Reverberation decay times are generally listed for mid-frequency octaves (speech frequencies). The various classroom standards and regulations do not specifically refer to lower frequencies, except for the occasional C-weighting for noise. This lack of LFN control limits effectiveness of standards.

Review of Standards and Regulations

Many countries have established acoustical criteria for classrooms and other learning facilities. Those criteria are extrapolated from building noise regulations by adapting for speech intelligibility in classrooms or they are specifically developed, for the hearing and speech characteristics of students and teachers. In response to inquiries, many colleagues have provided information about the standards in their countries. The International Institute of Noise Control Engineers (I-INCE), Technical Initiative #4, Noise and Reverberation control for School Rooms discusses technical knowledge, experience and international policies[7]. Classroom characteristics, noise control measures and other recommendations are discussed.

Public policies regarding acoustical standards are dynamic. It is difficult to acquire comprehensive and up-to-date information. Our collection of information still has gaps. Trends, become apparent, however, with even limited information. Most countries specify maximum allowable A-weighted background noise. The ANSI S12-60 in North America provides for a maximum difference between dBC and dBA as secondary low frequency criterion. Lower frequency reverberation criteria are unusual (re: LFN build-up), although some standards, such as the BB93 in UK mention lower frequency reverberation for auditoria. Sound isolation criteria are based on the limited frequency spans of STC or R'w. Summaries of acoustical criteria are discussed below with additional comments about low frequency noise.

Allowable Background Noise

COUNTRY	Type	Descriptor	Criterion	Low Freq.
Australia/New Zealand	Standard, AS/NZS 2107:2000	A-wtd Leq	35-45 (max)	
Belgium	Standard, '87	A-wtd Leq	30-45, re: extr.	
Chile	N/A			
Egypt	N/A			
France	Decree, '95	A-wtd Leq	33, 38	
Germany	Standard, '83	A-wtd Leq	35-40	
Italy	Std, UNI 8199 '75	A-wtd Lmax	36	
Netherlands	Guideline, NEN5077	A-wtd Leq	30-35-40	
Portugal	Decree, '02	A-wtd Leq	35	
Spain				
Sweden	Standard, '01	Leq	26-40	
Turkey	Regulation, '86	A-wtd Leq	45	
UK	Std, BB93'04	A-wtd Leq, 30 min	35	
USA	Standard, '02	A-wtd 1 Hr avg	35-40	dBC≤(dBA+20)

Allowable Reverberation Decay Time

COUNTRY	Type	Descriptor	Criterion*	Low Freq.
Australia/New Zealand	Standard, '00	A-wtd Leq	0.4-0.6 sec.	
Belgium	Standard, '87	A-wtd Leq	Varies w/ size	
Chile	N/A			
Egypt	N/A			
France	Decree, '95, '03	Seconds	0.4-0.8 sec.	0.5k/1k/2K Hz
Germany	DIN 18041 (d)'03		0.3, 0.45, 0.55	
Italy	Standard, '75			
Netherlands	Guideline, NEN5077		0.8 sec	
Portugal	Decree, 129/2002	Sec. +/- 25%	0.15*Vol^(0.333)	0.5k/1k/2K Hz
Sweden	Std, SS02 5268 '01	Seconds	0.5-0-0.6 sec.	250-4K Hz
Turkey	Regulation, '86			
UK	Std, BB93'04	Seconds	0.4-0.6-0.8 sec.	
USA	Standard, '02		0.6-0.7 sec	0.5k/1k/2K Hz

* Multiple time spans are for varying conditions, age groups or room types.

Sound Isolation (Internal)

COUNTRY	Type	Descriptor	Criterion	Low Freq.
Australia/New Zealand	N/A			
Belgium	Standard, '87	R Dn	25-49	100-3150 Hz
Chile	N/A			
Egypt	N/A			
France	Decree, '95, '03	STC	44 Room, 28 Corr.	125 – 4000 Hz
Germany	DIN 4109 '89	R'w	47	
Italy	Standard, '75	R, D	40	
Netherlands	Guideline, NEN5077	Unique Dutch	~?? dB	
Portugal	Decree, 129/2002	Dn, w (+/-3 dB)	45 Room,	
Sweden	Std, SCBR94 '96	R'w	48	
Turkey	Regulation, '86			
UK	Std, BB93'04	Dn*T*(*T*mf,max)w	Varies	source vs rcvr
USA	Standard, '02	STC	50	125 – 4000 Hz

LOW FREQUENCY NOISE EFFECTS ON HUMANS

Low frequency noise effects on adults has been researched and reported on by many, but LFN effects on children appear under researched. Can findings of research on adults be applied to children? Should extrapolation of conclusions from adult studies affect public policy or implementation of classroom acoustics regulations?

An interesting study by Dockrell and Shield focuses on school children's (6-7 and 10-11 years old) awareness and perception of noise at home and in school[8]. Annoyance from various noise sources, distractions and speech interference difficulties affecting students' ability to hear and understand teachers and are documented but other findings may illuminate the effects of low frequency noise. Annoyance levels due to aircraft were greater in communities with more or louder aircraft. Also, the level of noise may not be the key factor in annoyance. The same study reported that trains, motorbikes, trucks and sirens were rated as most annoying, compared with wind in trees as least annoying. The higher the external noise recorded, the less likely children reported hearing their teachers. This study recorded exterior sound levels in A-weighted Leq and Ln, but no spectral analysis measurements were made, so specific low-, mid- or high-frequency noise comparisons are not made. Of the four "worst" noises, however, three are low-frequency dominant, as is the aircraft noise mentioned earlier. While specific conclusions were not drawn relative to similarities between adult and children's noise perceptions, the children and teachers reported hearing similar noise sources in the classrooms. We wonder if studied further, whether the source(s) of annoyance could be correlated with tonality and temporality of noise, and perhaps, specifically with low frequency intrusions.

It is difficult to draw many conclusions about low frequency noise effects on children, because so much research is documented only with single number descriptors to represent overall noise level. Per V. Bruel presented a historical reminder to Inter-Noise 2001 of the origins and proper use of A-weighted sound levels[9], saying that it is wrong to use A-weighting for levels over 50-60 dBA, because the A-curve was developed only for low level noise. Comparison with equal loudness hearing contours and subjective testing have shown that A-weighting underestimates the lower frequencies by increasingly greater amounts as the frequency is lowered.

Studies have been done on adult subjects that show correlations between noise spectrum and annoyance, task performance, learning and behavior. Some of these studies also illustrate inadequacy of the A-weighted measurement when considering noise effects on humans.

Person Waye, Rylander, Benton and Leventhall carried out a study to investigate affects of low frequency noise on performance[10]. Subjects carried out similar tasks in a controlled

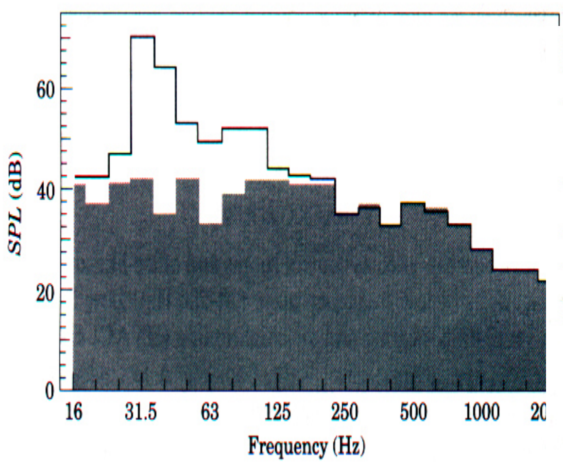

Fig. 1. 45 dBA Broadband and 46 dBA Low Frequency Dominated Spectra Used in Persson Waye, et. al Study.

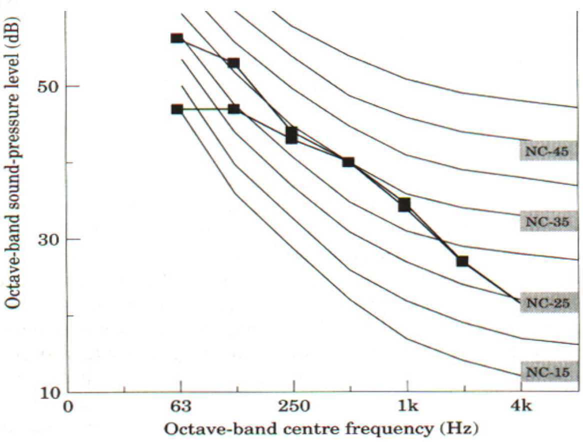

Fig. 2. Both Spectra Used in Persson Waye, et. al are NC-35, but Low Frequency dominates one.

noise environment with relatively flat spectrum meeting NC-35 and also in a low frequency dominated spectrum that was also NC-35. The second spectrum was different from the first only in 31 – 125 Hz octaves, where the low frequencies were significantly louder, but the A-weighted levels were only 1 dB apart, because the a-weighting curve so deeply attenuates very low frequencies. The study showed greater annoyance with the LFN environment and decreased performance and longer response times on tasks. There were also unconfirmed indications of fatigue effects.

A later study investigated the fatigue factor[11]. Five different tests of performance and learning were conducted on subjects, also in two environments with equivalent NC and A-weighted levels, but significantly greater low frequency noise in one. The conclusions stated that LFN impaired performance on tasks sensitive to tiredness. Interestingly, no significant affects were found on motivation related variables.

Many other studies of the effects of low frequency noise on humans can be found in the literature. Leventhall's 2003 review of published research[12], covers many aspects of LFN, including objective effects, annoyance, behavior, performance, social attitudes and stress. The difference between A-weighted and C-weighted noise as an indicator of low frequency content in sound is discussed as a predictor of annoyance. The only study in this review specifically referring to children (Ising and Ising, 2002), dealt with sleep interference from truck noise and the resulting problems with concentration and memory. Based on L_C - L_A analyses, one of the conclusions were that A-weighting is inadequate and safer limits are needed for low frequency noise at night. Similar studies on adults (Persson Waye, et.al, 2003) reached similar conclusions. Again there are indications that the LFN effects on children are similar to those on adults, but few studies specifically compare or correlate children and adults, or determine which LFN effects are similar and which are different.

CONCLUSIONS

Studies on adults have indicated fatigue, performance, annoyance, behavioral, speech interference and other effects due to low frequency noise. Few studies have been done to document similar effects on children, although a significant body of research has established speech and hearing characteristics of children in broadband noise environments. Children require improved signal to noise ratios to achieve listening comprehension similar to adults. Good learning environments, however, may involve other facets of performance beyond listening comprehension, including annoyance, fatigue and behavior. Research should be undertaken to correlate low frequency noise effects on children and adults.

Standards for classroom acoustics should control low frequency noise, but criteria are generally expressed in A-weighted levels for noise, which can permit excess low frequency noise. Reverberation decay time criteria are generally prescribed for 500, 1K and 2K Hz, but not lower frequency octaves, thereby allowing greater reverberant build-up of lower frequencies. Sound isolation partitions, regulated by STC and R'w criteria, do not control sound transmissions below 100 Hz. With inadequate low frequency noise criteria, LFN affects on children may limit student performance in the classroom.

Based on these findings, it would be prudent to incorporate low frequency noise criteria in classroom acoustics standards for background noise, reverberation decay time and sound isolation. Use of C-weighting as a supplemental noise criterion, or prescribing a maximum difference between C-weighted and A-weighted measurements of noise could reduce LFN. Extending reverberation time criteria to lower frequencies could reduce the build-up of noise that reinforces LFN. Requirements for low frequency noise reduction through partitions and exterior walls could reduce the intrusion of building equipment room noise–or exterior noise into classrooms. These improvements would reduce upward masking of speech from LFN and possibly maintain better learning environments that are substantially free of annoyance, fatigue and behavior problems.

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