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Editor in Chief
Miguel Ausejo
Editorial Assistant
Francesco Aletta
Edited by
European Acoustics Association (EAA)
secretary@european-acoustics.net • office@european-acoustics.net
www.euracoustics.org
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Improving acoustic quality in classrooms by adequate sound absorption

Helmut V. Fuchs
Casa Acustica Berlin
E-mail: hvfuchs@hotmail.com

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ABSTRACT

Various basic parameters and effects determining speech intelligibility and noise self-generated by users in classrooms are recalled: emission spectra, room mode excitation, masking of high by low frequencies, *Lombard* reflex, library effect. Standard psychoacoustic tests with students of different age in simulated classrooms under varying acoustic conditions and background noises yield informative intelligibility scores. With these objective results and comprehensive practical experience from previous restorations in mind, two contradictory acoustical concepts are applied on two lecture rooms of an initially similar structure, outfit, and furniture. The one which finally came out with an almost flat reverberation spectrum over all relevant frequencies received better marks than the other with a much lower reverberation time at mid and high frequencies, but with a continuous ascent towards the lower frequencies. The discussion of results culminates in a critical comparison of the new DIN 18041: 2016 with several other European standards.

1. INTRODUCTION

A large body of literature exists on the detrimental effects of noise and reverberation on speech and communication in classrooms of one kind or another, e.g. [1]. In many standard text books, e.g. [2], it is explicitly pointed out that low frequency (lf) reverberation time (RT) should be appropriately controlled, otherwise the important mid and high frequency sounds would be masked. A large variety of innovative approved absorption tools have been developed and introduced into the market to cope with an omnipresent problem of booming modes excited in small to medium-sized rooms [3].

In a striking contrast to all the apparent evidence and necessity, however, valid standards and regulations continue to underestimate the relevance of the lf characteristics of a room's reverberation, see section 10. The persuasive power of the numerous successful restoration projects reported in [3] on the administrators in charge remains very limited. One reason for this dilemma certainly is a difficulty for subjective assessments, as the initial highly deplorable situation for teachers and students can hardly be properly stored in mind for comparison.

The demonstration project presented in section 9 will allow a much better objective and subjective comparison of three quite different room acoustics situations in two medium-sized lecture rooms of a very similar architectural structure at Graz University in Austria:

a) both rooms conventionally equipped with standard mineral fiber suspended ceilings, as may be found anywhere,

b) additionally installed wall panels with an absorption characteristic again culminating at medium frequencies similar to case a), in accordance with [4],

c) additionally installed compact edge elements with a broadband absorption culminating at low frequencies as suggested in [5].

Several sources, e.g. [6], already address speech intelligibility as the key problem to be solved in order to improve room acoustic quality and reduce a still growing noise burden in schools. But for far too long comprehensive scientific studies were missing which could yield definite scores of exactly how much the intelligibility is reduced by different levels and frequency spectra of RT and types of noises. In section 8 some quantitative results of recently performed investigations are therefore compiled to fill that gap.

Apart from adding some fundamentals and presenting another example of alternative practical measures to its topic, this paper is also meant as a warning: An English version of [4] is presently recommended by the DIN for international acceptance. The author, however, is convinced that

- the sharpening of the recommendation in [4, Fig. 1 there] as compared to its 2004 version [7] concerning the mid frequency (target) RT, T_{soll} according to A4 “usage type education/communication inclusive”, is unnecessary, extremely costly, and therefore counter-productive. It would, e.g., require T_{soll} < 0,5 s for a volume V = 270 m^3
- the widening of the tolerance range in [4, Fig. 2 there] as compared to its 2004 version [7] concerning the lf RT (+45 % at 125 Hz and 70 % at 63 Hz), on the other hand, is to be rejected, as it would tolerate a continuous ascent of the RT from very high to very low frequencies, see Fig. 20 b) compared to a).

Instead of taking [4] as a model for other standards and regulations it is recommended to closely consider the studies in [8] which arrive at quite similar conclusions as in this paper from acoustic refurbishments in the *Sweyne Park School* in Essex following the recommendations of the *British Association of Teachers of the Deaf* BATOD. The Graz project discussed in section 9 has, of course, followed the prescription in [9] for a flat RT spectrum as depicted on Fig. 20 a).

2. ACOUSTICAL REQUIREMENTS IN AUDITORIA FOR SPEECH AND COMMUNICATION

The acoustical demands in classrooms or lecture theatres differ

- for the teachers or lecturers with respect to voice support and local effort: For example, 13 % of 487 teachers of 22 Swedish schools, interrogated in a study cited in [10], suffered from serious voice problems as only one of several other indications of room acoustics affecting work satisfaction and well-being,
- for the pupils or students with respect to speech intelligibility and noise control: No doubt, a large majority of students have severe listening problems due to acoustically deficient environments affecting their intellectual comprehension, personal engagement, and academic development.

There is a long-standing awareness of these problems. Five earlier papers in another applied acoustics journal already presented a variety of adequate tools to cope with them:

- *Membrane absorbers* as a combination of *Helmholtz* and panel resonators [11]
- *Compound panel absorbers* as a particularly efficient low-frequency absorber [12, 13]
- *Broadband compact absorbers* as unique broadband sound absorbers [14]
- *Edge absorbers* as broadband absorbers particularly suited for praiseworthy acoustical refurbishments [5]

Yet, although meanwhile a number of representative demonstration projects [15 - 18] have shown how efficient broadband sound absorbers of one kind or another can and should be installed in auditoria of different size and use, the above addressed nuisance has not been cured on a larger scale. One reason for this deficit is a still lasting controversy among experts about the relevance of the lf absorption in rooms. Standard text books have far too long stuck to the conviction that the always favored and now almost omnipresent suspended “ceiling assembly must be highly sound-absorptive, especially at those frequencies important for determining speech intelligibility (500 Hz to 4000 Hz)” [19].

More recently, however, one has more and more realized that most conventional ceilings do not satisfy the requirements of high comfort and low noise in more demanding rooms used for speech and communication purposes. Some clever manufacturers therefore offer, quite successfully, wall absorber modules of very creative designs as “complement to an acoustic ceiling in environments where a full covering ceiling isn't sufficient on its own to create a good sound environment”. But does such an additional investment really solve the problem?

A much more effective restoration concept was tested in a number of dining rooms at the *J.-Miró* Primary School in Berlin-Charlottenburg and in a music tuition room at the *M.-v.Ardenne* Grammar School in Berlin-Lichtenberg, see sections 14.1.7 and 14.4.2 in [20]. It took advantage of a large hollow space behind the suspended ceilings in replacing the ceiling elements near the walls by sound-transparent perforated plaster-board tiles. On top of the latter a thick layer of mineral fibers was placed to form another kind of broadband edge absorbers. In both cases the efficiency of these simple measures showed up in equalized reverberation characteristics as proposed in standards [7] and [9]. Before reporting on two very dissimilar restoration examples, a few basics shall briefly be recalled.

3. RELEVANCE OF DIFFERENT FREQUENCIES IN SPEECH

Room acoustics planning should never rely on merely single-number ratings but always differentiate and specify a range between 125 (even better: 63) Hz and 4 (less important: 8) kHz. **Fig. 1** shows an averaged unweighted spectrum of human speech as measured under free-field conditions and standardized according to [21]. What is felt as loudness levels of normal speech (not shouting or crying) clearly relates to frequencies below 800 Hz. On the other hand, all valuable information which is contained in speech and is relevant for its intelligibility relates mainly to frequencies above 800 Hz, probably up to 4 kHz, see **Fig. 2**.

4. EXCITATION OF ROOM MODES

In closed ordinary rooms the decay of the speech spectrum between 250 and 63 Hz is only about 6 dB due to the inevitable excitation of room modes, see Fig. 7 of [18] as reproduced from [23]. The more or less discrete amplification of the lower frequencies is known to take place for all sounds generated in an enclosure, be it

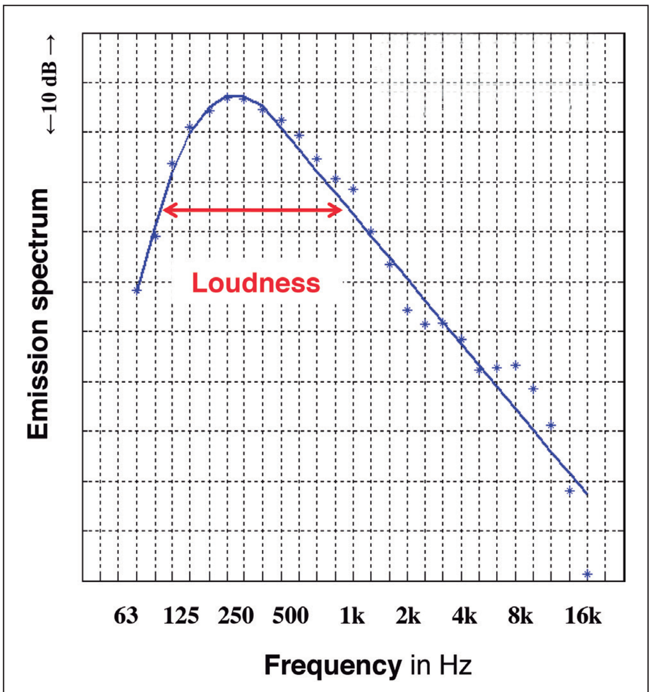

Figure 1. Averaged spectral distribution of speech under free-field conditions after [21].

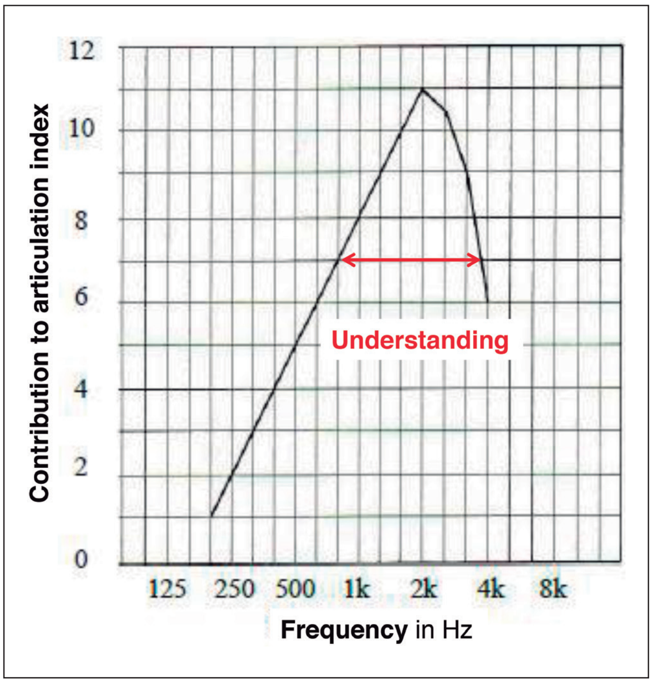

Figure 2. Relevance of frequency components in speech for its intelligibility after [22].

speech and music or the rumbling of chairs scrubbing on a hard floor or noise from a ventilating system or noise from a loud neighboring room or traffic noise intruding from outside. This fundamental lf problem is more thoroughly discussed in [17] or text books like [3]. As speech spectra according to Fig. 1 as well as most of the other disturbances also peak at the lower frequencies, the dramatic effects of the room resonances cannot easily be identified by its mostly untrained users. It may therefore be very helpful to now have two differently treated rooms as discussed in section 9 for demonstration purposes. When measurements of the absorption in or the reverberation of a room are performed, the booming resonances always manifest themselves as large variations in the sound pressure levels at different positions, even in standardized reverberation rooms according to ISO 354. This hurdle, however, does not exempt an acoustics expert from planning an auditorium for the whole frequency range. To fulfill this task, it comes as an invaluable relief that the sound energy of all the modes is always concentrated in the corners of a room. These corners are therefore the best suited locations for powerful broadband absorbers to efficiently damp the different mode families.

5. MASKING OF HIGHER BY LOWER FREQUENCIES

Strong lf disturbances are bad enough, especially when these are amplified by room resonances. But still another physiological effect can dramatically hamper speech intelligibility: The lf rumbling and hum may not only mask sound at the same but also that at much higher frequencies. Fig. 12 of [18] as reproduced from [24] shows a clear trend for this effect to increase as the frequency of the masker decreases and its level is raised. It goes without saying that masking particularly affects individuals with auditory defects, especially concerning the higher frequencies as particularly relevant for all elder individuals.

6. THE *LOMBARD* REFLEX VERSUS CALM LIBRARY EFFECT

In an environment that is disturbed by background noise and/or booming modes still another psychological effect inevitably triggers an acoustically hazardous loudness spiral. In [25] the author describes the subconscious reaction of every healthy human being to elevate his or her own voice as soon as he or she feels misunderstood in any vocal effort affected by noise, see Fig. 6 of [26]. The opposite effect may be observed in an environment where a certain emotional atmosphere prevails or where one realizes people to quietly read or study. What one may call a “calm library effect”, can also be provoked in more sensitive individuals when entering a room the acoustics of which has been optimized such that it enables best understanding even among many participants in a lively conversation. An acoustically well designed room may train its users to even lower their voices the more participants enter into a conversation. This very comfortable environment may at best instruct rational adults as well as pupils and students eager to learn to rather whisper than shout to each other! This psychological effect can amount to an additional noise reduction on top of the physical damping $\Delta\bar{L}$ calculable from differences in equivalent absorption areas A or reverberation times T according to

$$\Delta\bar{L} = -10\lg\frac{A_2}{A_1} = -10\lg\frac{T_1}{T_2} \qquad (1)$$

7. EMISSION SPECTRA OF SPEECH COMPONENTS

The necessity of lf absorption in rooms for speech and communication becomes very obvious when the emission spectra of those components of speech are considered on which the intelligibility so heavily depends: The fricatives (f, s, x) and the explosives (p, t, k) always carry less energy than the less relevant vowels (a, e, i, o) and semi-vowels (v, l, r), see Fig. 11 of [18] as reproduced from [27]. Singing or speaking actors on stage are forced to not only raise the power of vowels but also to well articulate the consonants in order to be understood by their audience. Reflective surfaces in their vicinity are always advantageous. Note, however, that *all* phonemes, nevertheless, have their energy maximum at the lower frequencies. In smaller rooms it is therefore absolutely necessary to absorb these in order to avoid the masking by modes according to sections 4 and 5. Absorption of merely the higher frequencies at surfaces which are known to be essential to transmit the valuable sound (above 800 Hz) from the source to the receiver (→ walls and ceilings) turns out to definitely be contra-productive.

However, before proceeding to the real situations established with three different absorption measures according to section 9 it may be interesting to consider the various influences on the intelligibility scores obtained for a large variety of acoustic conditions in simulated classrooms. With 252 m^3 their size was chosen just in between that of the lecture rooms treated in sections 9.1 and 9.2.

8. SPEECH INTELLIGIBILITY SCORES IN SIMULATED ENVIRONMENTS

8.1. Simulation test conditions

Comparing sound quality in rooms and relating it to diverse acoustical treatments is not an easy undertaking. As far as the comfort for speech and communication and the control of the associated noise are concerned, standard subjective syllable recognition tests are informative. Yet rarely is it possible to perform such elaborate investigations in situ before and after restoration measures as described e.g. in [3]. For an appropriate alternative, however, one may apply a simulation program like ODEON to provide a variety of environments for testing the influence of different spectral characteristics of the absorption in a model room and of the noise superimposed on standard test words. Stimulated by a conference paper [28], comprehensive research projects at universities of Guangzhou and Xi'an in China have fully confirmed the arguments and subjective findings put forward in [3].

In [29] the following parameters were moderately varied in a simulated classroom with dimensions 8,4 x 7,7 x 3,9 m = 252 m^3 :

- the mean reverberation times

$$T_m = \frac{T_{500} + T_{1000}}{2} \qquad (2)$$

with T_m = 0,6 (room 1) or 1,2 s (room 2);

- the reverberation spectra, characterized by the bass ratios

$$BR = \frac{T_{125} + T_{250}}{T_{500} + T_{1000}} \quad (3)$$

varying between BR = 0,86 and 1,24 according to **Fig. 3**;

- the signal-to-noise ratios

$$SNR = L_S - L_N \quad (4)$$

with the speech levels L_S and the noise levels L_N, both in dB(A), for SNR = 10 or 0 dB(A);

- the noise spectra chosen as either “white” noise or “lf-dominated” noise according to **Fig. 4**.

With these parameters quite different impulse responses could be generated for the model room and the corresponding acoustical environments were transmitted to the test persons via earphones. The difference between simulated speech spectra for rooms with BR > 1 and BR < 1, as based on a free-field spectrum according to Fig. 1, was depicted on **Fig. 5**. It illustrates a modal structure which is even more pronounced in the less reverberant model room with T_m = 0,6 s.

8.2. Results obtained with students

The intelligibility was determined as an average for male and female speakers. Their voices were presented to 32 normal hearing students aged between 19 and 21 years. 25 syllables had to be recognized by binaural listening via earphones at constant speech levels of 70 dB(A)

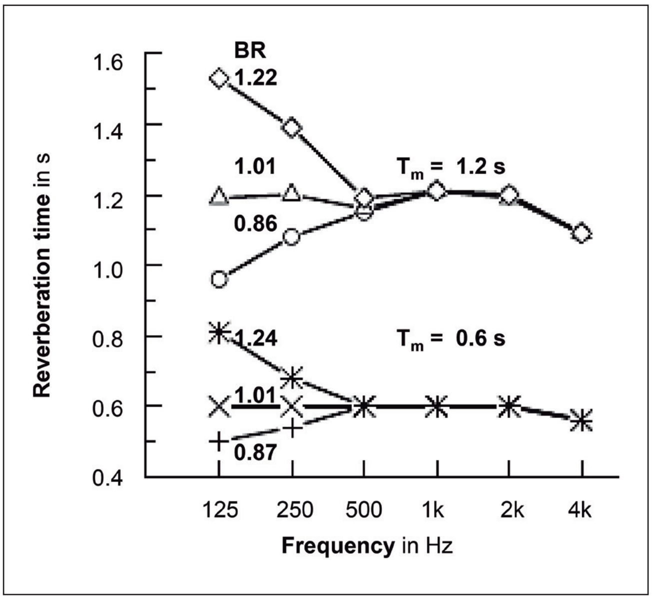

Figure 3. Reverberation time characteristics resulting from the impulse responses of the 6 simulated rooms 1.a (+), 1.b (x), 1.c (#) and 2.a (o), 2.b (Δ), 2.c (◊).

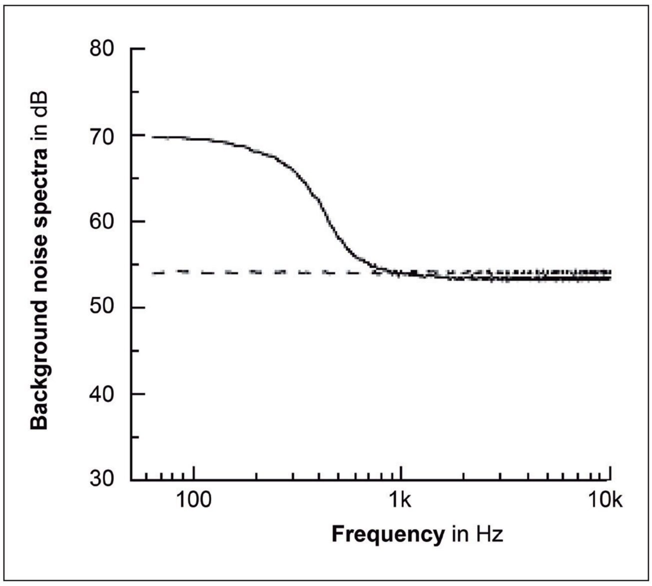

Figure 4. Noise spectra to be superimposed on speech in the rooms according to Fig. 3; “white” noise (dashed), “lf-dominated” noise (full line).

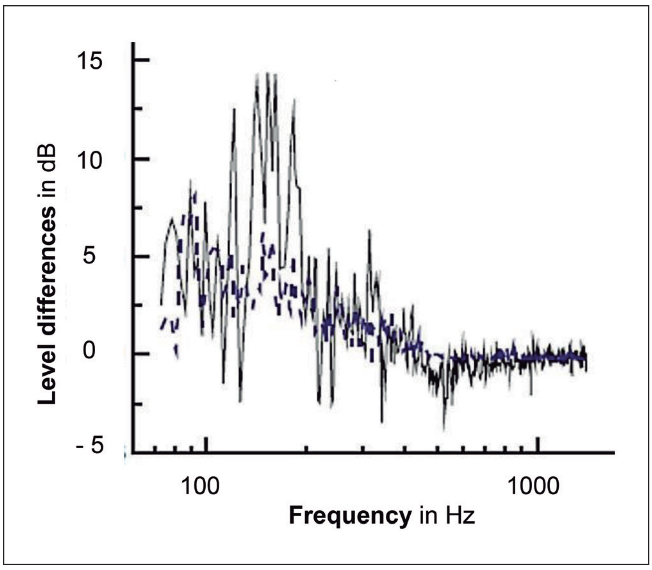

Figure 5. Differences in speech levels reproduced in the rooms according to Fig. 3 between 1.c or 2.c (BR>1) and 1.a or 2.a (BR<1) for T_m = 0,6 s (full) or T_m =1,2 s (dashed lines).

and background noise at 35 dB(A). More details of the test procedures may be found in [29].

The results in **Fig. 6** perfectly confirm all subjective findings in the earlier papers and books cited: In 5 groups of 6 columns the percentage of correctly recognized test words is reproduced for the 6 room environments according to Fig. 3. There is a clear trend for the speech intelligibility to be reduced by different disturbances in the following order:

- no superimposed noise (NN)
- “white” noise with SNR = 10 dB(A) (WN 10)

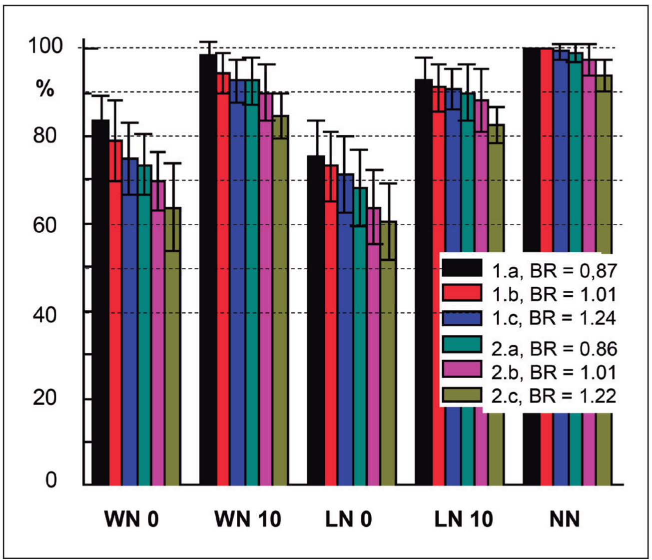

Figure 6. *Averages and spreading of intelligibility scores from 32 students in varying room and (continuous) noise situations.*

- "lf-dominated" noise with SNR = 10 dB(A) (LN 10)
- "white" noise with SNR = 0 dB(A) (WN 0)
- "lf-dominated" noise with SNR = 0 dB(A) (LN 0).

The difference between each of these groups amounts to 10 % on average. Within these groups, the upper 3 columns are always linked to room 1 with T_m = 0,6 s, the lower ones to room 2 with T_m = 1,2 s. For each room the intelligibility score always decreases with increasing BR. It may be noted that with decreasing intelligibility the spreading of the results, as indicated by the black girders, becomes progressively larger. As a general conclusion one may state that it is not only T_m but no less BR which is important, even more so for room 2 as compared to room 1.

8.3. Results obtained with pupils of different age

The tendencies observed in section 8.2 for young adults are even more pronounced when looking at the results after [30] in **Fig. 7**. The younger the children are, the more does their ability to recognize the words suffer from poor acoustical environments. The difference for model rooms with T = 0,6 s or T = 1,2 s, both simulated with BR = 1, amounts to 10 %. The positive influence of the age turns out to be stronger in the more reverberant room.

8.4. Intelligibility affected by different noises

For up-to-date teaching in classrooms and kindergartens the disturbances are rarely continuous "white" or "lf-dominated" noise but more or less discontinuous noises. This investigation would therefore be incomplete if one had not also studied the effects of different spectral and temporal characteristics of the disturbances at comparable L_{eq} levels of 70 dB(A), for details see [31]:

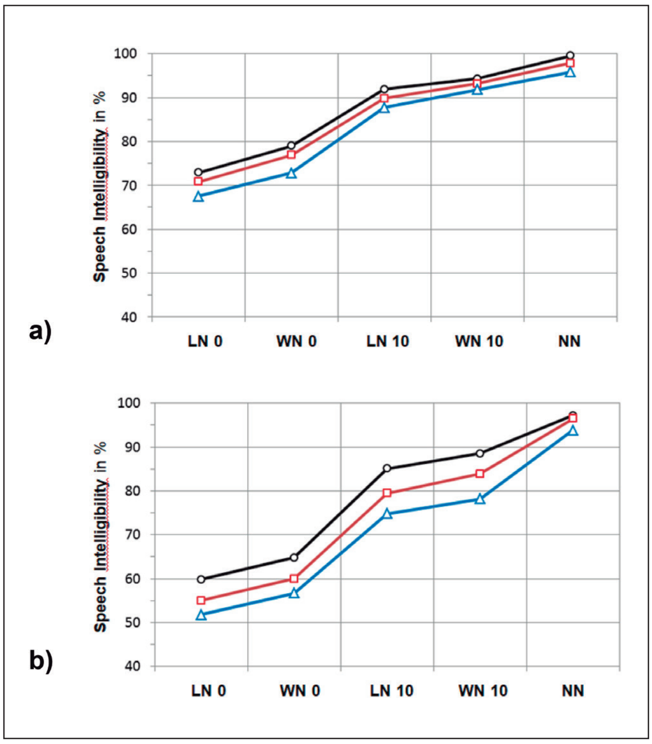

Figure 7. *Intelligibility scores obtained from testing pupils aged 8 - 9 (Δ) or 10 - 11 years old (□) and adults (o) for simulated room situations with a) T = 0,6 s, b) T = 1,2 s.*

- *Impact* noise (intermittent every 1,5 s)
- *Traffic* noise
- *Fan* noise
- *Speech* (standardized according to Fig. 1)
- *Babble* (of any conversation, understood or not).

Fig. 8 shows results from a total of 60 children aged 7 - 8, 9 - 10, and 11 - 12 years old in simulated rooms with T_m = 0,83, respectively 1,3 s, both with (unfortunately very typical) BR = 1,3. The SNR was again varied between 10 and 0 dB(A). Not very surprising, the intelligibility scores are lowest for the babble noise superimposed with SNR = 0 dB(A) in the more reverberant room, namely about insufficient < 40 % for the youngest and 56 % for the oldest children. The relatively higher scores for the impact noise may be due to the pauses between subsequent strokes which enable a much better recognition of the test words.

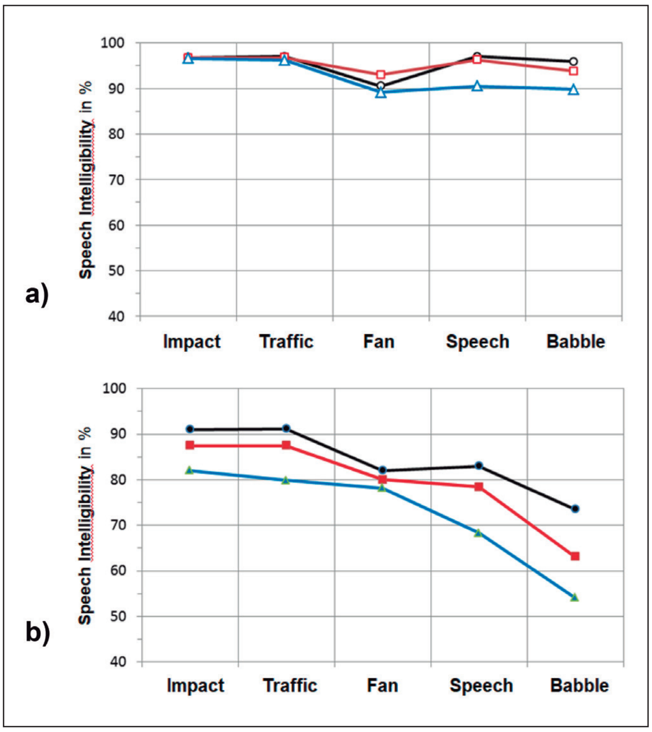

Figure 8. *Intelligibility scores from students of different age (∆ grade 2, □ grade 4, o grade 6) affected by different noises at SNR = 0 dB(A) (dark), respectively SNR = 10 dB(A) (light markings) for rooms with a) and c) T_m = 0,83 s, b) and d) T_m = 1,3 s, all with BR = 1,3.*

9. ROOM ACOUSTICS CONCEPTS FOR LECTURE ROOMS

A course of lectures on *advanced acoustics and audio engineering* recently given by the author at the Graz University provoked a vivid discussion on different strategies and materials aimed at improving the comfort and noise control in classrooms. A comparison study as already announced in the introduction thus became part of a bachelor thesis parts of which were first published in [32].

9.1. Conventional absorption measures

The two lecture rooms chosen at Graz University differ but slightly in size, background noise, and reverberation time T_{soll} required according to [9],

- room i14; total surface: S = 13,6 x 5,3 m = 72 m², effective volume: V = 267 m³, background noise: A-weighted 35 dB(A), unweighted 60 dB, T_{soll} = 0,76 s
- room i15; S = 10.8 x 5.3 = 58 m², V = 214 m³, 40 dB(A), 70 dB, 0,72 s.

Both represent a very similar and common architecture and have originally been equipped with an “acoustic ceiling” suspended 0,5 m under the 4 m high concrete surface and staying 1 m away from the windows according to **Fig. 9**. All walls and floors were left acoustically hard. The rooms are furnished with up to 7 tables and 40 chairs which produce a terrible roar when scrubbing the floor.

The reverberation time in room i14 is reasonably low at medium and high frequencies but exceeds the upper limit set by the standard (which is binding in Austria) for all frequencies below 500 Hz, see **Fig. 10**. This room was meant to stay unaltered for later comparison with room i15 perfectly restored according to section 9.2. Unexpectedly, however, another initiative made an attempt to also restore i14, at the same time but with quite different, more conventional measures.

Ten only 5 cm thick acoustic wall panels, with dimensions 1,8 x 1,2 m = 2,16 m² each, are installed at three walls as shown in **Fig. 11**. They add absorption, again mainly at medium and high frequencies similar as the suspended ceiling, on a total surface corresponding to 30 % of the ground surface of the room. From the corresponding change in reverberation

Figure 9. *The lecture rooms (here: i14), equipped with standard acoustic ceilings, call for additional absorption measures.*

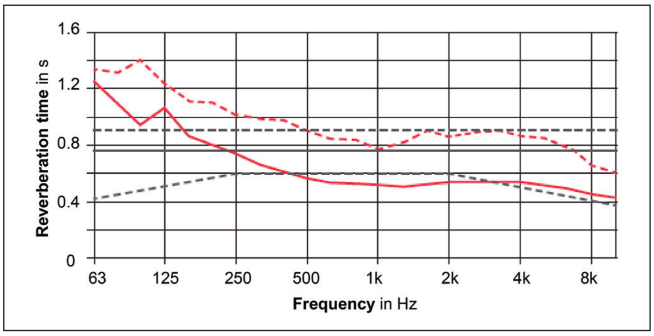

Figure 10. *Reverberation time in i14 (dashed red curve) exceeds the tolerance region (dashed black lines) of the valid standard ÖNORM B 8115-3 below 500 Hz. Additional absorbent wall panels according to Fig. 11 only amplify the harmful increase towards the low frequencies (solid red curve).*

Figure 11. Ten prefabricated panels cladding large parts of three walls of room i14 were meant to improve the acoustical comfort for lectures and communication.

time one may, very roughly, estimate an absorption coefficient as depicted on **Fig. 12**.

The objective results of this measure cannot surprise: The reverberation now drops below T_{soll} by 30 % above 500 Hz which, as such, would not create much of a problem. At 125 and 63 Hz, however, it surpasses T_{soll} by 40 and 65 %, respectively. When occupied, the users will add even more absorption above 250 Hz. Such a steep ascend from the high to the low frequencies is known to definitely result in inconvenient acoustics with booming modes, low clarity of sound, poor intelligibility of speech and high levels of background noise and, most important, still a kind of roaring associated with any communication in the room. It was therefore concluded that the absorption at higher frequencies was definitely overdone while that at lower frequencies still remains deficient.

9.2. Innovative broadband absorption measures

The measured reverberation time in i15 obviously exceeds the standard requirements over the whole

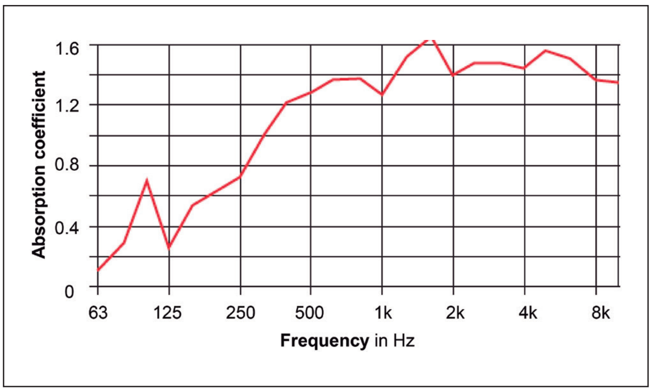

Figure 12. The absorption coefficient of the panels estimated from the results in Fig. 11 resembles that of the ceiling.

range of relevant frequencies, culminating at 1,5 s at 63 Hz (**Fig. 13**). This situation calls for an introduction of powerful compact broadband absorbers to equalize the room response. The massive protrusions at the door-side wall (**Fig. 14**) motivated an envelopment by 65 cm broad and up to 40 cm deep vertical coffers accompanied by corresponding horizontal edge absorbers under the ceiling along this wall. These smooth claddings with their optically attractive appearance (**Fig. 15**) were finally supplemented by edge absorbers hidden inside the hollow space of the suspended ceiling along both partition walls, see **Fig. 16**. This alternative acoustical treatment turned out to be nearly 50 % less expensive than the conventional one described in section 9.1.

The result in Fig. 13 now shows a fairly uniform reverberation time spectrum around 0,72 s, i.e. well within

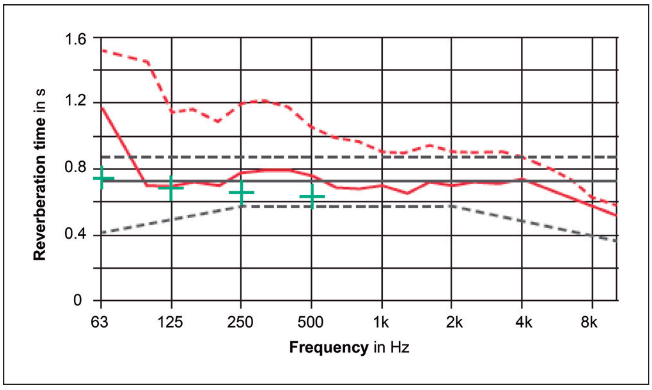

Figure 13. Reverberation time in i15 (dashed red line) exceeds the upper limit (dashed black lines) set by the valid standard [9] between 63 and 4000 Hz. Additional compact broadband absorbers according to Figs. 15 and 16 equalize the room response within the prescribed tolerance (solid red line); rough estimate from earlier restorations (+).

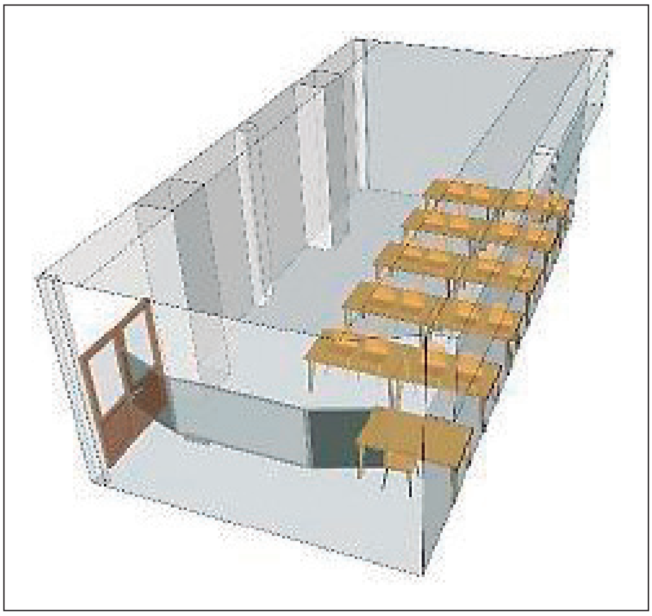

Figure 14. Sketch-up simulation of room i15 before its restoration.

Figure 15. Door-side wall of room i15 equipped with horizontal edge absorbers 1 and vertical coffers 2 (two-sided) and 3 (one-sided) resembling the original protrusions 4.

Figure 16. Absorber packages behind perforated gypsum plates within the cavity in front of both partition walls accomplish the alternative broadband installations.

the tolerance range according to the Austrian standard. A separate section 9.3 will be devoted to the discussion of the exceeding value measured at 63 Hz. When users now enter the room they report that its reverberance is what one expects for an enclosure of that size. The rumbling and hum has completely disappeared, speech intelligibility has been considerably improved, the voices sound remarkably vivid, comfortable, and relaxed.

9.3. Measurements to be performed in a non-diffuse sound field

One strong incentive for developing absorbers extending to the bass regime originally was the problem of measuring at the lower frequencies in small and medium-sized indoor test facilities [14]. With the respective sound fields here being everything but diffuse, the repeatability, reproducibility, and standard deviations of results still leaves much to be desired. This holds even more so for measurements as performed in the preceding sections. The variance of the reverberation time at 8 measuring positions for 4 source locations in room i15 (**Fig. 17)** before its restoration shows a tremendous spreading which could be considerably reduced but is still large, see **Fig. 18**.

With a spreading of T_{30} at 63 Hz between 1,0 and 2,2 s before and between 0,68 and 1,55 s one can hardly rely on the *Sabine* equation to derive an equivalent absorption area and from this an average absorption coefficient α linked to the absorber elements installed. Hence it may not surprise that the corresponding result of 0,3 falls well apart from the long-term averaged value of 1,1 as derived from previous similar restorations, see the green + in **Fig. 13** and **Fig. 19**. This discrepancy between the prediction and the deduction from widely spreading experimental data calls for further research. It should, however, never serve as an excuse for not applying as much as possible lf absorption. The subjective results will always justify such an effort!

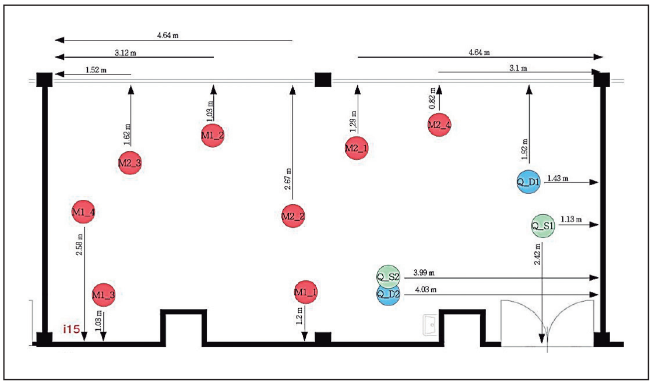

Figure 17. Measurement configuration chosen in lecture room i15; 4 source and 8 microphone positions .

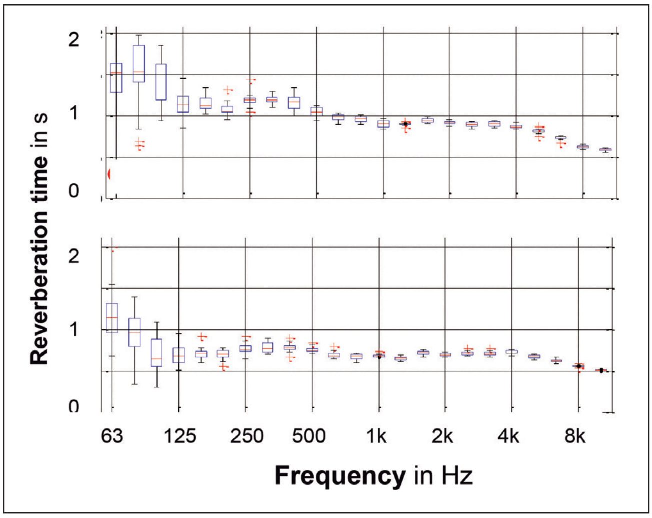

Figure 18. Measurements of T_{30} in room i15 before (upper) and after the restoration (lower graphic); variance (dashed girders), average (-), boxes (containing 50% of the results).

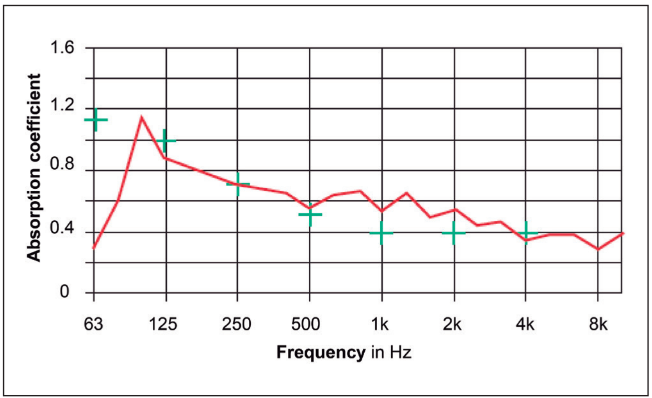

Figure 19. Estimated absorption coefficient of the absorber elements in Figs. 15 and 16 estimated from the results in Fig. 18; long-term average (+).

10. CONCLUSIONS AND DISCUSSION

Acoustic quality in classrooms is strongly linked to their reverberation characteristics. Both background and noise self-generated by their users may be tremendously amplified by the excitation of discrete lf room modes when these are not adequately tamed by suitable sound absorbers. If, instead, they are allowed to mask the important higher frequencies they reduce speech intelligibility, provoke the *Lombard* reflex and inevitably trigger a loudness spiral. Similar arguments also apply to all smaller venues for musical uses like orchestra pits and rehearsal rooms [33, 13].

Two adjacent lecture rooms at Graz University with a comparable, yet inacceptable reverberation spectrum continuously increasing from high to low frequencies were treated following two opposed concepts: The one added thin absorbent panels to the existing acoustic ceiling on large parts of three walls, the other concentrated the missing necessary broadband absorption only in edges and corners of the room, leaving all walls mostly untouched.

The users voted definitely in favor of the second, in which an almost flat reverberation spectrum was achieved while the other spectrum afterwards increased even more from high to low frequencies. The equalized characteristic is in accordance with the binding Austrian regulation ÖNORM B 8115-3:2005 [9] which once took the German DIN 18041-2004 [7] as a valid model, see **Fig. 20** a). The results of this study confirm the Austrian and other European standards [1, 8] and indicate that the new DIN 18041-2016 [4] has completely failed to sensibly update this important acoustics regulation. The question mark in Fig. 20 b) is to ask if such an irresponsible characteristic should really be tolerated e.g. in classrooms. In [34] it reads: "Some standards allow a longer reverberation at low frequencies … Shouldn't it be the opposite in rooms where speech intelligibility is important?"

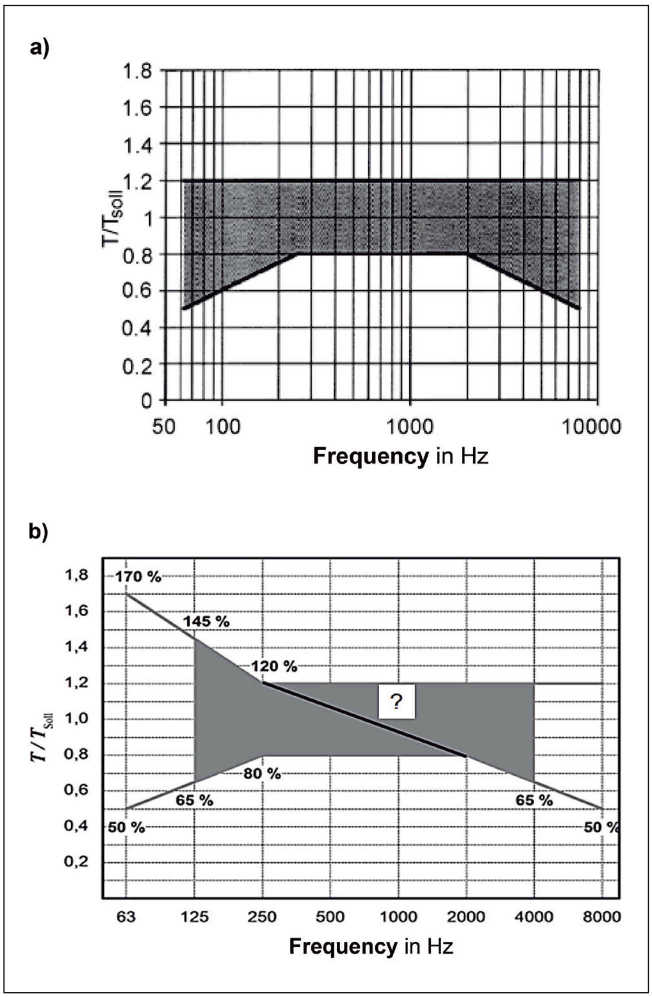

Figure 20. Tolerance area for the reverberation spectra as recommended according to a) DIN 18041-2004 and ÖNORM B 8115-3:2005, respectively b) DIN 18041-2016.

NOTE ADDED IN PROOF

Readers interested in noise control in communication rooms may also refer to a preceding article in this journal: In [35] *J.H. Rindel* very vividly describes the intolerably loud environment experienced in most restaurants and banquet halls. He identifies a ´Lombard slope´ in vocal effort of 0,5 dB per 1 dB increase in background noise, in best agreement with Fig. 21, which was already alluded to in section 6 of the present paper. When defining the ´acoustic capacity´ of a room, *Rindel* concentrates on the reverberation time as the most relevant parameter of the total absorption in the room with a focus on just the mid frequencies (500 – 1000 Hz) as is common and usual. According to the preceding sections, however, the cause for the development of an almost unavoidable loudness spiral in so many communication rooms is not its actual reverberance but, initially, its rumbling at much lower frequencies. This is always due to an uncontrolled excitation of its eigenfrequencies(´modes´) which

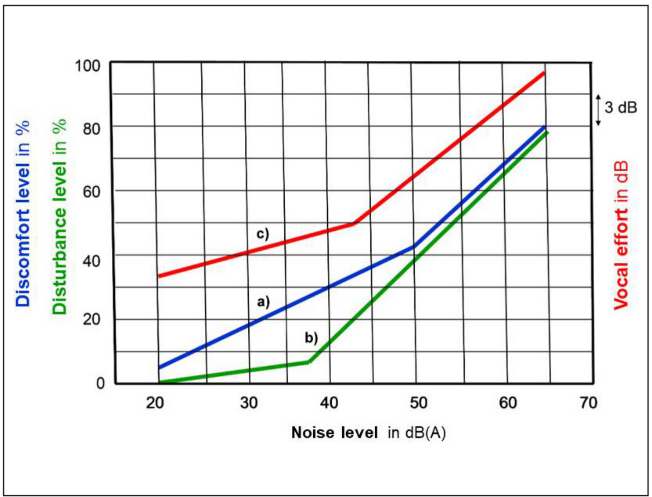

Figure 21. ´Lombard slopes´ as measured in [36] for the discomfort level (a), disturbance level (b), and resulting vocal effort (c).

always tend to mask the mid and high frequencies which are most relevant for the speech intelligibility, thus evoking the additional vocal effort of all participants in a conversation, be it in classrooms or restaurants. The solution for this universal problem therefore may be sought in adequate *broadband* absorption measures. These are able to create the ´calm-library effect´ according to section section 6 and thus considerably raise the ´acoustic capacity´ – a real challenge and great chances for practitioners in acoustics!

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