ACOUSTIC DESIGN CRITERIA FOR HIGHER-EDUCATION LEARNING ENVIRONMENTS

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1. INTRODUCTION

1.1 CURRENT STANDARDS AND LIMITATIONS

The acoustic performance standards contained in the BB93 satisfy requirement E4 of England's Part E of the Building Regulations, the School Premises Regulations and the Independent School Standards[1]. Moreover, the 'Acoustics of Schools: a design guide', has been published in 2015 to provide more information and advice related with the acoustic design of schools[2]. Additionally, the ANC Good Practice Guide published in 2015 describes in more detail how to conduct measurements for the BB93 performance standards[3] in accordance with several ISO standards. Nevertheless, the current legislation does not cover higher education environments, which are different and may offer other challenges compared to primary or secondary school teaching spaces. Therefore, since poor acoustic conditions might reduce students' level of engagement and attention during lectures, and cause vocal fatigue and stress to lectures[4], this project aims to investigate the acoustics requirements of a university environment. Several acoustical parameters will be evaluated across two classrooms and three lecture theatres at Solent University, including background noise, reverberation time (RT), speech intelligibility (SI), speech clarity (C50) and sound strength (G). All the measurements will be performed according to actual ISO standards. Subjective data will also be gathered by the use of dedicated questionnaires for both students and staff members. In section 2, the different methods employed to gather the required data as well as the measurement procedures will be discussed. Section 3 will present and analyse the collected data in comparison with the current BB93 document. Section 4 will compare the project results with external valid literature. Finally, section 5 will introduce a new proposed design procedure for future acoustics requirements for higher-education learning environments while possible future work needed to improve this study will be discussed.

2. METHODOLOGY

2.1 Classrooms description

Three lecture theatres and two classrooms were selected across two buildings at Solent University. The spaces were considered to be five good samples of different types of teaching spaces across the entire University environment. All the classrooms properties are reported in fig.1.

CLASSROOM	LENGTH	WIDTH	HEIGHT	VOLUME	CAPACITY	IANL (Background Noise)
JANE AUSTEN LECTURE THEATRE	17.715m	11.354m	- 6.114m (max) - 2.446m (min)	930 m^3	200	39.8 dBA
PALMERSTON LECTURE THEATRE	13.470m	14.479m	- 3.291m (max) - 2.583m (min)	559m^3	150	35.5 dBA
SOLENT LECTURE THEATRE	13.992m	11.382m	- 3.602m (max) - 2.381m (min)	494 m^3	174	33.9 dBA
SM009-10	- 15.456m (max) - 14. 103 (min)	8.588m	2.782m	357.29 m^3	32	38.6 dBA
TS202	13.819m	8.125m	3.188m	357.95 m^3	30-35	38.9 dBA

Fig.1: Classrooms data.

2.2 Background noise measurements

Background noise measurements were conducted according to standard guidelines[3]. BB93 specifies values of indoor ambient noise levels (IANL), which excludes noise caused by teaching activities, classroom's equipment and rain noise. The values take mainly into account noise from building services such as ventilation and air conditioning systems and external sound sources outside the learning environment. The values were measured by employing a class 1 sound level meter. According with the available guidance, a height of 1.30m was chosen for all the measurements positions and all microphone positions were kept at more than 1 meter of distance from other room surfaces. As required by the standards and the current regulations, indoor ambient noise levels (IANL) were measured in terms of $L_{\mathrm{A\,eq},T}$.

2.3 Sti-Pa measurements in classrooms

The measurements were performed according with standards and guidelines[5,6]. To emulate different listener positions and voice levels two microphone positions were measured for two different settings and positions of the mouth simulation speaker (talkbox) in each classroom. For Configuration 1, the talkbox was placed directly in front of the classroom microphone. This allowed to evaluate the sound reinforcement system contribution to speech intelligibility by simulating a hypothetical lecturer talking directly into the desk capture microphone with a STI-PA test signal of 60 dBA (normal voice level). Conversely, for Configuration 2 the talkbox was placed approximately at the centre of the lecturer area with a STI-PA test signal of 70 dBA in order to simulate a typical lecturer teaching position and the vocal increased level without the support of the sound reinforcement system. Additionally, in order to assess the impact of the classroom's microphone position on SI of captured lectures, a further measurement procedure was employed based on the standard STI-PA method (see appendix).

2.4 Impulse Response measurements in classrooms

The exponential sine sweep (ESS) method[7] was performed to measure the impulse response in all five teaching spaces and all measurements were conducted according with standards[8,9] and technical guidance[3]. The ESS and its inverse filter were generated by employing the AURORA modules developed for Audacity software[10]. The modules made also possible to both convolve the sine sweep recordings with the inverse filter and then to analyse them by retrieving the standard ISO3382 acoustical parameters. According to the engineering method, six measurement positions were chosen for two different sound source positions and so a total of twelve measurements were recorded in each of the five classrooms under test[8].

2.5 Subjective questionnaires

Along with the in-situ acoustics measurements, two dedicated questionnaires were developed and distributed among staff members and students of Solent University. A total of 11 responses from staff members and 15 responses from students were collected and analysed. The questionnaires aimed to analyse how background noise and other room properties such as its dimensions and reverberation time could influence the lecturer vocal effort and the SI perception of students during teaching periods. Staff members were asked to both give information about the average duration of the lectures, the vocal effort perceived during lectures, the necessity to increase voice levels while teaching and to evaluate the degree of annoyance caused by different types of background noise sources. Conversely, participating students were asked to provide information about speech perception during lectures and to assess the effectiveness of captured lessons on their study. Despite the limited amount of data, the comparison between subjective and objective data allowed to assess whether the current acoustics requirements or the existing standards might be sufficient to provide the needed acoustics performance to guarantee optimal speaking and listening conditions in a University environment.

3. RESULTS ANALYSIS

3.1 Background noise measurements results

Although all the background noise levels (reported in Fig.1) were within the required standards for refurbishment, only the Solent Lecture Theatre showed a level below the maximum limit required for new building structures (35 dBA). Furthermore, by comparing the objective values with the answers collected from the multi-choice questionnaire, a good link between subjective and objective results was observed. Indeed, the highest background noise levels measured in the Jane Austen Lecture theatre (39.8 dBA) and the lowest background noise levels measured in the Solent Lecture Theatre (33.9 dBA) reflected well with the subjective responses from the questionnaire which confirmed that the greatest noise annoyance was perceived in the Jane Austen Lecture Theatre while only one response argued a sense of noise annoyance experienced in the Solent Lecture Theatre. Moreover, from the subjective questionnaire it was possible to roughly estimate the most relevant noise source perceived during lectures. Among ten responses given to the question, most of the answers indicated that the main noise sources were related students and teaching activities within the classroom. On the other hand, a good balance among other possible noise sources such as HVAC noise and noise generated by activities outside the classrooms is encountered.

3.2 Reverberation time results

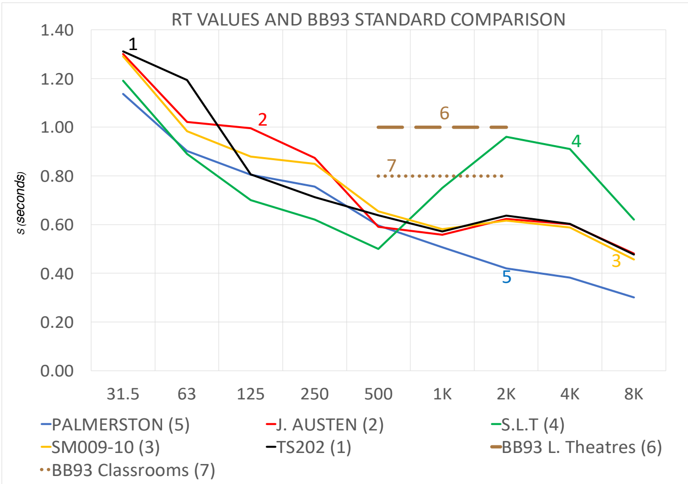


Fig.2: Reverberation time measurements results.

As can be seen from Figure 2, all the measured RT are within the required standards specified for the 500Hz-1kHz-2kHz frequency bands. However, apart from the Palmerston lecture theatre, none of the classrooms show a constant slope for the values of RT. Comparing the Jane Austen lecture theatre with the older Solent Lecture Theatre, a significant improvement given by the acoustic treatment of the newest theatre is observed. Indeed, despite the higher volume of the Jane Austen (930 m^3) compared to the Solent Lecture Theatre (494 m^3), the latter shows higher RT values at the mid-high frequency bands (from 1 kHz to 4 kHz). Moreover, highly similar RT values can also be observed between the newest classroom type (TS202) and the older one (SM009-10) with an equal room volume of 357 m^3.

3.3 C50 and G results

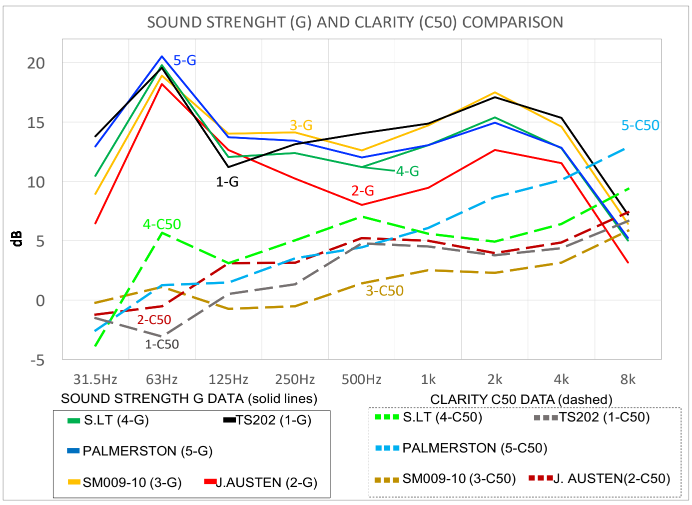


Fig.3: C50 and G measurements results.

As can be seen from the results, values of C50 are inversely proportional to the RT values for all the five classrooms. Generally, as can be seen from the graph, high G values are found at around 2 kHz frequency band. Therefore, taking into account the relevance of the 2 kHz frequency band on speech[11], G values might be considered good to support speech levels in classrooms. However, by inspecting C50 and G results, it can be noticed how speech clarity and sound strength for the two smallest classrooms (SM009-10 and TS202), despite having an equal room volume and reverberation time, show different values. Indeed, while the SM009-10 provides C50mid (500hz-1khz-2khz) results of approximately +2 dB and Gmid values of +14.97 dB, the TS202 shows higher C50mid values of +4.38 dB corresponding to higher Gmid values of +15.36 dB. This discrepancy between the two classrooms supports other research studies in which, because of the different absorbing ceiling materials (class E vs class A absorber panels), different C50 and SPL values were found for two identical classrooms having approximately the same reverberation time and room volume[12]. Similarly, different absorbing materials are installed in the two classrooms. While SM009-10 shows absorbing ceiling panels, TS202 provides vertical acoustic absorbing panels installed in the classroom ceiling. Lastly, a further comparison of the C50 and G acoustical parameters can be done by analysing their values over distance. Because of the main relevance of the mid-frequency bands on speech, the plotted results are averaged over mid-frequency octave bands (500hz-1khz-2khz).

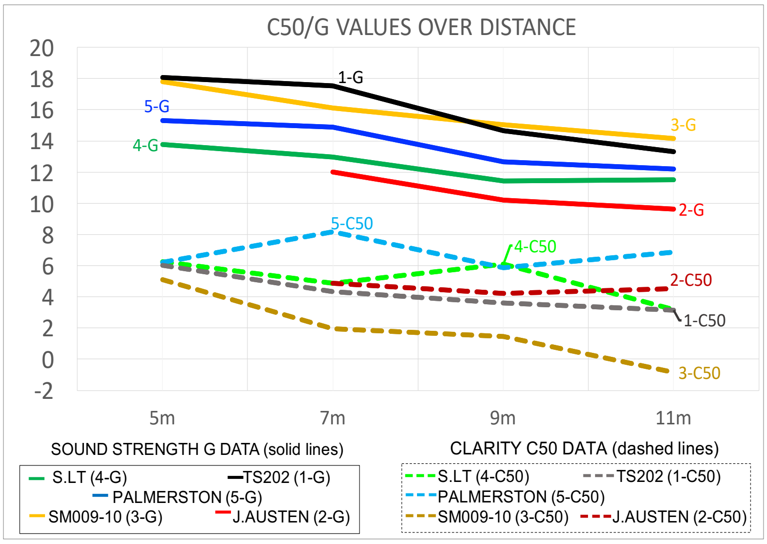


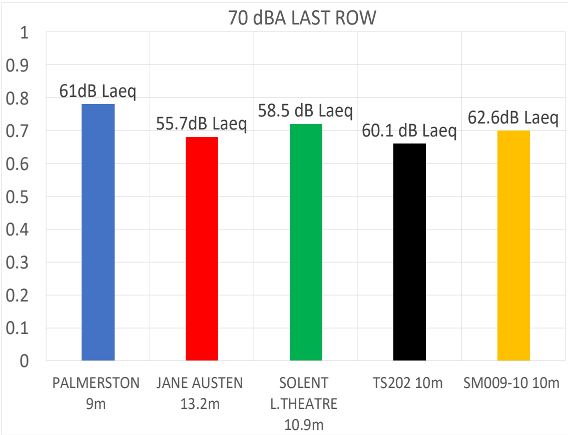
Fig.4: C50mid and Gmid measurements results over distance.

As can be observed, despite some peaks due to possible strong reflections from walls or ceiling, there is a general decrease of C50 and G parameters over distance for each classroom. Apart from the SM009-10 where lowest C50 values are found between -1/-2dB at longer distances (last audience rows), minimum C50 values for the classrooms are always higher than +2dB.

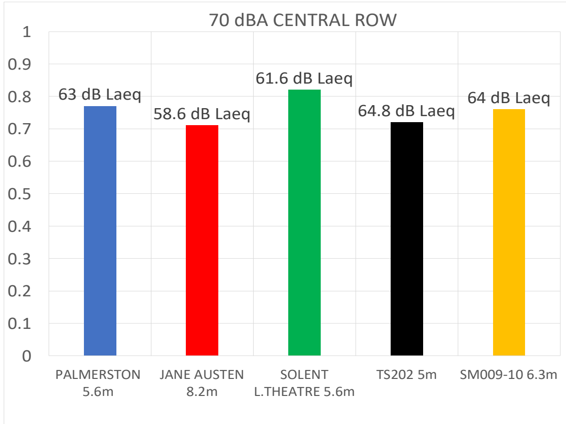
3.4 STI-PA standard measurements results

Measurements distances and measured SPL values (dBA) at receiver positions are reported for each result. However, it should be considered that since it was not possible to arbitrarily control the output gain stage for the installed classrooms sound systems, the output level of the classrooms loudspeakers could not be calibrated to a reference setting level. Therefore, measurements were performed with sound reinforcement systems in normal teaching conditions.

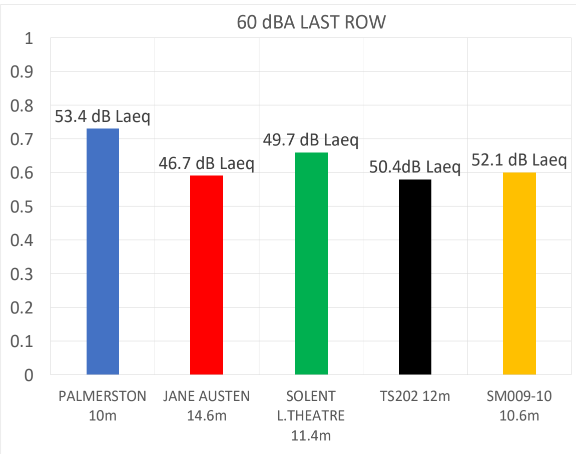
Furthermore, it should also be noticed that due to the absence of an installed sound system in room TS202, no contribution by additional ceiling loudspeakers was given for classroom TS202 in configurations c and d.



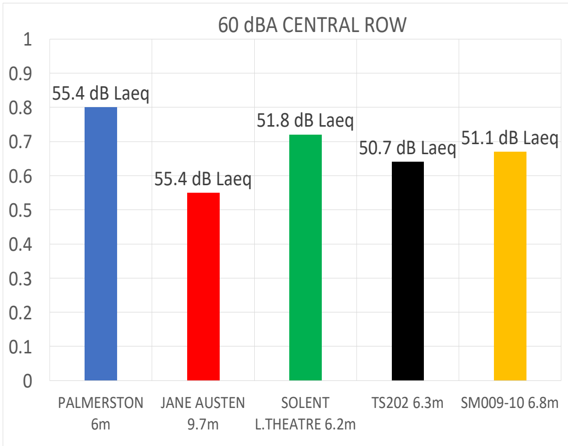
(a): Talkbox at 70 dBA in the centre of the lecturer area with minimum contribution from the installed sound system. Microphone placed in the last audience row.



(b): Talkbox at 70 dBA in the centre of the lecturer area with minimum contribution from the installed sound system. Microphone placed in the central audience row.



(c): Talkbox at 60 dBA in front of the lecturer microphone to maximize the contribution of the installed sound system. Microphone placed in the last audience row.



(d) : Talkbox at 60 dBA in front of the lecturer microphone to maximize the contribution of the installed sound system. Microphone placed in the central audience row.

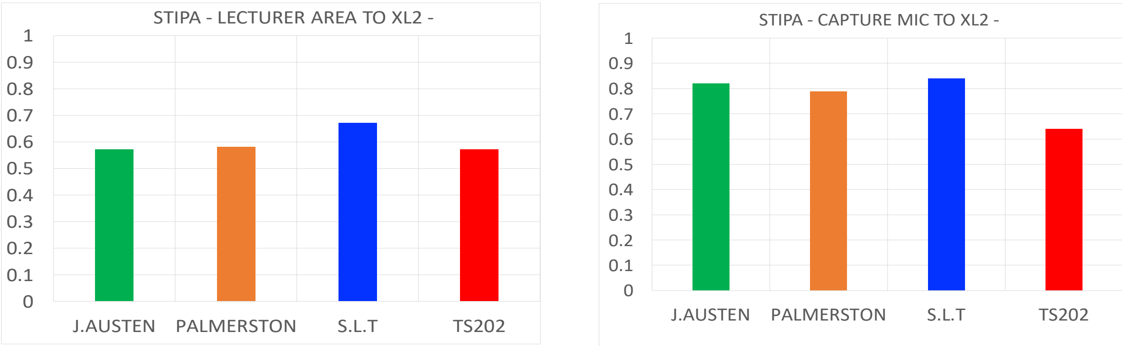
Fig.5: STI measurements results for all setup configurations.

Although BB93 does not require determined STI values neither for classrooms nor for lecture theatres, the measured results could be generally considered acceptable for classrooms according with BS EN 60268 which recommends STI values ≥ 0.62 for classrooms or lecture theatres[5]. Finally, as can be seen from fig.5, because STI values mainly depend on reverberation time and background noise levels, higher measured SPL (dBA) values at specific receiver positions do not necessary correspond to higher STI values. For instance, although Jane Austen Lecture Theatre shows a higher SPL value (55.4 dBA) than the other classrooms in configuration d, it provides the lowest STI value (0.55).

3.5 STI-PA experimental measurements results

- STI-PA experimental measurements to XL2

The following plots show STI results for the first two steps of the experimental STI-PA measurements described in Appendix, performed close to the centre lecturer area (configuration A) and from the capture microphone (configuration B). As stated in Appendix, for both the configurations a STI-PA test signal of 70 dBA was used as the sound source.



(a) Configuration A: STI-PA values for recordings taken from the lecturer centre area (approximately 2-3m from capture microphone).

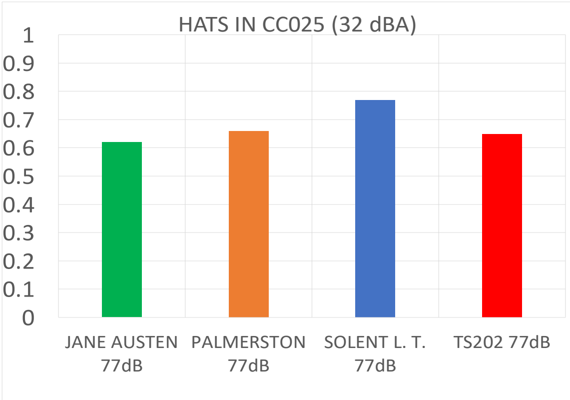
(b) Configuration B: STI-PA values for recordings taken as close as possible to the classroom capture microphone (approximately 4-5cm from capture microphone).

Fig.6: STI measurements results from recordings to XL2.

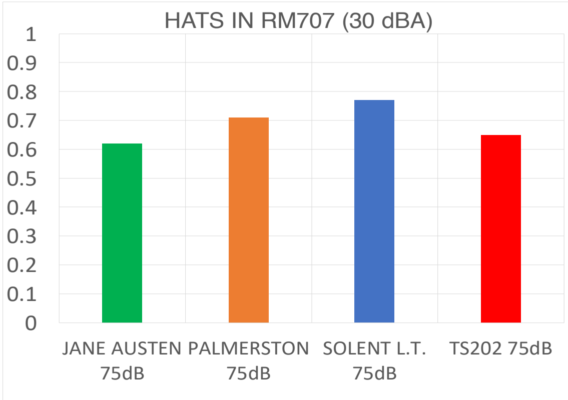
The results show excellent STI values for the three lecture theatres in configuration B. However, because the capture microphone in the TS202 was installed on the wall behind the interactive board, it was not possible to place the talkbox directly in front of the microphone, therefore lower STI values were found. On the other hand, a noticeable decrease from configuration B to A can be seen for all the classrooms. Thus, the results confirm a significant intelligibility loss due to a longer distance from the classroom capture microphone and the sound source (talkbox).

- STI-PA measurements to Head and Torso Simulator (HATS)

Lastly, STI results for STI-PA measurements performed with the HATS are here shown. As described in appendix, the recordings captured in the five classrooms from the lecturer's centre areas (at 70 dBA) to the classroom capture microphone were used as the test signals for these final STI-PA measurements. Because the impact of background noise may reduce STI values measured by the HATS, the results are separately plotted dependently on the room in which the HATS was placed (RM707 and CC025). Measured background noise levels of the two rooms, together with SPL (dBA) values captured by the SLM during the HATS measurements within the two different rooms are also reported.



(a) STI-PA measurements with HATS performed in room CC025.



(b) STI-PA measurements with HATS performed in room RM707.

Fig.7: STI measurements results from recordings (centre lecturer's area) to HATS.

As it can be noticed from fig.7, while the low measured background noise levels (32 dBA and 30 dBA) helped to guarantee good STI values, the impact of the classrooms acoustics properties on the recordings (e.g. caused by the distance between the classrooms capture microphones and the talkbox positions), did not probably allow for better (excellent) STI results.

4. DISCUSSION

4.1 Background noise considerations

The objective and subjective data showed how background noise levels higher than the required standards for new building structures defined in BB93 can cause noise annoyance which might consequently lead to vocal fatigue and speech intelligibility issues. It should therefore consider crucial to guarantee low background noise for optimal teaching and learning conditions and possibly make this parameter even more stringent for future legislation for higher-education environments. Moreover, because speech sound pressure levels within a room may vary according with the speaker (female or male) and with the voice levels (normal or raised), Bradley suggested maximum background noise values according with speech levels[13]. Additionally, due to the different room volumes of University environments, it would be preferable to set background noise levels accordingly to the classroom's volumes in future standards.

4.2 Reverberation Time considerations

According to literature, RT can contribute to add energy and increase voice levels, therefore nonzero values for optimal reverberation time are preferred[14]. Among several European acoustic norms for schools, DIN18041[15] seems to provide the most detailed and accurate specifications for school's requirements. Indeed, the revised DIN18041 published in 2016, not only provides RT targets dependent on the room volume and on the frequency but also specifies the requirements for environments of different usages and purposes. Furthermore, according with subjective questionnaires, a relation between experienced vocal fatigue and relative low RT values can be established. Therefore, appropriate values of RT should also be identified. The impact of RT on speech comfort can be demonstrated by taking in consideration the LT1 classroom, which according with the questionnaire's answers, required increased voice levels and therefore higher vocal efforts by lecturers while teaching. Because the classroom was designed to be a standard Dolby digital cinema according the Dolby requirements, a comparison can be made with DIN18041 in order to evaluate the RT time of the LT1. Since the LT1 complies with the RT standard provided by Dolby guidelines[16], upper and lower RT targets can be determined.

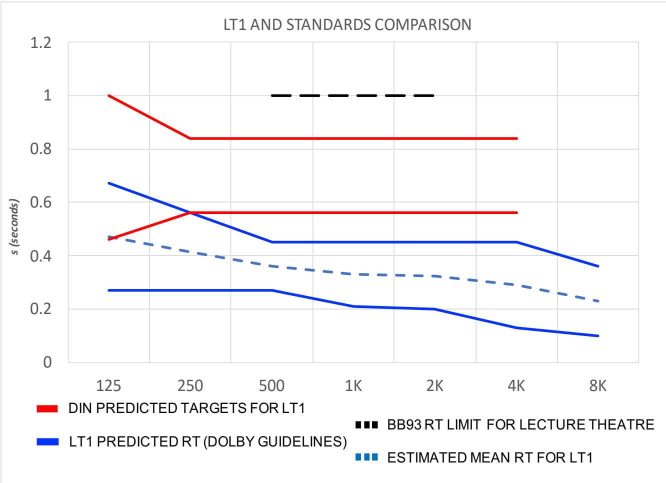


Fig.8: LT1 comparison with DIN18041 and BB93 standard legislation.

As can be seen from fig. 9, the estimated RT values for LT1 are significantly below the required lower tolerance limits defined by the DIN18041. However, by only considering BB93 recommendations, LT1 would fully comply with the RT requirements which only give a maximum RT limit value. Because of the general evidence of vocal fatigue problems, the comparison demonstrates that minimum target limits values dependent on both frequency and room volume might be required to guarantee good speech comfort in classrooms and large volume lecture theatres.

4.3 C50, G and STI considerations

The comparison between C50 and G acoustical parameters in room TS202 and room SM009-10 classrooms confirms that two similar rooms with equal RT values and room volumes do not necessary provide the same acoustic experience. Other acoustical indexes are thus required in order to more accurately evaluate SI in classrooms. Nevertheless, too high C50 values might correspond to excessive low RT which will not provide enough support for speech levels for the last classrooms rows[17]. Therefore, high C50 should be correlated to appropriate RTmid values in order to assure good SI and optimal speech comfort conditions. Sound strength values (G) should be referred to high C50 since excessive G values compared to low speech clarity results would indicate a predominance of late energy reflections over the useful early sound energy within the room. However, as clearly pointed out by literature, the C50 acoustical parameters cannot evaluate the combined effect of both room acoustic properties and background noise[18]. Thus, the standardized STI-PA method should be employed to accurately evaluate classrooms sound systems intelligibility. Furthermore, considering the evidence of SI issues argued by students and staff members, requirements should probably aim for excellent STI values ($\geq$ 0.75) while minimum acceptable values $\geq$ 0.60 should be specified according with the available legislation such as the English BB93[1], the Italian standard UNI11367[19] and the BS EN 60268-16 standard[5] in order to guarantee optimal speech intelligibility within large volume Lecture halls.

5. CONCLUSIONS

5.1 A new proposed design procedure

According to the results of this project, a new possible acoustics design procedure can be proposed for future acoustical parameters for higher-education learning environments. Considering a decrease for normal speech levels (60 dBA at 1 m) as a function of volume, more restrictive background noise levels should be put forward as suggested by literature[13]. Minimum and maximum RT values should be imposed, taking into account the classroom's volume and type, to both reduce vocal effort and to allow for appropriate G values across the entire listening area. Furthermore, relatively high C50 and G values should be achieved in order to ensure optimal speech intelligibility at multiple listener positions. This is particularly important when considering large teaching spaces (e.g. lecture theatres/halls). The STI-PA method should be employed to accurately size sound reinforcement system in order to provide excellent STI results by considering a normal voice level of 60 dBA from the classroom microphone. Finally, according to the results, if captured lessons are supposed to be recorded, the use of a lapel microphone should be recommended in future standards.

5.2 Future work

The need to establish acoustic requirements for higher education environments is confirmed by several studies which testify poor acoustic conditions in more historical University environments[22,23,24,25]. The research highlighted possible future standard parameters for higher education learning environments. Future work is required in order to establish an empirical formula to correlate C50 and G values for classrooms and lecture theatres according to room volume and use. Because of the evidence of vocal fatigue in classrooms, the relationship between the RT with other two parameters, the Reverberation time mouth-to-ears ($T_{30,ME}$)[20] and the Room gain (RG)[21], should be investigated to test their possible practical utility and usage as future acoustic requirements for vocal comfort within higher education learning environments. The influence of early reflections arriving to the speaker within the lecturer area should be considered in order to decrease the vocal fatigue experienced by members of staff.

6. ACKNOWLEDGMENTS

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APPENDIX: STI-PA experimental measurements procedure

In addition to classrooms STI-PA measurements, it was considered relevant for the purpose of the project to simulate speech intelligibility values of the captured lectures. Indeed, it is a common practice in a University environment to record lectures which can then be easily play back by students directly from their personal computer. In order to recreate a similar listening condition, three different experimental procedures based on the Sti-PA method were performed.

- **STEP 1:** The first step was to capture a stipa signal of 70 dBA by positioning the talkbox as close as possible to the capture mic on the classroom desk. The captured audio files were then reproduced from a portable computer directly in the XL2 sound level meter. This first position allowed to obtain STI values which would only evaluate the quality of the capture microphone. Therefore, this measurement position represented the best-case scenario and results should provide the highest STI values.

- **STEP 2:** the talkbox was placed at the centre of the lecturer area in each classroom with a distance of approximately 3 meters from the desk capture microphone. Measurements were performed with a stipa signal of 70 dBA and the recordings were then reproduced directly from the portable computer to the sound level meter from which the STI values have been estimated. This second position allowed to consider the impact of room acoustics on SI while emulating a typical lecturer teaching position in classrooms.

- **STEP 3:** Lastly, the recordings captured during the second step, which represented the captured lectures, were sent to the input channel of a Brüel and Kjær HATS throughout a consumer pair of earphones, allowing to emulate STI values by taking in consideration a simulated human factor. The HATS output channel was then connected to the XL2-TA sound level meter by which the STI values were finally retrieved.