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Indoor acoustic quality of educational buildings in South West Europe: Influence of current ventilation strategies

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ABSTRACT

The quality of the classroom environment has a great impact on the physical and mental health of students and teachers. The COVID-19 pandemic has highlighted the need for new measures and ventilation strategies to be implemented in educational buildings, to ensure indoor air quality in classrooms and to minimise the risk of airborne virus transmission. However, these ventilation protocols can influence the acoustic quality of classrooms and negatively affect students' speech perception and learning performance. This study presents the results obtained from a field measurement campaign carried out to assess the acoustic characteristics of classrooms of the Fuentenueva Campus (University of Granada) and Azurém Campus (University of Minho). Different ventilation operating scenarios (active and inactive) were assessed to evaluate their impact on the indoor acoustic conditions. The reverberation time (RT), the only parameter used in both countries' regulations to assess acoustic conditions, was found to be higher on both campuses than the RT limits values. Comparison of the measured Speech Transmission Index (STI) and background noise values in the active and inactive ventilation scenario showed a clear variation of the indoor acoustic conditions. The background noise was higher in the active ventilation scenarios (40–57 dBA) than in the inactive ventilation scenarios (34–48 dBA). The average STI values obtained on both campuses for the inactive and active scenarios were 0.54 and 0.51, respectively. In some classrooms an STI difference of 0.1 was found between scenarios. The results obtained in this study provide a broader understanding of the acoustic conditions in university classrooms in Spain and Portugal. The results evidence the need of consider the synergies between the indoor acoustic and air quality conditions to ensure both: the spaces are safe and the acoustic conditions do not interfere with students' learning. The findings show that compliance with the current RT requirements does not ensure that classroom acoustic conditions do not interfere with student performance, and therefore, regulations need to be revised to include additional factors to ensure proper acoustic performance.

1. Introduction

The quality of the indoor environment in educational buildings is essential for modern societies to pursue excellence in education. The learning capacity of students can be greatly influenced by the absence of good indoor environmental conditions [1]. The acoustic

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conditions in classrooms are among the most concerning environmental factors in educational buildings. Poor acoustic quality, such as reverberation or excessive noise, can negatively affect speech perception by students and teachers [2], reading speed scores [3], response times [4] and memory [5]. This situation is particularly worrying for students who have hearing impairments or who are studying in a language other than their mother tongue [2]. These negative effects also lead to a perception of mental and physical discomfort [6], reducing students' attention, motivation and well-being [7,8].

However, despite the impact of acoustic conditions on student satisfaction and performance, current research is mostly focused on the impact of indoor environmental conditions on the performance and health of workers. This fact was noted by Fang and Luo [9], who conducted a reviewed research on indoor environmental health in classrooms. They identified this research gap and stated that the indoor environmental indicators relating to physical and mental health in classrooms are being systematically ignored. Recent studies have also highlighted the significance of acoustic conditions on other indoor environmental factors and human perception. Wu et al. [10] analysed the relationships between different indoor environmental parameters (i.e. acoustics, thermal and lighting) and concluded that, in terms of the contributions of each of these individual factors to overall satisfaction, acoustic satisfaction played the most important role. In fact, individual factor satisfaction showed a one-vote veto tendency over the overall satisfaction, with the acoustic rating having the most obvious one-vote veto tendency.

In view of the influence of acoustic conditions on the performance and satisfaction of students and teachers, many countries and international organisations have developed standards and guidelines for the design of educational buildings [11–14]. However, there is still no agreement on the preferred acoustic criteria for a successful learning environment, not only with regard to the parameters but also with regard to their values and acquisition features, such as background noise levels in the time window or reverberation time (RT) frequency averaging [15,16]. Moreover, Minelli et al. [16] pointed out that many educational buildings were built before these standards were published and, therefore, they do not met the minimum requirements. This fact is evidenced by the results of dissatisfaction with acoustic conditions in educational buildings reported by previous studies. Pinho et al. [17] conducted acoustic measurements in eight schools in Portugal and found that only two of the studied school buildings complied with the Portuguese legal requirements; the remaining six revealed disabled constructive aspects in relation to their acoustic requirements, thus compromising the quality of education. Escobar and Morillas [18] analysed the acoustic performance of 17 auditoria and multi-purpose conference rooms at the University of Extremadura (Spain) and concluded that the RT values measured in their study were generally higher than those proposed in the five recommendations analysed. Tang et al. [19] conducted a post-occupancy evaluation of indoor environmental quality in ten non-residential buildings in Chongqing (China) and found that the lowest average satisfaction score in schools was related to acoustic conditions. Furthermore, the reported results showed that the sound pressure level was higher than 45 dBA in these buildings. Sadick and Issa [20] assessed the building elements' physical conditions on indoor environmental quality in 52 classrooms in new, renovated and non-renovated schools. They found that acoustic parameters (RT at 1 kHz and 2 kHz) were, statistically, significantly higher in non-renovated schools than in the renovated ones. The acoustical survey carried out at the University of British Columbia showed that the equivalent background noise level exceeded 45 dBA in 12 occupied classrooms and exceeded 35 dBA in 29 unoccupied classrooms [21]. Choi [22] reported similar results in a recent study conducted in 12 university classrooms at Kangwon National University (Korea); the mean background noise levels for occupied and unoccupied rooms were 41.2 dBA and 40.2 dBA, respectively. High background noise values are especially important in teaching learning spaces. The reviewed research on indoor environmental health in primary and secondary classrooms conducted by Fang and Luo [9] found that noise is an environmental indicator to which children and adolescents are more sensitive compared to adults. Prior studies concluded that, for excellent speech conditions, the speech-to-noise level difference should exceed a value of about 15 dB [23], above which no improvement in quality has been observed. Therefore, not exceeding 35 dBA of background noise in classrooms is often recommended, given typical teacher speech levels [24].

In the same context, several experimental and theoretical studies conducted by Hodgson, Bradely and Bistafa [2,21,25] analysed the acoustic quality in university classrooms. Hodgson [2] found that classroom quality is not correlated with classroom size, speech level, or early decay time, while a strong correlation was found with the background-noise level and signal-to-noise level difference. Bradley et al. [26] concluded that the most significant factor in understanding speech is the ambient noise, while the most important parameter for speech intelligibility is the signal to noise ratio. Nevertheless, other aspects of the classroom are factors that also affect the acoustic quality of these spaces [23]. Among these factors, the ventilation system has a fundamental role in achieving proper indoor air quality (IAQ). Its importance has become more evident since the COVID-19 outbreak, as it is not only used to prevent poor air quality conditions that can affect students' cognitive function [27], cognition [28] and health [14], but improved ventilation also prevents the transmission of airborne viruses [29]. International organisations have published guidelines and recommended ventilation control measures after recognising the potential for indoor airborne hazards [30,31]. The spreading of an airborne virus can be prevented by increasing window opening times in naturally ventilated buildings [32]. The World Health Organisation (WHO) recommended effective ventilation by frequently opening windows and doors [33].

These ventilation protocols were implemented because of the COVID-19 pandemic but they could change the acoustic quality of classrooms. However, these international guidelines and recommendations do not consider the possible effects that these protocols may have on the acoustic environment and, consequently, on the students' performance and well-being [34]. This fact reveals the lack of integration concerning the different interrelationships of indoor environmental factors in the international guidelines and standards [35]. Similarly, building codes and international standards often require that doors and windows remain closed when assessing acoustic parameters such as background noise and RT in educational buildings [13,36,37], without considering that the opening of doors and windows in naturally ventilated classrooms is necessary to ensure adequate IAQ and prevent the spread of airborne viruses. The focus on a single indoor environmental factor is an aspect of standards and practice guidelines that has been pointed out in previous studies [38]. As a consequence, end-users (i.e. students and teachers) are responsible for choosing which environmental factor to prioritise over others, which can lead to potential health and cognition risks [35].

In this context, few studies have been found on indoor acoustic conditions in university classrooms in Southwest Europe: Escobar and Morillas [18] analysed the acoustic performance of auditoria and multi-purpose conference rooms at the University of Extremadura (Spain), Pinho et al. [17] conducted acoustic measurements in different educational buildings (from kindergarten to college) in Viseu (Portugal) and Chiara Visentin et al. [39] conduced speech-in-noise tests were conducted in a university classroom (University of Bozen-Bolzano, Italy). However, these studies did not analysed indoor acoustic performance after implementing ventilation strategies. Since most educational buildings in Europe do not have mechanical ventilation systems, increasing ventilation rates in these spaces can only be achieved through natural ventilation [40] and so a special focus will be given to this issue. Up to now, there are no previous studies in which measurement results were reported on acoustic conditions or an assessment made of speech intelligibility for young adult listeners in university classrooms, before and after implementing strategies to minimise airborne virus transmission. To cover this gap, the objectives of this study are: (i) to carry out field measurement campaigns to assess the acoustic conditions of Portuguese and Spanish university classrooms in different ventilation operating scenarios, (ii) to analyse the influence of different acoustic parameters (RT, background noise, STI and C50) for both scenarios and (iii) to analyse the correlation between these measured acoustic parameters. For this purpose, in-situ objective measurements and assessments of acoustic characteristics of classrooms on the Fuentenueva Campus (University of Granada) and Azurém Campus (University of Minho) were conducted. The analysis of the acoustic parameters enables the identification of some prominent features of the classroom acoustics in Southern Europe and the practical challenges related to the ventilation strategies that ensure that classrooms are healthy spaces. The results shown in this study can serve as a guidance to perform an assessment of the impact of the application of ventilation measures in educational buildings to ensure both air quality and acoustically-suitable spaces, and to include some measurements in the protocols or guidelines developed for ventilation in classrooms.

2. Materials and methods

2.1. Buildings and selected classrooms

In this study, educational buildings were selected from two universities located in Southern Europe: the Azurém Campus of the University of Minho (Guimarães, Portugal) and the Fuentenueva Campus of the University of Granada (Granada, Spain). The location of both campuses is shown in Fig. 1. They combined a series of characteristics that make them of special interest: previous studies have shown that outdoor environmental conditions influence the ventilation strategies implemented in indoor spaces, so campuses with climates typical of the Iberian Peninsula were selected (Azurém Campus with Csb climate and Fuentenueva Campus with Csa climate). In addition, these campuses constitute two representative examples of typical university building locations: the Azurém Campus is located on the outskirts of the city of Guimarães, surrounded by a green area, while the Fuentenueva Campus is in the centre of the city of Granada, next to a principal road of the city and a green-pedestrian university area.

A representative sample of teaching learning spaces were selected for the analysis of the indoor acoustic quality of both campuses. The study comprised 6 buildings and 16 classrooms. Table 1 shows the characterisation of the studied classrooms. The classroom selection process was based on the identification of the different ventilation systems (natural ventilation through doors and windows and mechanical ventilation) present on both campuses. Central mechanical ventilation system brings fresh air into the classrooms. This process is controlled by central appliance. In addition, a set of representative classrooms was selected, in terms of size, classroom shape and occupancy. Two types of classrooms were identified on the Azurém Campus: classrooms with a rectangular geometry and flat floor, and auditorium type classrooms with a rectangular shape and stepped floor. On the Fuentenueva Campus, all classrooms are rectangular in shape and have a flat floor.

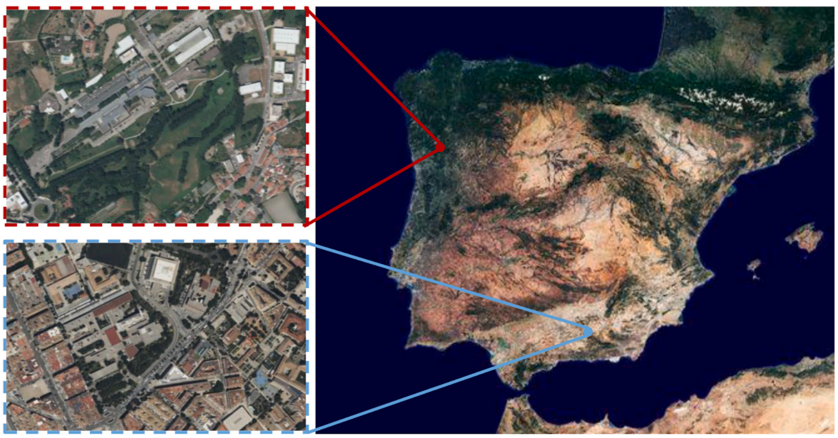

Fig. 1. Location of the selected Campuses. a) Azurém Campus, b) Fuentenueva Campus.

Table 1
Characterisation of the studied classrooms.

Campus	Building	Class	Ventilation System	Window orientation	Area (m^2)	Volume (m^3)	Occupation (seat)	Occupation ratio (m^2/student)	Type of window	Finishing materials		
										Wall	Ceiling	Floor
Azurém	A1	A1-1	MS	SE	132	470	130	1.02	AGW	GP + WP	APC	V
		A1-2	NV	SE	48	151	30	1.60	AGW	GP	MSC	V
	A2	A2-1	MS	SW	85	287	80	1.06	–	GP + WP	APC	W
		A2-2	NV	SE	76	218	48	1.58	AGW	GP + WP	GP	V
	A3	A3-1	MS	SW	50	148	60	0.79	–	GP + WP	GP	W
		A3-2	NV	SE	68	185	30	2.27	AGW	GP	GP	V
	A4	A4-1	MS	NW	127	341	122	1.04	AGW	GP + C	APC	CT
		A4-2	NV	NW	68	196	41	1.66	MGW	GP	C	CT
Fuentenueva	F1	F1-1	NV	W	265	796	45	5.89	AGW	CT	APC	NS
		F1-2	NV	N	172	518	78	2.21	AGW	CT	APC	NS
		F1-3	NV	S	174	522	78	2.23	AGW	CT	APC	NS
		F1-4	NV	E	206	643	70	2.94	AGW	CT	APC	NS
	F2	F2-1	NV	SW-NE	175	500	35	5.00	AGW	GP	GP	T
		F2-2	NV	W	167	524	48	3.48	AGW	GP	RSC	T
		F2-3	NV	S	106	319	38	2.79	AGW	GP	GP	T
		F2-4	NV	W	164	542	62	2.65	AGW	GP	APC	T

NV: natural ventilation; MS: mechanical ventilation system; AGW: Aluminium glazed windows; MGW: Metal glazed windows; GP: Gypsum plaster; WP: Wood panel; APC: Acoustic plasterboard ceiling; MSC: Metal suspended ceiling; V: Vinyl coating; W: Wood; GPB: Gypsum plasterboard; C: Cork; CT: Ceramic tile; NS: Natural stone; T: Terrazzo; RSC: Registrable suspended ceiling.

2.2. Measurement procedures and acoustic parameters

The acoustic parameters RT, clarity (C50), background noise and STI were measured in the selected classrooms. Impulse responses were recorded in the unoccupied classrooms. The frequency-dependent RT30 and the C50 were calculated based on the recorded signal. These parameters were calculated according to ISO 3382–2:2008 [41]. The selected source signal was a logarithmic sine sweep which was radiated from an Omni-directional dodecahedron loudspeaker (Brüel & Kjaer) into the classroom. Two source positions were selected in each classroom, located more than 1.0 m away from the walls and at 1.6 m above the floor. Twelve measurement positions were selected, evenly distributed among the seats in each classroom, at a height of 1.5 m and separated more than 1 m from the walls. Appendix A shows the distribution and position of the different microphones and sources in the classrooms tested in this study (see the figures in Appendix A).

The average background noise levels were measured from the 125 Hz to 8 kHz octave band in unoccupied classrooms. These measurements were carried out in two ventilation operating scenarios: (i) with doors and windows closed and, for those classrooms which were mechanically ventilated, the ventilation system was turned off; (ii) with the ventilation protocols implemented because of the COVID-19 pandemic. Two different scenarios were selected for each classroom according to the type of ventilation system operated. In naturally ventilated classrooms, 'doors and windows closed' and 'doors and windows open' were selected for 'Inactive ventilation scenario' and 'Active ventilation scenario', respectively. While for mechanically ventilated classrooms, 'Mechanical system turned off' were selected for 'Inactive ventilation scenario' and 'Mechanical system turned on' for 'Active ventilation scenario'.

In addition, to provide a more detailed understanding of the effects of pandemic ventilation strategies on the acoustic quality of speech in the classrooms, the STI was measured at twelve different positions (a set of typical and representative of the positions in which students usually sit during a lecture, see the figures in Appendix A). The IEC 60268–16:2020 stated that the STI is a method defined to quantify the deterioration of speech intelligibility induced by the transmission channel and is expressed in a value between 0 and 1. The STI was calculated using the indirect method based on the system's impulse response. The modulation transfer function MTF was calculated from the impulse response, using the process known as the 'Schroeder method' [42], which is used to calculate the STI according to the IEC 60268–16:2020 Standard. According to Section 7.7 of this Standard, STI predictions and measurements should always incorporate a level of background noise that is realistic for the application. Therefore, given that the background noise might be different in the two different ventilation operating scenarios, these field measurements were also carried out for the inactive and active ventilation scenarios. Signals were recorded with an M2230 microphone connected to XL2 audio analyser (NTi Audio).

2.3. Acoustic standard requirements in classrooms

The results obtained from the field measurements were compared with the acoustic parameter limits for Portugal and Spain, as well as other international standards (Tables B1 and B2 in Appendix B). In contrast to the RT and background noise, there are only a few guidelines set requirements for STI in classrooms. Table B3 (Appendix B) shows the STI values and their relation to five speech qualification labels (from 'bad' to 'excellent') according to the ISO 9921:2003 [43] for occupants with normal hearing. Other international standards also recommend minimum STI values for classrooms: UNE EN IEC 60268–16:2020 [44] recommends STI $\geq$0.62 for good speech intelligibly in classrooms, and UNI 11532–2:2020 [12] recommends STI $>$0.55 (V $<$ 250 m^3) and STI $>$0.50 (V $>$ 250 m^3). In addition, a STI value above 0.6 is recommended by the UK Department for Education and Skills [11].

3. Results

3.1. RT and C50 in classrooms

The RT results obtained from the field measurements in each of the classrooms are shown in Table B4 (Appendix B). In addition, Fig. 2 shows the mean $RT_{0.5–2kHz}$ values against the classroom's volume. In view of these results, it is remarkable that the $RT_{0.5–2kHz}$ values are higher in all classrooms in both campuses than the RT limits defined in the standards of their respective countries.

Regarding the Azurém Campus classrooms (Portugal), higher RT values were obtained in the auditorium-type classrooms than in the rest of the classrooms, except for A4-1, which presented the lowest RT value for this Campus and was very close to the Portuguese RT_{limit}. In the case of the classrooms on the Fuentenueva Campus (Spain), the RT values were lower compared to those obtained at the Azurem Campus. According to the values defined in the Spanish regulations, the RT limit is applicable to classrooms with volumes of less than 350 m^3. This characteristic is only met by classroom F2-3 (V = 319 m^3). Therefore, since the limit cannot be applied to most of the classrooms on the Fuentenueva Campus due to their size, other standards have been considered. The ANSI/ASA S12.60 [45] recommends that $RT_{0.5–2kHz}$ should not exceed 0.7 s for unoccupied furnished classrooms between 283 m^3 and 566 m^3. Regarding this recommendation, all classrooms exceed this RT limit, with classrooms F1-2 and F1-3 showing the lowest values.

The Spanish and Portuguese regulations do not define requirements for RT at different frequencies. In contrast to the regulations in these countries, the German DIN 18041:2016 and Italian UNI 11532–2:2020 Standards define a tolerance range for the frequency-dependent RT between 125 Hz and 4000 Hz, as shown in Fig. 3, for usage in classrooms. Although these international standards are not mandatory in Spain and Portugal, their recommendations have been considered and the verification of the RT measurement results between 125 Hz and 4 kHz have been performed. Since the range of acceptability is defined for occupied rooms, the sound absorption area per person value for a "person sitting on non-upholstered seating" [13] was applied to the conversion. The optimal RT range (solid black lines) and the adjusted results, as a function of frequency, are shown in Fig. 3.

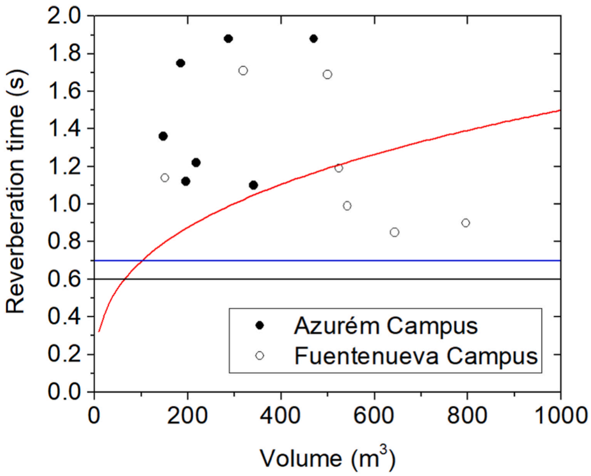

Fig. 2. RT as a function of the classroom volume. Red line indicates the RT limit recommended by Portuguese regulations. Black line indicates the RT limit recommended by Spanish regulations. Blue line indicates the RT limit recommended by ANSI S12.60 regulations. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

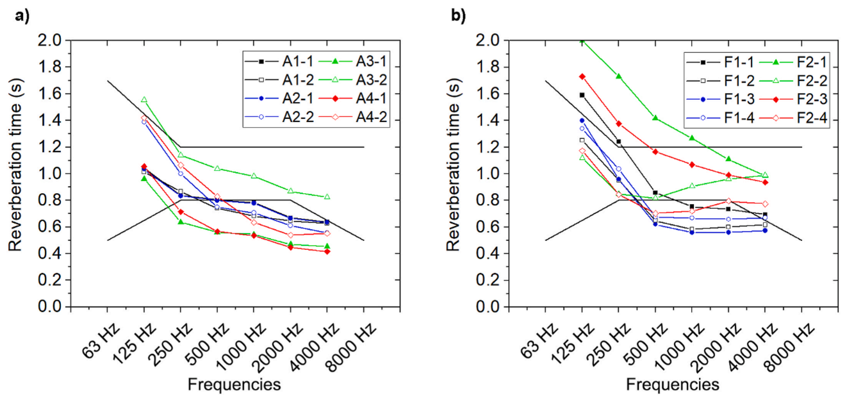

Fig. 3. RT measurement results converted to 100 % occupancy, in accordance with DIN 18041:2016 and UNI 11532–2:2020 Standards. (a) Azurém Campus. (b) Fuentenueva Campus. The solid black lines indicate the tolerance range for frequency-dependent RT according to DIN 18041:2016.

Fig. 3a shows the results obtained from the Azurém Campus. It should be noted that only classroom A3-2 lies in the acceptable RT optimal range (except for the frequency 125 Hz), while the rest of the classrooms present an RT outside the optimal range in more than one octave band frequency. As for the Fuentenueva Campus (Fig. 3b), all classrooms show similar results except for classroom F2-2, which remains within the optimal range for all frequencies. It is worth pointing out that DIN 18041:2016 states that a moderate increase in RT at low frequencies does not compromise acoustic quality, and that in rooms designed for spoken information and speech communication, the RT should be shorter rather than longer [13]. Therefore, if these considerations are taken into account, classrooms F2-1, F2-3 and F1-1 (Fuentenueva Campus) are the only ones that show an RT in some frequency bands above the optimal RT ranges after conversion.

The RT and the distance between the student and the teacher determine the amount of acoustic energy in a direct and reflective sound wave reaching the students [46]. The sound that first reaches the listener is called direct sound, which is followed by some early reflections. The early reflections that reach the listener within 50 ms are integrated with the direct sound and, thus, have a positive effect on speech clarity. The reflections that come later may be perceived as disturbing in speech-based scenarios. The C50 parameter compares the sound energy in early sound reflexes with those that arrive later. A high value is positive for speech clarity.

A summary of the C50 values obtained from the field measurement campaign is shown in Table B5 (Appendix B). As mentioned in the methodology section, Spanish and Portuguese regulations do not contemplate the C50 parameter but other regulations, such as UNI 11367 [47], recommend a value of C50 ≥ 0 dB for spaces intended for speech communication (e.g., classroom). The average values on the Azurem campus ranged from −2.7 to 0.3 dB and on the Fuentenueva campus they ranged from −1.7 dB to 5.3 dB. It is worth noting that on the Azurém Campus, a C50 value above 0 was found in A1-2 and A2-2 while, on the Fuentenueva Campus, a value above 0 was found in all classrooms except F2-1 and F2-3.

A larger deviation from the average value of C50 is observed at higher frequencies than at lower frequencies in the classrooms of the Azurém Campus. At the Fuentenueva Campus, a larger deviation is observed at lower frequencies, especially at 125 Hz. The classrooms in the F1 Building show a very similar C50 distribution at frequencies between these.

3.2. Background noise in classrooms

Table B6 and Fig. 4 show the equivalent background noise levels measured in each classroom in the two different ventilation operating scenarios. The background noise levels measured in the inactive ventilation scenario show that only 50 % of the classrooms met the background noise limit recommended by the WHO (i.e., 35 dBA). However, if the background noise limit recommended by ANSI or DIN 18041:2016 is considered (i.e., 40 dBA), the percentage of classrooms complying with this limit rises to 87.5 %. Only two classrooms in this scenario, both on the Azurém Campus, do not comply with background noise limits recommended in these standards. The measured background noise levels were 47.9 dBA and 42.4 dBA in classrooms A1-2 and A4-1, respectively. With regard to classroom A1-2, this room is located close to an electrical room of the building and has an installation passage through the false ceiling (ventilation system conduits). In classroom A4-1, the inactive ventilation scenario could not be measured because the configuration of the building did not allow the mechanical ventilation system to be switched off.

Regarding the background noise levels measured in the active ventilation scenario, no classroom complied with the recommended limits. In addition, if both ventilation-operating scenarios are compared, different relationships are observed as commented below. Regarding the mechanically ventilated classrooms (Azurém Campus) the largest differences were found between both ventilation op-

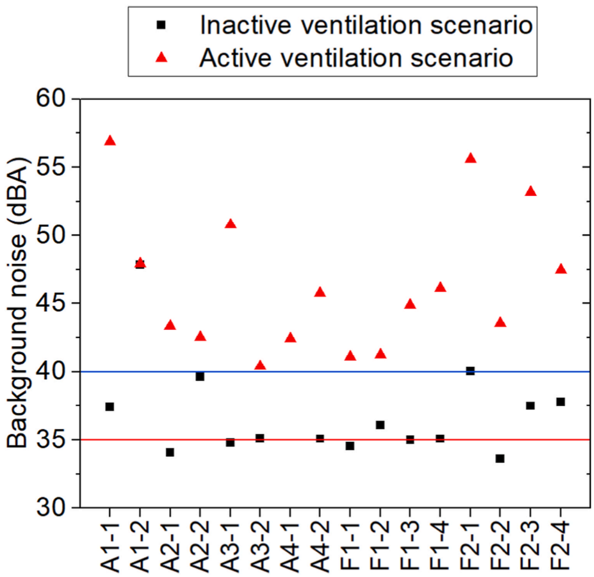

Fig. 4. Background noise measurement for different scenarios. The red line indicates 35 dBA; The blue line indicates 40 dBA. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

erating scenarios in the classrooms A1-1 and A3-1 (with a difference between scenarios of 19.4 dBA and 16.1 dBA), followed by classroom A2-1 (with 9.3 dBA). This is due to the type of air renewal system in these classrooms: they are all mechanically ventilated, and the activation of the ventilation system increases the background noise. In contrast to naturally ventilated classrooms where natural or anthropogenic external noise sources may influence the indoor acoustic conditions, the activation of the mechanical ventilation system in these classrooms will always result in increased background noise, as the ventilation system itself constitutes a noise source.

Regarding the naturally ventilated classrooms in this Campus, the classrooms that showed the greatest difference were A4-2, A3-2 and A2-2, with a difference in levels between the scenarios of 10.7 dBA, 5.3 dBA and 2.9 dBA, respectively. The classroom where the greatest difference in background noise level was found between scenarios was classroom A4-2. This classroom is oriented towards a parking area and pedestrian traffic outside and its doors face a corridor (a passageway for classrooms and offices). The other classrooms are oriented towards green areas of the campus and corridors. By contrast, classroom A1-2 stands out because the difference between scenarios is minimal. Classroom A1-2 is influenced by a passage of installations through the ceiling, which is a source of noise inside de classroom, so opening windows for natural ventilation does not further increase the background noise.

In addition, it is particularly interesting to compare the values obtained in both scenarios according to the ventilation mode of the classrooms (natural or mechanical). In the inactive ventilation scenario, the background noise values measured in naturally ventilated classrooms ranged from 35.1 to 47.9 dBA (mean value = 39.4 dBA), while in mechanically ventilated classrooms ranged from 34.1 to 37.4 dBA (mean value = 35.4 dBA). These values increased in the active ventilation scenario: background noise ranged from 40.4 to 47.9 dBA (mean value = 44.2 dBA) in naturally ventilated classrooms, and from 42.4 to 56.9 dBA (mean value = 48.4 dBA) in mechanically ventilated classrooms. As can be seen, in the inactive scenario, the mean value of background noise is below 40 dBA in all classrooms. However, if the values measured in the active ventilation scenario are compared, the background noise measured in mechanically ventilated classrooms is on average 4.2 dBA higher than that measured in naturally ventilated classrooms.

In the case of the Fuentenueva Campus, the classrooms with the greatest difference were F2-3 and F2-1, with a difference of 15.7 dBA and 15.6 dBA, respectively. These classrooms are oriented towards an avenue that is a principal traffic route in the city of Granada. The next classrooms where the greatest difference between scenarios was found were F1-4, F1-3, F2-2 and F2-4, with 11.1 dBA, 9.9 dBA, 9.9 dBA and 9.7 dBA, respectively. These classrooms are oriented towards green and pedestrian areas outside the campus and towards corridors. Finally, classrooms F1-1 and F1-2 have the smallest difference in background noise levels between scenarios.

Fig. 5 shows the noise criteria (NC) curves used for evaluating background sound in buildings. The results obtained from the Azurém Campus show that, in the inactive ventilation scenario, all the classrooms have an NC-35 curve, except classroom A1-2 which has an NC-45 curve. In the active ventilation scenario, classrooms A4-1, A2-1, A2-2 and A3-2 were below the NC-40 curve, classrooms A3-1 and A1-2 were below the NC50 curve and classrooms A1-1 and 1.50 were below NC-55. ANSI S12.2 2019 recommends that, for classrooms with a volume of less than 566 m^3, as in the case of the Azurém Campus, the background noise should be below the NC-25 curve.

Regarding the background noise levels measured in the Fuentenueva Campus classrooms, in the inactive ventilation scenario, all classrooms presented an NC-35 curve. For the active ventilation scenario, classrooms F1-2, F2-2 and F1-1 presented results below the NC-40 curve, classroom F1-3 and F2-4 levels below the NC-45 curve and for classroom F2-3, F2-1 and F1-4 below the NC-55 curve.

3.3. STI in classrooms

Table B7 and Fig. 6 summarise the STI results measured in the classrooms for the two ventilation operating scenarios. As for the Azurém Campus, in almost all the classrooms the average STI showed fair values (0.45–0.58) in both scenarios, except for the classroom A1-1, which showed poor values for both scenarios (0.41–0.43). In the mechanically ventilated classrooms, the STI worsens slightly in the active ventilation scenario. For the naturally ventilated classrooms, greater differences are observed between the scenarios. In particular, classroom A4-2 shows a difference in the average STI between the two scenarios of almost 0.1. No remarkable differences in the STI values were found between the different positions (front, middle and end) (Fig. 6a), except for classrooms A2-2 (active scenario) and A1-1 (both scenarios), with a variation in STI between the front and end seats of 0.08 and 0.06, respectively. The comparison of STI between classrooms with different ventilation modes (natural or mechanical), in the inactive ventilation scenario, shows that the mean STI measured in naturally ventilated classrooms (0.55) was higher than that measured in mechanically ventilated classrooms (0.47). In the active ventilation scenario, the mean STI value was 0.52 in classrooms with natural ventilation and 0.46 in classrooms with mechanical ventilation, showing a difference of 0.06 between the two types of classrooms.

Regarding the Fuentenueva Campus, the average STI values obtained were good in the classrooms F1-1, F1-2, F1-3 and F1-4 (between 0.60 and 0.62) in the inactive ventilation scenario and acceptable values for the rest of classrooms (ranging between 0.48 and 0.59) in both ventilation operating scenarios. Exceptions to this were classrooms F2-1 and F2-3, in the active ventilation scenario, with a poor average STI (0.39–0.43).

Comparing the STI values obtained between scenarios, classrooms F1-4 and F2-1 had the largest STI differences (around 0.1). In contrast to the Azurém Campus, differences were found between the initial and final seats in Fuentenueva Campus (Fig. 6b), with classrooms F1-1, F1-4, F2-2 and F2-4 showing the largest differences.

4. Discussion

The results obtained from the measurement campaign showed that the RT measured in all classrooms was higher than the optimum level recommended for spaces intended for communication and speech transmission (in Portugal and Spain). However, although the regulations in both countries only consider RT as the parameter for assessing indoor acoustic conditions in classrooms,

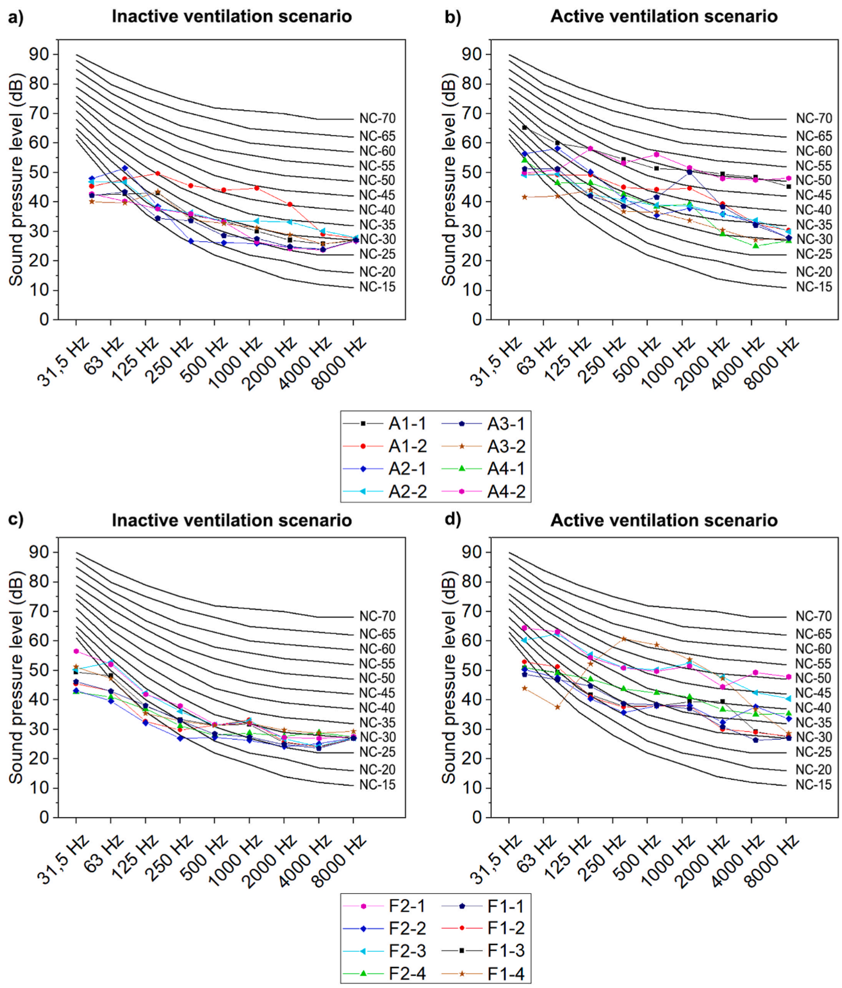

Fig. 5. Noise criteria (NC) curves for each classroom. a) Inactive scenario in Azurém Campus; b) Active scenario in Azurém Campus; c) Inactive scenario in Fuentenueva Campus; d) Active scenario in Fuentenueva Campus.

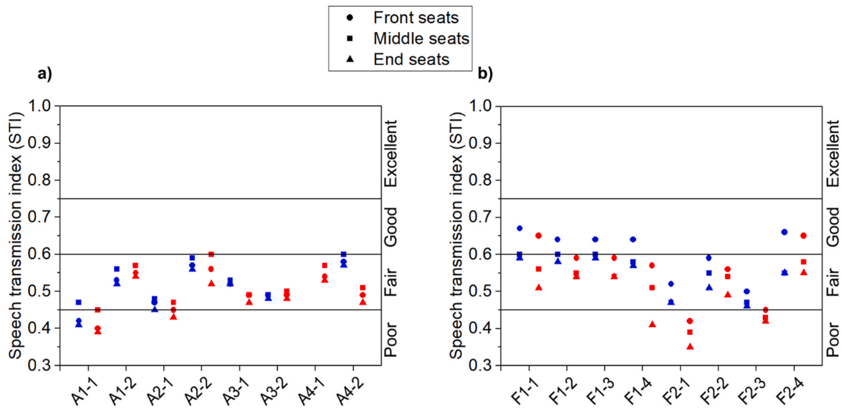

Fig. 6. STI values in front, middle and end seats in the classrooms, in active (red) and inactive (blue) ventilation scenarios. (a) Azurém Campus. (b) Fuentenueva Campus. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

other parameters defined in international standards (such as C50 and STI) have been calculated in this study to gain an overview and to assess the transmission of speech in classrooms.

Fig. 7 (a) shows the relationship between RT and STI for each classroom evaluated in the different scenarios. An inverse relationship is shown, the higher the RT, the lower the STI in all classrooms, with a Pearson coefficient of $p = -0.96$ in the inactive ventila-

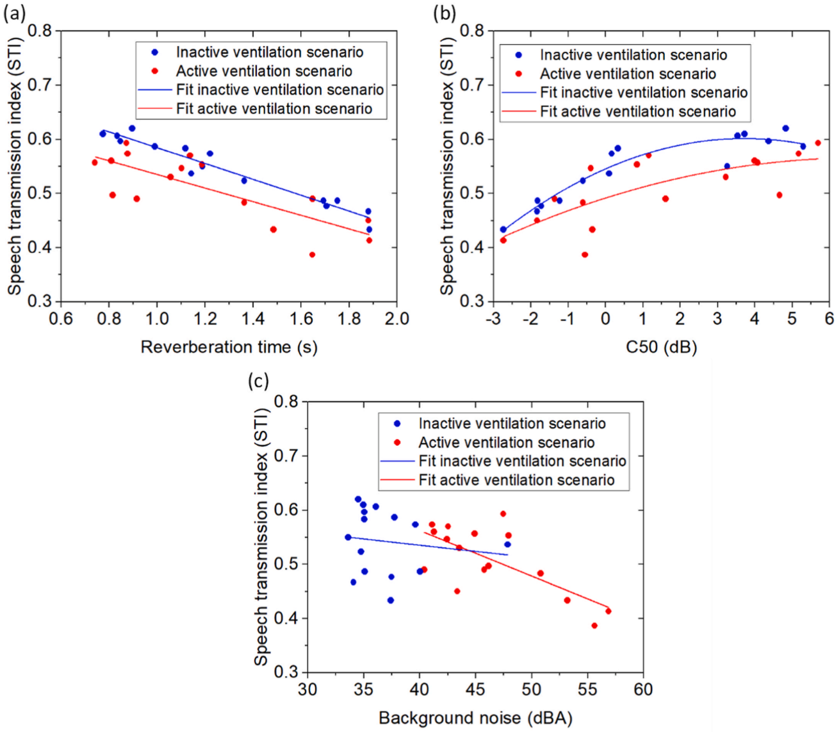

Fig. 7. (a) Relationship between RT and STI. (b) Relationship between C50 and STI in both scenarios. (c) Relationship between BN and STI in both scenarios.

tion scenario and $p = -0.78$ in the active ventilation scenario. As can be seen from these values, there is a higher correlation between the RT and STI in the inactive ventilation scenario. This is due to the fact that the STI parameter calculation is conditioned by other factors in addition to the RT, such as background noise, whose level increases in the active ventilation scenario compared to the inactive ventilation scenario.

Nevertheless, the comparison of the STI and C50 values measured in both ventilation scenarios shows that there is no linear relationship (Fig. 7b). Similar classroom performance is observed in both scenarios, with a positive relationship between C50 and STI: $p = +0.88$ for STI and C50 in the inactive ventilation scenario, and $p = +0.71$ for STI and C50 in the active ventilation scenario. In this regard, it should be noted that the C50 parameter, like RT, does not consider the influence of background noise, unlike the STI. Therefore, this ratio is subject to change in each classroom, depending on the characteristics of the background noise. When the signal-noise-ratio is high enough that the effect of background noise can be negligible, an increase of the C50 parameter can have a positive relationship with the STI value.

Fig. 7c shows the relationship between the background noise and STI. A better relationship between both values in the active ventilation scenario ($p = -0.7$) is obtained than in the inactive ventilation scenario ($p = -0.1$). The better relationship between these two parameters for the active ventilation scenario is due to the fact that the STI parameter has a relationship with the background noise in the classroom. In the inactive scenario, if the signal-noise ratio is high enough, other parameters such as reverberation must be considered for the increase or decrease in the STI value.

These results highlight that there is a relationship between all the evaluated acoustic parameters and that they should be taken into account as a whole during the design of classrooms. Good acoustic performance is a key feature in educational buildings, in order to assist teachers' vocal efforts and to increase students' attention, both relevant aspects in the teaching-learning process. However, many of the educational buildings which are currently in operation were built prior to the publication of the minimum legal acoustic requirements in Spain and Portugal and, therefore, do not meet these requirements. This issue is a weak point in educational buildings, and it has been brought to the fore recently, in the wake of the COVID-19 pandemic. This is due to the fact that strategies implemented to minimise the risk of virus spreading (i.e., increased ventilation rates, minimum interpersonal distance of 1.5 m and the use of face masks) have resulted in altered acoustic conditions in classrooms, not always in a positive sense.

In this sense, all these measures have had a direct impact on indoor acoustic conditions. The improvement of ventilation was achieved through the opening of windows and doors favouring cross ventilation in naturally ventilated classrooms and the increase of air renewal rates, with 100 % air exchange with the outside in mechanically ventilated classrooms. These conditions can lead to an increase in the level of background noise, as seen in the analysis of results in the previous section. One example is the increase in background noise level due to road traffic noise in classrooms F2-1 and F2-3 (Fuentenueva Campus). This fact results in a deterioration of speech intelligibility and worse STI values between the active and inactive ventilation scenarios. Background noise caused by road traffic can be a problem, as has been observed in classroom A4-2 (Azurém Campus) but an increase in other external noises, such as those coming from the parking area or the pedestrian crossing area inside the campus, also produce an increase in background noise levels.

Nevertheless, it should be noted that the opening of windows and doors does not cause the same interference in all classrooms, since the orientation and design of a classroom has a different effect on them. For example, in classrooms F1-2 (Fuentenueva Campus) and A3-2 (Azurém Campus), the opening of windows did not result in a high background noise level (41.3 and 40.4 dBA during this scenario). These levels can be kept close to the recommended ranges of different standards [13,45]. Furthermore, unlike background noise in mechanically ventilated classrooms where the activation of the ventilation system generates continuous noise, the increase in background noise in naturally ventilated classrooms can vary depending on external sound sources (road traffic noise, people talking in neighbouring areas, birds, etc.) Recent research has pointed out the need to evaluate how the indoor soundscape should be designed beyond noise annoyance reduction [48]. Pellegatti et al. [35] assessed the impact of sound stimuli related to natural and mechanical ventilation in classrooms and concluded that, under natural ventilation conditions, outdoor anthropogenic sounds have negative or no effect, while natural sounds from open windows had a positive effect on students' learning and comfort. These results evidenced the importance of the educational building's location and outdoor context since ventilation can sometimes improve the classrooms soundscape.

In addition to this, setting the minimum interpersonal distance at 1.5 m results in a wider distribution of students in the classroom, increasing the distance between the teacher and the students as they occupy the seats furthest away from the speaker. Moreover, increasing the amount of air exchange in the classroom (such as through doors and windows in naturally ventilated classrooms) may lead to an increase in background noise level and consequent worsening of speech intelligibility in these seats. This effect is observed in classrooms such as F2-1, F2-3, F1-4 (Fuentenueva Campus) or A1-1 and A2-2 (Azurém Campus), where the STI_{end} worsens in the ventilated scenario, with respect to the non-ventilated scenario.

Another important factor is the impact of facemask use. The facemask, in combination with an increase in background noise level, also leads to a reduction in signal noise ratio and may result in increased vocal effort for teachers [49]. Choi [49] found that the mean speech intelligibility scores obtained in lower signal noise ratio settings (6 dBA or less) with the presence of visual cues from the speaker's mouth, increased speech intelligibility scores by 11–12 %, compared to scores obtained without visual cues. However, no significant effect of visual cues on speech intelligibility was found in conditions of higher signal-noise-ratio. In this sense, it is especially important to minimise background noise in classrooms, to favour effective verbal communication between teacher and student, especially in pandemic scenarios where the use of facemasks is mandatory in order to minimise airborne virus transmission. As previously noted, students located in the seats farthest away from the teacher may have lower signal-noise-ratio conditions and be more affected by the acoustic conditions. Previous studies [4,5,7] also agree with the importance of acoustic and visual cues in this context. Therefore, in real classroom situations during a pandemic scenario, where masking is required and students may be forced to use seats away from the speaker, additional measures should be taken to help ensure speech intelligibility, even if listeners do not have access to visual cues.

The obtained results evidenced that the provision of natural or mechanical ventilation changed the indoor acoustic conditions of classrooms. However, the interaction between the environmental requirements for acoustic and air environmental quality is a key aspect that is often not covered by research, practice, and standards. Keeping an acceptable level of IAQ in classrooms is necessary to avoid health problems, such as infection by COVID-19 or other viruses. Yet it is also necessary to maintain adequate indoor acoustic conditions so as not to affect the performance of the students. Failure to provide guidance to building users results in the occupants themselves having to decide what actions to take to prioritise acoustic conditions or air quality conditions and may result in a risk to their health and academic performance.

Finally, this study offers experimental findings that can serve as reference for the assessment of indoor acoustic quality in university classrooms. However, some limitations should be noted: in this study, indoor acoustic conditions have been assessed with different ventilation strategies in university classrooms of South West Europe (at the Azurém campus in Portugal and the Fuentenueva campus in Spain). Future studies are needed to extend the evaluation to other European campuses where, in addition to objective evaluations through testing, subjective evaluations would be conducted through occupant questionnaire surveys. Moreover, future studies could include other types of educational buildings (kindergarten, primary and secondary schools, etc) to understand the needs and the acoustic performance of these buildings.

5. Conclusions

Educational buildings are designed to maintain a high density of occupancy for long periods of the day, so maintaining acceptable IAQ is critical to providing a healthy, safe, and comfortable space for teachers and students. The effects of poor IAQ in classrooms have recently been brought into the spotlight due to the global pandemic caused by COVID-19, as they are high risk environments for the transmission of airborne viruses. Ventilation of classrooms, by natural or mechanical means, is essential to minimise the risk of spreading the virus. In this context, the aim of this study was to analyse the impact of ventilation on indoor acoustic conditions in educational buildings under two ventilation operating scenarios: active and inactive, in classrooms of university buildings in Portugal and Spain. The results obtained from the field measurements were used to assess the speech intelligibility for young adult listeners in university classrooms before and after implementing strategies to minimise airborne virus transmission (different ventilation strategies).

The RT was higher than the limits indicated by each country's standards for all unoccupied and furnished classrooms. However, when the simulated RT values for occupied classrooms are considered, a reduction of this parameter is observed. In fact, for full occupancy, the RT values may be more acceptable. In the case of the C50 parameter, better results were found at the Fuentenueva Campus

(−1.7 to 5.3 dB) than at the Azurém Campus (−2.7 to 0.3 dB). The background noise levels measured in most of the classrooms in the inactive ventilation scenario were found to be close to the values recommended by the international standards (35–40 dBA). In contrast, for the active ventilation scenario, a greater difference in results was found between classrooms and campuses. The highest background noise levels were found for classrooms facing roads (F2-1 and F2-3) and for those facing parking and pedestrian areas (1.50). Regarding the speech intelligibility, only 4 classrooms located on the Fuentenueva Campus were found to have mean values equal to or higher than 0.6. On the Azurém Campus, the obtained values ranged between 0.43 and 0.58 in the inactive ventilation scenario and from 0.41 to 0.57 in the active ventilation scenario. At the Fuentenueva Campus, the values ranged from 0.48 to 0.62 and from 0.38 to 0.59 in the inactive and active ventilation scenarios, respectively.

Finally, stronger relationships were observed between the RT and C50 parameters with the STI parameter in the inactive ventilation scenario. While, for the active ventilation scenario, a good relationship between background noise and STI was also observed. The results shown in this study should be taken into account to reformulate the standards and guidelines for the practical application of ventilation measures in educational buildings, to ensure that the spaces are safe and that acoustic conditions do not interfere with students' learning. In this sense, two major findings can be drawn from this research: 1) the need of taking into account the synergies between the environmental requirements for acoustic and air environmental quality should lead to actions to counterbalance acoustic and air quality conditions, by measuring the impact of the ventilation strategies to be applied. The findings of this study contribute especially to the practice as they highlight the need to evaluate indoor acoustic conditions under real ventilation scenarios, a key aspect that is not covered by current regulations in Spain and Portugal. 2) In terms of measurement parameters, it is, therefore, important to take into account parameters other than RT in classroom design when different ventilation scenarios exist. The obtained results show that, although the RT meets the requirements defined in the national regulations, other parameters may compromise the classrooms' acoustic quality. Only few guidelines set requirements for STI and/or background noise in classrooms, and the introduction of these requirements would clearly improve a global assessment in terms of acoustic and air environmental quality.

CRediT authorship contribution statement

María L. de la Hoz-Torres and **Antonio J. Aguilar**: conceptualization, formal analysis, methodology, investigation, performed the experiments, data curation, and writing of the original draft; **Nélson Costa** and **Pedro Arezes**: conceptualization, resources and supervised the manuscript; **Diego P. Ruiz** and **Ma Dolores Martínez-Aires**: conceptualization, resources, project administration, funding acquisition and supervised the manuscript.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Appendix A. Supplementary data

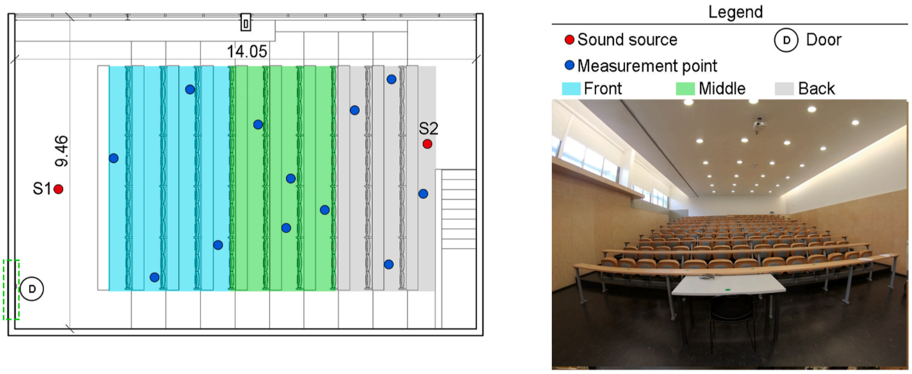

Fig. A1. Dimension and layout configuration of classroom A1-1 (Dimensions in meters).

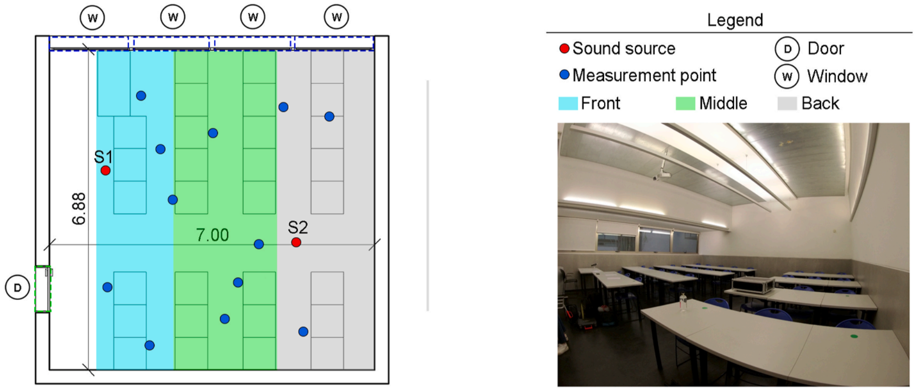

Fig. A2. Dimension and layout configuration of classroom A1-2 (Dimensions in meters).

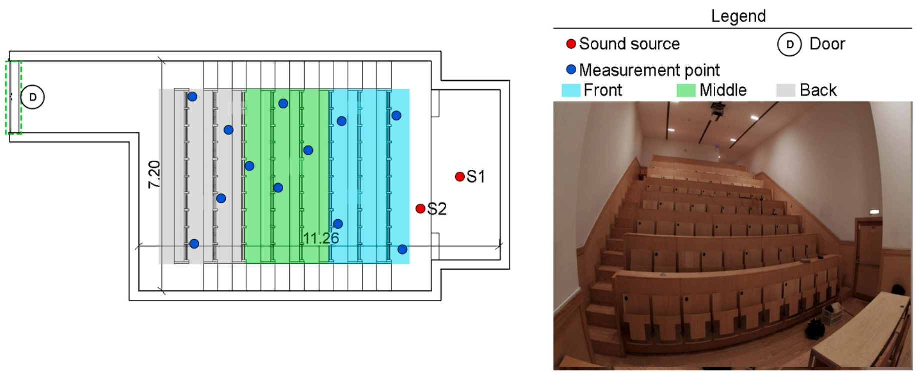

Fig. A3. Dimension and layout configuration of classroom A2-1 (Dimensions in meters).

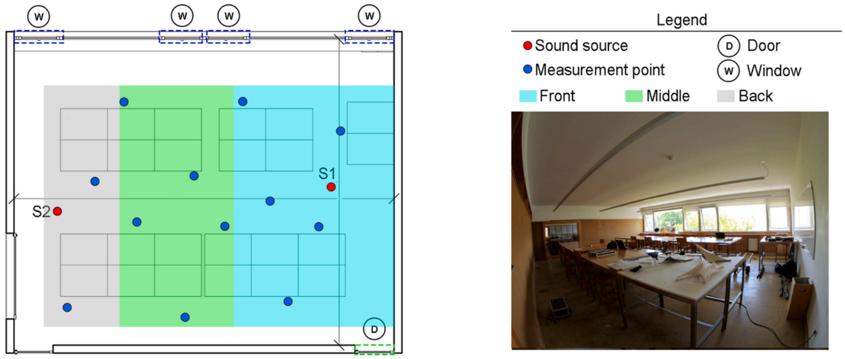

Fig. A4. Dimension and layout configuration of classroom A2-2 (Dimensions in meters).

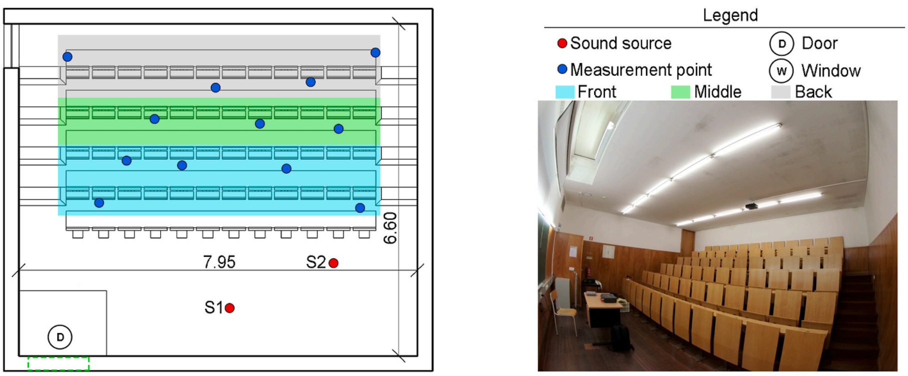

Fig. A5. Dimension and layout configuration of classroom A3-1 (Dimensions in meters).

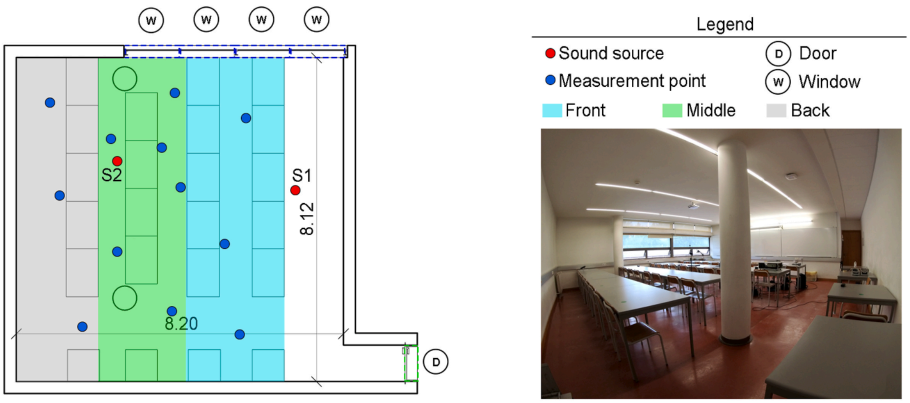

Fig. A6. Dimension and layout configuration of classroom A3-2 (Dimensions in meters).

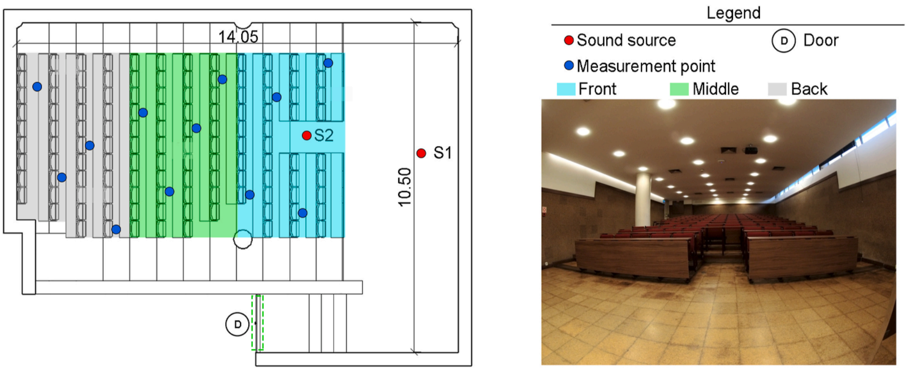

Fig. A7. Dimension and layout configuration of classroom A4-1 (Dimensions in meters).

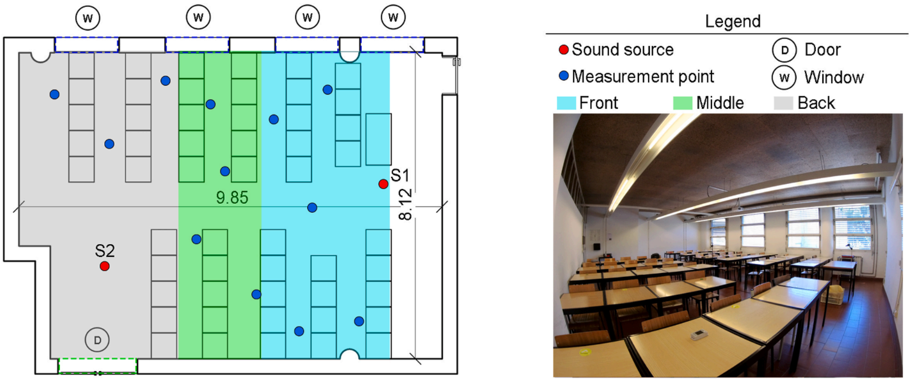

Fig. A8. Dimension and layout configuration of classroom A4-2 (Dimensions in meters).

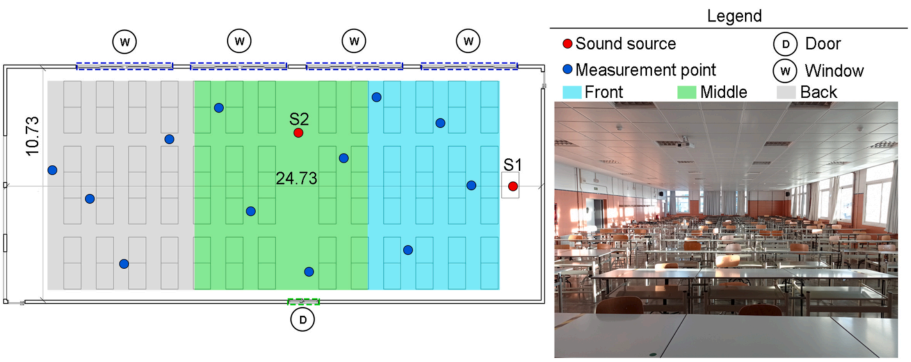

Fig. A9. Dimension and layout configuration of classroom F1-1 (Dimensions in meters).

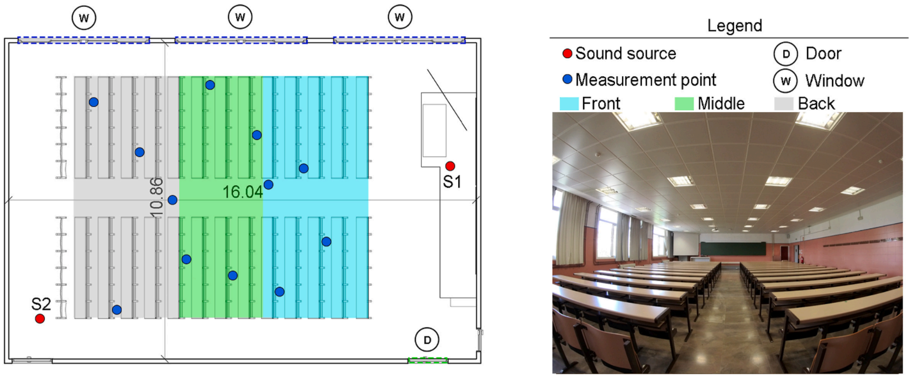

Fig. A10. Dimension and layout configuration of classroom F1-2 (Dimensions in meters).

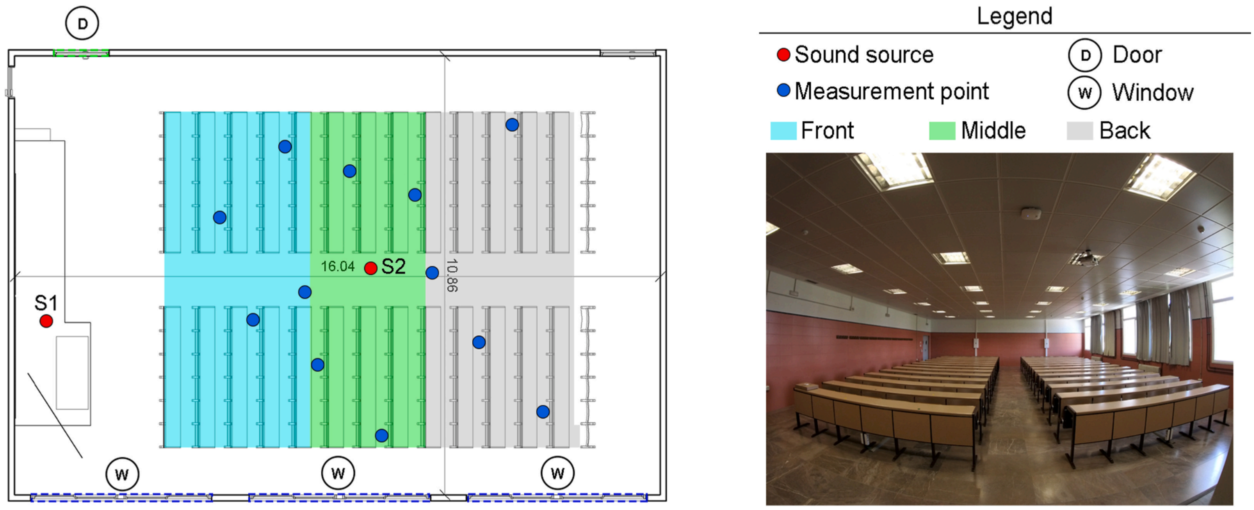

Fig. A11. Dimension and layout configuration of classroom F1-3 (Dimensions in meters).

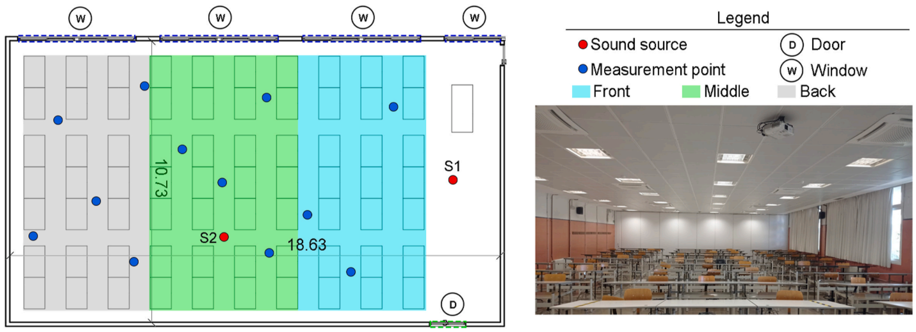

Fig. A12. Dimension and layout configuration of classroom F1-4 (Dimensions in meters).

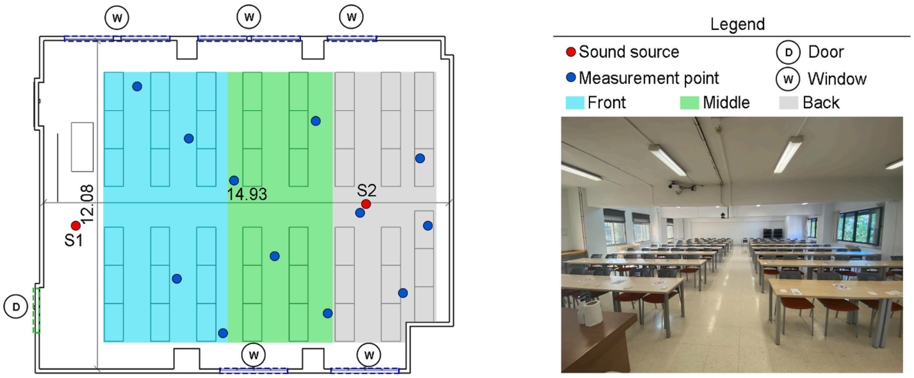

Fig. A13. Dimension and layout configuration of classroom F2-1 (Dimensions in meters).

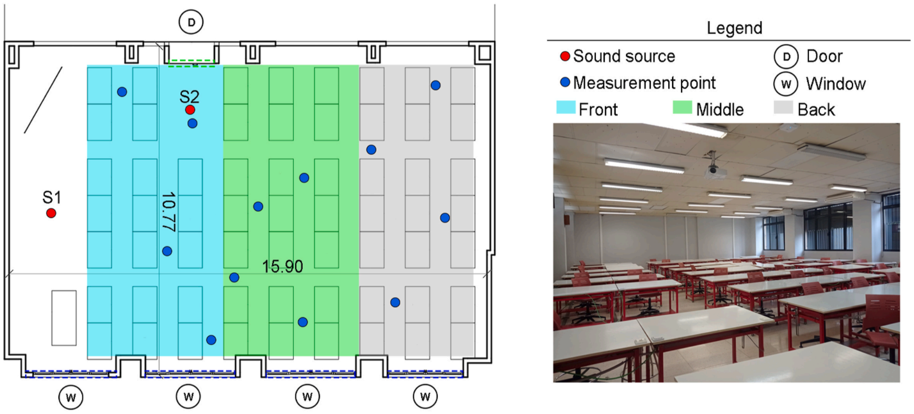

Fig. A14. Dimension and layout configuration of classroom F2-2 (Dimensions in meters).

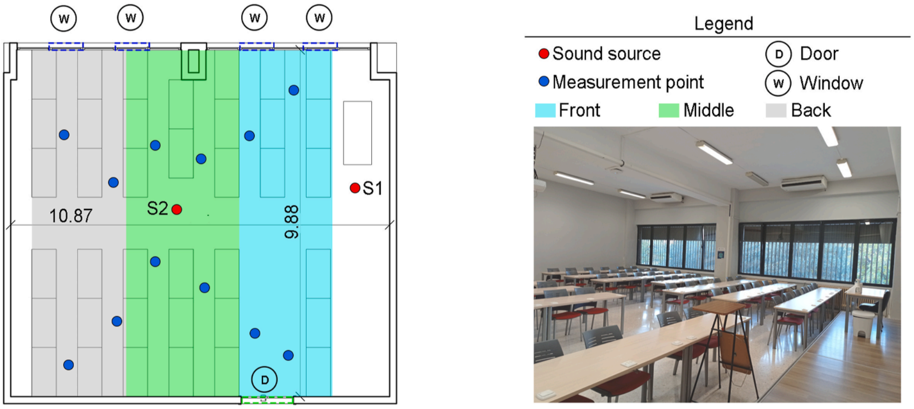

Fig. A15. Dimension and layout configuration of classroom F2-3 (Dimensions in meters).

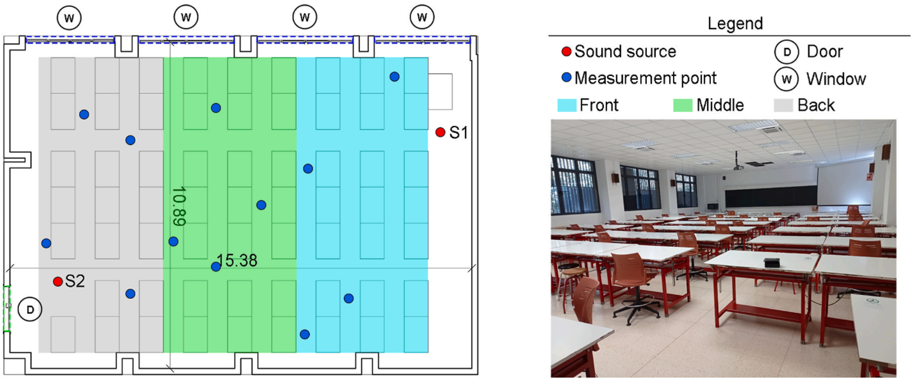

Fig. A16. Dimension and layout configuration of classroom F2-4 (Dimensions in meters).

Appendix B

Table B1
RT and C50 limits.

Standard	RT limits (s)	C50 (dB)	Type of classroom
Portuguese legal acoustic requirements [37]	$RT_{500Hz-2KHz} = 0.15V^{\frac{1}{3}}$	–	Furnished and unoccupied classrooms
Spanish legal acoustic requirements [36]	$RT_{500Hz-2KHz} \leq 0.7s$	–	Unfurnished and unoccupied classrooms (V < 350 m^3)
	$RT_{500Hz-2KHz} \leq 0.5s$	–	Furnished and unoccupied classrooms (V < 350 m^3)
ANSI Standard S12.60 [45]	$RT_{500Hz-2KHz} \leq 0.6s$	–	Furnished and unoccupied classrooms (V < 283 m^3)
	$RT_{500Hz-2KHz} \leq 0.7s$	–	Furnished and unoccupied classrooms (283 m^3 ≤ V < 566 m^3)
Building Bulletin BB93 [11]	$RT_{500Hz-2KHz} < 0.6$ s	–	Primary school classrooms, class bases, general teaching areas and small group rooms
	$RT_{500Hz-2KHz} < 0.8$ s	–	Secondary school classrooms, general teaching areas, seminar rooms, tutorial rooms, language laboratories
	$RT_{500Hz-2KHz} < 0.8$ s	–	Small lecture room (<50 people)
	$RT_{500Hz-2KHz} < 1.0$ s	–	Large lecture room (>50 people)
	$RT_{125Hz-4KHz} < 0.4$ s	–	Classrooms designed specifically for use by hearing impaired pupils.
UNI 11532–2:2020 [12]	$RT = \left(0.37 \ \lg \frac{V}{m^3} - 0.14\right) s$	C50 ≥ 2 dB (V < 250 m^3)	Classroom (High speech intelligibility) [Category A.2] 50 m^3 ≤ V < 5000 m^3
	$RT = \left(0.32 \ \lg \frac{V}{m^3} - 0.17\right) s$		A2 environments for hearing-impaired or non-native speakers or special classrooms and communication with simultaneous presence of several speakers in the classroom. 30 m^3 ≤ V < 5000 m^3
	$RT = \left(0.26 \ \lg \frac{V}{m^3} - 0.14\right) s$		More than one person speaking in the room (as Category A3.2) and intended for people with special needs (special classroom). 30 m^3 ≤ V < 500 m^3
UNI 11367 [47]	$RT_{500Hz-1kHz} = (0.32 \ \lg(V + 0.03)\ s$	C50 ≥ 0 dB	Spaces intended for speech communication
DIN 18041:2016–03 [13]	$RT = \left(0.32 \ \lg \frac{V}{m^3} - 0.17\right) s$	–	"Education/communication" 30 m^3 ≤ V < 5000 m^3
	$RT = \left(0.26 \ \lg \frac{V}{m^3} - 0.14\right)$	–	"Education/communication (inclusive)" (Type A4). 30 m^3 ≤ V < 5000 m^3
WHO [14]	RT < 0.6 s	–	RT < 0.6 s is desirable for adequate speech intelligibility even in a quiet environment.

Table B2
Background noise limits

Standard	Upper limit for the indoor ambient noise level (dBA)	Type of classroom
ANSI S12.60 [45]	35 dBA	V < 283 m^3
	35 dBA	283 m^3 ≤ V < 566 m^3
	40 dBA	V > 566 m^3
ANSI S12.2 [50]	35 dBA (Noise Criteria NC-25)	V ≤ 566 m^3
	40 dBA (Noise Criteria NC-30)	V > 566 m^3

(*continued on next page*)

Table B2 (*continued*)

Standard	Upper limit for the indoor ambient noise level (dBA)	Type of classroom
BB93 [11]	35 dBA	Primary school classrooms, class bases, general teaching areas and small group rooms
	35 dBA	0.8 s Secondary school classrooms, general teaching areas, seminar rooms, tutorial rooms, language laboratories
	35 dBA	Small lecture room (<50 people)
	35 dBA	Large lecture room (>50 people)
	30 dBA	Classrooms designed specifically for use by hearing impaired pupils
DIN 18041:2016–03 [13]	Between 30 dB and 40 dB	Classroom with speech intelligibility without interference
UNI 11532–2:2020 [12]	34 dBA	Classroom <250 m^3
	38 dBA	Classroom ≥250 m^3
WHO [14]	35 dBA	Classrooms

Table B3
Relation between speech intelligibility qualification labels and STI values [43].

STI values	<0.30	0.30–0.45	0.45–0.60	0.60–0.75	0.75–1.00
Speech intelligibility rating	Bad	Poor	Fair	Good	Excellent

Table B4
RT results of each unoccupied furnished classroom.

Campus	Classroom	Frequency (Hz)								
		125 k	250 k	500 k	1 k	2 k	4 k	8 k	$RT_{0.5-1kHz}$	$T_{0.5-2kHz}$
Azurém	A1-1	1.43	1.48	1.81	2.00	1.84	1.61	1.26	1.91	1.88
	A1-2	1.25	1.28	1.17	1.10	1.16	1.10	0.93	1.14	1.14
	A2-1	1.42	1.48	1.81	2.00	1.84	1.62	1.25	1.90	1.88
	A2-2	1.95	1.70	1.27	1.25	1.13	0.96	0.75	1.26	1.22
	A3-1	1.52	1.23	1.30	1.43	1.36	1.23	0.99	1.36	1.36
	A3-2	2.03	1.75	1.79	1.78	1.68	1.52	1.17	1.78	1.75
	A4-1	1.63	1.37	1.15	1.16	0.99	0.85	0.68	1.16	1.10
	A4-2	1.97	1.83	1.46	1.01	0.88	0.92	0.70	1.24	1.12
Fuentenueva	F1-1	1.74	1.43	0.98	0.86	0.86	0.80	0.63	0.92	0.90
	F1-2	1.52	1.30	0.86	0.77	0.87	0.91	0.73	0.81	0.83
	F1-3	1.74	1.31	0.81	0.73	0.79	0.81	0.66	0.77	0.77
	F1-4	1.55	1.31	0.83	0.84	0.87	0.89	0.76	0.83	0.85
	F2-1	2.34	2.24	1.88	1.69	1.51	1.29	0.83	1.78	1.69
	F2-2	1.24	0.99	1.00	1.18	1.38	1.43	1.10	1.10	1.19
	F2-3	2.14	1.99	1.79	1.67	1.67	1.52	1.15	1.73	1.71
	F2-4	1.34	1.03	0.88	0.94	1.16	1.11	0.89	0.91	0.99

Table B5
C50 values obtained for each classroom.

Campus	Classroom	Frequency								
		125 k	250 k	500 k	1 k	2 k	4 k	8 k	$C50_{(500\text{-}1k)}$	$C50_{(500\text{-}2k)}$
Azurem	A1-1	0.7	−1.6	−2.1	−3.4	−3.1	−2.6	−0.2	−2.7	−2.8
	A1-2	0.4	1.0	0.2	0.0	−0.3	−0.2	1.7	0.1	0.0
	A2-1	0.7	−1.6	−2.1	−3.4	−3.1	−2.6	−0.2	−1.8	−2.8
	A2-2	−3.4	−1.7	−0.2	0.5	1.2	2.3	5.2	0.2	0.5
	A3-1	−0.5	0.7	0.0	−1.3	−1.4	−0.7	1.4	−0.6	−0.9
	A3-2	−2.5	−1.8	−1.8	−1.9	−1.7	−1.1	1.5	−1.8	−1.8
	A4-1	−2.2	−0.9	−0.1	−0.7	0.5	1.2	3.4	−0.4	−0.1
	A4-2	−2.7	−3.0	−1.7	1.7	2.2	2.2	4.8	0.3	1.1
Fuentenueva	F1-1	−0.5	2.0	4.3	5.3	4.6	5.3	7.2	4.8	4.8
	F1-2	1.8	3.7	3.4	3.6	4.2	4.2	5.6	3.5	3.8
	F1-3	−0.3	2.4	3.5	3.9	4.7	4.0	6.2	3.7	4.1
	F1-4	−1.4	2.0	4.9	3.8	4.1	4.0	5.4	4.4	4.3
	F2-1	−2.3	−1.5	−1.6	−0.9	−0.9	−0.2	3.0	−1.2	−1.1
	F2-2	0.8	3.4	4.6	1.2	−1.0	−1.8	0.3	3.3	2.2
	F2-3	−2.1	−2.4	−2.1	−1.4	−1.6	−1.4	1.1	−1.7	−1.7
	F2-4	3.1	5.0	5.8	4.7	4.8	4.9	5.4	5.3	5.1

Table B6
Equivalent background noise (L_{Aeq}) (dBA).

Campus	Classroom	Inactive ventilation scenario	Active ventilation scenario	Difference between scenarios
Azurém	A1-1*	37.4	56.9	19.4
	A1-2	47.8	47.9	0.1
	A2-1*	34.1	43.4	9.3
	A2-2	39.6	42.5	2.9
	A3-1*	34.8	50.8	16.0
	A3-2	35.1	40.4	5.3
	A4-1*	–	42.4	–
	A4-2	35.1	45.8	10.7
Fuentenueva	F1-1	40.0	55.6	15.6
	F1-2	33.6	43.5	9.9
	F1-3	37.5	53.2	15.7
	F1-4	37.8	47.5	9.7
	F2-1	34.5	41.1	6.6
	F2-2	35.1	46.1	11.1
	F2-3	35.0	44.9	9.9
	F2-4	36.1	41.3	5.2

* Classroom mechanically ventilated.

Table B7
STI values of classroom measurements

Campus	Classroom	Ventilation	Seat in classroom			Mean
			Front	Middle	End	
Azurem	A1-1*	Inactive	0.47	0.42	0.41	0.43
		Active	0.45	0.40	0.39	0.41
	A1-2	Inactive	0.56	0.53	0.52	0.54
		Active	0.57	0.55	0.54	0.55
	A2-1*	Inactive	0.48	0.47	0.45	0.47
		Active	0.47	0.45	0.43	0.45
	A2-2	Inactive	0.59	0.57	0.56	0.57
		Active	0.60	0.56	0.52	0.56
	A3-1*	Inactive	0.53	0.52	0.52	0.52
		Active	0.49	0.49	0.47	0.48
	A3-2	Inactive	0.49	0.49	0.48	0.49
		Active	0.50	0.49	0.48	0.49
	A4-1*	Inactive	–	–	–	–
		Active	0.57	0.54	0.53	0.55
	A4-2	Inactive	0.60	0.58	0.57	0.58
		Active	0.51	0.49	0.47	0.49
Fuentenueva	F1-1	Inactive	0.67	0.60	0.59	0.62
		Active	0.65	0.56	0.51	0.57
	F1-2	Inactive	0.64	0.60	0.58	0.61
		Active	0.59	0.55	0.54	0.56
	F1-3	Inactive	0.64	0.60	0.59	0.61
		Active	0.59	0.54	0.54	0.56
	F1-4	Inactive	0.64	0.58	0.57	0.60
		Active	0.57	0.51	0.41	0.50
	F2-1	Inactive	0.52	0.47	0.47	0.49
		Active	0.42	0.39	0.35	0.39
	F2-2	Inactive	0.59	0.55	0.51	0.55
		Active	0.56	0.54	0.49	0.53
	F2-3	Inactive	0.50	0.47	0.46	0.48
		Active	0.45	0.43	0.42	0.43
	F2-4	Inactive	0.66	0.55	0.55	0.59
		Active	0.65	0.58	0.55	0.59

* Classrooms mechanically ventilated.

References

[1] P. Ricciardi, C. Buratti, Environmental quality of university classrooms: subjective and objective evaluation of the thermal, acoustic, and lighting comfort conditions, Build. Environ. 127 (2018) 23–36, https://doi.org/10.1016/j.buildenv.2017.10.030.

[2] M. Hodgson, Rating, ranking, and understanding acoustical quality in university classrooms, J. Acoust. Soc. Am. 112 (2) (2002) 568–575, https://doi.org/

10.1121/1.1490363.
[3] G.E. Puglisi, A. Prato, T. Sacco, A. Astolfi, Influence of classroom acoustics on the reading speed: a case study on Italian second-graders, J. Acoust. Soc. Am. 144 (2) (2018) EL144–EL149, https://doi.org/10.1121/1.5051050.
[4] N. Prodi, C. Visentin, Listening efficiency during lessons under various types of noise, J. Acoust. Soc. Am. 138 (4) (2015) 2438–2448, https://doi.org/10.1121/1.4932053.
[5] A. Kjellberg, R. Ljung, D. Hallman, Recall of words heard in noise, J. Appl. Res. Mem. Cogn. 22 (8) (2008) 1088–1098, https://doi.org/10.1002/acp.1422.
[6] R.B. Chowdhury, R. Dey, M.S. Alam, P. Chakraborty, Extent of traffic induced noise in the noise sensitive institutions of Chittagong city, Bangladesh, Noise Vib 41 (1) (2010) 28–36, https://doi.org/10.1260/0957-4565.41.1.2.
[7] J. Kristiansen, R. Persson, S.P. Lund, H. Shibuya, P.M. Nielsen, Effects of classroom acoustics and self-reported noise exposure on teachers' well-being, Environ. Behav. 45 (2) (2013) 283–300, https://doi.org/10.1177/0013916511429700.
[8] K. Mealings, Classroom acoustics and cognition: a review of the effects of noise and reverberation on primary school children's attention and memory, Build, Acoust 29 (3) (2022) 401–431, https://doi.org/10.1177/1351010X221104892.
[9] Y. Fang, X. Luo, A review of research on the impact of the classroom physical environment on schoolchildren's health, J. Build. Eng. (2022) 105430, https://doi.org/10.1016/j.jobe.2022.105430.
[10] H. Wu, X. Sun, Y. Wu, Investigation of the relationships between thermal, acoustic, illuminous environments and human perceptions, J. Build. Eng. 32 (2020) 101839, https://doi.org/10.1016/j.jobe.2020.101839.
[11] BB93: Acoustic Design of Schools—Performance Standards, Department for Education. Education Funding Agency, Manchester, England, 2015 2015. Available online: https://www.gov.uk/government/publications/bb93-acoustic-design-of-schools-performance-standards. (Accessed 10 June 2023).
[12] UNI 11532-2, Caratteristiche acustiche interne di ambienti confinati - Metodi di progettazione e tecniche di valutazione - Parte 2: Settore scolastico, 2020.
[13] DIN 18041, Acoustic Quality in Rooms - Specifications and Instructions for the Room Acoustic Design, 2016-03.
[14] B. Berglund, T. Lindvall, D.H. Schwela, W.H. Organization, Guidelines for Community Noise, 1999. https://apps.who.int/iris/handle/10665/66217.
[15] D. Pelegrín-García, J. Brunskog, B. Rasmussen, Speaker-oriented classroom acoustics design guidelines in the context of current regulations in European countries, Acta Acustica 100 (6) (2014) 1073–1089, https://doi.org/10.3813/AAA.918787.
[16] G. Minelli, G.E. Puglisi, A. Astolfi, Acoustical parameters for learning in classroom: a review, Build. Environ. 208 (2022) 108582, https://doi.org/10.1016/j.buildenv.2021.108582.
[17] P. Pinho, M. Pinto, R.M. Almeida, S. Lopes, L. Lemos, Aspects concerning the acoustical performance of school buildings in Portugal, Appl. Acoust. 106 (2016) 129–134, https://doi.org/10.1016/j.apacoust.2016.01.002.
[18] V.G. Escobar, J.B. Morillas, Analysis of intelligibility and reverberation time recommendations in educational rooms, Appl. Acoust. 96 (2015) 1–10, https://doi.org/10.1016/j.apacoust.2015.03.001.
[19] H. Tang, Y. Ding, B.C. Singer, Post-occupancy evaluation of indoor environmental quality in ten nonresidential buildings in Chongqing, China, J. Build. Eng. 32 (2020) 101649, https://doi.org/10.1016/j.jobe.2020.101649.
[20] A.-M. Sadick, M.H. Issa, Assessing physical conditions of indoor space enclosing elements in schools in relation to their indoor environmental quality, J. Build. Eng. 20 (2018) 520–530, https://doi.org/10.1016/j.jobe.2018.08.018.
[21] M. Hodgson, Experimental investigation of the acoustical characteristics of university classrooms, J. Acoust. Soc. Am. 106 (4) (1999) 1810–1819, https://doi.org/10.1121/1.427931.
[22] Y.-J. Choi, Effect of occupancy on acoustical conditions in university classrooms, Appl. Acoust. 114 (2016) 36–43, https://doi.org/10.1016/j.apacoust.2016.07.010.
[23] Y.-J. Choi, Evaluation of acoustical conditions for speech communication in active university classrooms, Appl. Acoust. 159 (2020) 107089, https://doi.org/10.1016/j.apacoust.2019.107089.
[24] B. Seep, R. Glosemeyer, E. Hulce, M. Linn, P. Aytar, Classroom Acoustics: A Resource for Creating Environments with Desirable Listening Conditions, 2000. https://eric.ed.gov/?id=ED451697.
[25] J. Bradley, S.R. Bistafa, Relating speech intelligibility to useful-to-detrimental sound ratios (L), J. Acoust. Soc. Am. 112 (1) (2002) 27–29, https://doi.org/10.1121/1.1481508.
[26] J. Bradley, R.D. Reich, S. Norcross, On the combined effects of signal-to-noise ratio and room acoustics on speech intelligibility, J. Acoust. Soc. Am. 106 (4) (1999) 1820–1828, https://doi.org/10.1121/1.427932.
[27] P. Wargocki, D.P. Wyon, The effects of outdoor air supply rate and supply air filter condition in classrooms on the performance of schoolwork by children (RP-1257), HVAC R Res. 13 (2) (2007) 165–191 10789669.2007.10390950.
[28] P. Wargocki, D.P. Wyon, Thermal and IAQ Effects on School and Office Work, Creating the Productive Workplace, Routledge, 2017, pp. 222–240.
[29] A.J. Aguilar, L. María, N. Costa, P. Arezes, M.D. Martínez-Aires, D.P. Ruiz, Assessment of ventilation rates inside educational buildings in Southwestern Europe: analysis of implemented strategic measures, J. Build. Eng. 51 (2022) 104204, https://doi.org/10.1016/j.jobe.2022.104204.
[30] Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA). COVID19 Guidance. How to operate HVAC and other building service systems to prevent the spread of the coronavirus (SARS-CoV-2) disease (COVID-19) in workplaces version 4.1. Available online: https://www.rehva.eu/fileadmin/user_upload/REHVA_COVID-19_guidance_document_V4.1_15042021.pdf. (Accessed on 10 June 2023)...
[31] American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). Epidemic task force Schools and university update 5-14-2021. Available online: https://www.ashrae.org/file%20library/technical%20resources/covid-19/ashrae-reopening-schools-and-universities-c19-guidance.pdf (Accessed on 10 June 2023)..
[32] C. Ren, S.-J. Cao, F. Haghighat, A practical approach for preventing dispersion of infection disease in naturally ventilated room, J. Build. Eng. 48 (2022) 103921, https://doi.org/10.1016/j.jobe.2021.103921.
[33] World Human Organization (WHO). Infection Prevention and Control during Health Care when COVID-19 Is Suspected: Interim Guidance, 19 March 2020. World Health Organization. Available online: https://www.who.int/publications/i/item/10665-331495 (Accessed on 10 June 2023)..
[34] P.M. Bluyssen, Towards an integrated analysis of the indoor environmental factors and its effects on occupants, Intell. Build. Int. 12 (3) (2020) 199–207, https://doi.org/10.1080/17508975.2019.1599318.
[35] M. Pellegatti, S. Torresin, C. Visentin, F. Babich, N. Prodi, Indoor soundscape, speech perception, and cognition in classrooms: a systematic review on the effects of ventilation-related sounds on students, Build. Environ. (2023) 110194, https://doi.org/10.1016/j.buildenv.2023.110194.
[36] Technical Building Code, Basic Document DB-HR Protection against the Noise, Ministerio de Fomento, 2009 Available online: https://www.codigotecnico.org/DocumentosCTE/ProteccionRuido.html. (Accessed 10 June 2023).
[37] Decreto-Lei n.° 96/2008. Diário da República n.° 110/2008, Série I de 2008-06-09. Ministério do Ambiente, do Ordenamento do Território e do Desenvolvimento Regional. Available online: https://dre.pt/home/-/dre/449682/details/maximized (Accessed on 10 June 2023)..
[38] S. Torresin, G. Pernigotto, F. Cappelletti, A. Gasparella, Combined effects of environmental factors on human perception and objective performance: a review of experimental laboratory works, Indoor Air 28 (4) (2018) 525–538, https://doi.org/10.1111/ina.12457.
[39] C. Visentin, N. Prodi, F. Cappelletti, S. Torresin, A. Gasparella, Using listening effort assessment in the acoustical design of rooms for speech, Build. Environ. 136 (2018) 38–53, https://doi.org/10.1016/j.buildenv.2018.03.020.
[40] World Human Organization (WHO), Europe, School Environment: Policies and current status (2015) 82 Available online: https://www.euro.who.int/_data/assets/pdf_file/0009/276624/School-environment-Policies-current-status-en.pdf. (Accessed 10 June 2023).
[41] ISO 3382-2, Acoustics — Measurement of Room Acoustic Parameters — Part 2: Reverberation Time in Ordinary Rooms, 2008.
[42] M.R. Schroeder, Modulation transfer functions: definition and measurement, Acta Acustica united Acustica 49 (3) (1981) 179–182.
[43] ISO 9921, Ergonomics — Assessment of Speech Communication, 2003.
[44] UNE-EN IEC 60268-16, Sound system equipment - Part 16: Objective rating of speech intelligibility by speech transmission index (Endorsed by Asociación Española de Normalización in January of 2021, 2020.
[45] ANSI/ASA S12.60, Part 1 American National Standard Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools, Part 1: Permanent

Schools, 2010.
[46] S. Ryan, Can your students hear you, Florida Journal of Health, Physical Education, Recreation, Dance, & Driver Education 47 (1) (2009) 26–27.
[47] UNI 11367, Acustica in edilizia - Classificazione acustica delle unità immobiliari - Procedura di valutazione e verifica in opera, 2023.
[48] S. Torresin, R. Albatici, F. Aletta, F. Babich, J. Kang, Assessment methods and factors determining positive indoor soundscapes in residential buildings: a systematic review, Sustainability 11 (19) (2019) 5290, https://doi.org/10.3390/su11195290.
[49] Y.-J. Choi, Effects of visual information on the face masked speech communication in Covid-secure classrooms, Appl. Acoust. 206 (2023) 109310, https://doi.org/10.1016/j.apacoust.2023.109310.
[50] ANSI/ASA S12.2, Criteria for Evaluating Room Noise, 2019.