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Technical Note

Statistical comparison of reverberation times measured by the integrated impulse response and interrupted noise methods, computationally simulated with ODEON software, and calculated by Sabine, Eyring and Arau-Puchades' formulas

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ABSTRACT

This paper evaluates several procedures to determine the reverberation time, RT, in a classroom. These procedures are: (1) measurement by the integrated impulse response method, (2) measurement by the interrupted noise method, (3) computer simulation using ODEON Version 9.0 software, and (4) calculations using the Sabine, Eyring, and Arau-Puchades formulas. The resulting data are analyzed statistically to verify their similarity. No statistical difference was found between the values obtained by the two measuring methods. The computer simulation produced accurate data. The best formula for calculating RT in the classroom in question is Eyring's formula.

1. Introduction

The literature on room acoustics indicates that researchers are not entirely satisfied with existing formulas for calculating reverberation time RT [1]. Sabine's formula assumes that sound energy diffuses equally through a room (homogeneously and isotropically). In fact, however, this condition is rarely met since the large areas in a room are characterized by diverse absorptions [1].

Eyring [2] states that Sabine's formula is invalid when there is considerable absorption in a room. In his article, he points out that Sabine's formula should be used for "live" rooms and claims that reverberation time depends on the shape of the room [2]. Eyring [2] presents a revised theory and derives a formula of the RT equation which is more general than Sabine's formula. Eyring's formula is based on the medium of unhindered propagation between reflections characterized by a diffuse sound field [1].

Another formula for calculating reverberation is that of Arau-Puchades, which should be used in rooms with asymmetric distribution of absorption. Arau-Puchades assumes that reverberation decay is a hyperbolic process. This decay is the superposition of three contributions: early decay, first and second linear portion of the decay, and third linear portion of the decay [1]. For rectangular rooms, Arau-Puchades defines an absorption coefficient based on Eyring's model for each parallel surface and each direction of the space [3].

Bistafa and Bradley [4] found that in spaces where the total sound absorption is high, prediction of the reverberation time using Sabine's formula results in longer values than those found by means of Eyring's formula, but the difference diminishes as the total sound absorption decreases. In studies conducted by these same authors, the reverberation times calculated in a classroom with a volume of 153 m^3 by means of Sabine and Eyring's formulas were practically the same. On the other hand, Arau-Puchades' formula resulted in longer reverberation times. A study by Dance and Shield [5] found that the precision of Eyring and Sabine's formulas is the same when suitable absorption coefficients are used.

Eyring and Sabine's formulas proved to be a reasonable choice for calculating the reverberation time in a classroom [4]. The results obtained by Bistafa and Bradley [4] did not justify the use of more complex analytical expressions for the prediction of reverberation time, since generally they did not yield a more accurate result. Moreover, according to these authors, a large variety of results can be obtained when the user has a free choice of coefficients of absorption.

These formulas for determining reverberation time are only some of the ones that exist for this calculation. Other formulas are those of Fitzroy, Tohyama and Suzuki, Kuttruff, Pujolle, Nilsson, and others [1,3]. Thus, there are many doubts about which formula

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should be used. These formulas produce better results according to the characteristics of the room in question.

The importance of evaluating reverberation time in classrooms lies in the fact that reverberating environments affect concentration ability and speech intelligibility, forcing teachers to speak louder [6], considering that this will contribute for the understanding of the teachefs speech by the students. However, speaking louder does not improve intelligibility inexcessively reverberant conditions.

In the present work, in addition to calculating reverberation time by means of several formulas and computer simulation of this parameter, *in situ* measurements were taken using two methods, the interrupted noise method and the integrated impulse response method. The main objective of this work was to evaluate different procedures for determining reverberation time in a classroom of approximately 250 m^3.

2. Materials and methods

Taking a classroom as the object of study, the following procedures were carried out to determine the RT:

(1) Measurement of RT by the interrupted noise method.
(2) Measurement of RT by the integrated impulse response method.
(3) Simulation of RT using the ODEON Version 9.0 computer program.
(4) Calculation of RT by Sabine's formula.
(5) Calculation of RT by Eyring's formula.
(6) Calculation of RT by Arau-Puchades' formula.

After obtaining the data for comparison of the aforementioned procedures, a statistical analysis was made of the RT values.

2.1. Object of study

The object of study here was an auditorium-type classroom located at the Polytechnic Center of the Federal University of Paraná in Curitiba, Brazil.

The room has an area of 85 m^2, a volume of 248 m^3 and seating capacity for 45 students. All the procedures were carried out in the same room in order to eliminate any space-related variables such as differences in physical dimensions and finishing materials. The room under analysis was empty and furnished.

Table 1 lists the absorption coefficients α of the materials in this room.

2.2. Measurement

According to the ISO 3382-2 standard [11], when using one sound source position, the measurement is of survey-grade precision and "the nominal accuracy is assumed to be better than 10% for octave bands". Therefore, since one source position was used in this work, a nominal accuracy of 10% is expected. Also according to [11], "source-positions may be chosen as the normal position according to the use of the room". Thus, since teachers spend most of the time during a class close to the whiteboard, the sound source was located in this area of the classroom.

The distance of the source and microphone in relation to the room's surfaces, and the distance between microphone positions and source/microphone positions were established following the recommendations of the ISO 3382-1 standard [12]. This standard recommends that the sound source be located at a height of 1.50 m from the floor and microphones at a distance of 1.20 m from the floor, "corresponding to the ear height of average listeners in typical chairs" [12]. The receivers were placed at a minimum distance of 1 m from vertical surfaces, while microphone positions were positioned no less than 2 m apart. Figs. 1 and 2 illustrate these distances.

2.2.1. Measurement by the interrupted noise method

Measurement of the RT by the interrupted noise method consisted of exciting the room with a pseudo-random pink noise and calculating the RT from the room's response to this excitation. This measurement was done with Brüel and Kjaer equipment and software, consisting of: (1) a omnidirectional source (distributes sound in the room); (2) a sound power amplifier (connects the source to the noise generator, amplifying the sound); (3) a BK 2260 noise analyzer (generates and receives noise, analyzing and storing it); (4) BZ 7204 software (installed in the noise analyzer, manages the analyzer's measurements); and (5) Qualifier Type 7830 software (installed in the computer, calculates the RT from the collected data).

The acoustic measurements were taken as recommended by the ISO 3382-1 [12] and ISO 3382-2 standards [11] with respect to the position of the source and receivers in the classroom under study. In this work, one sound source position and five receiver positions were used.

2.2.2. Measurement by the integrated impulse response method

RT measured by the integrated impulse response method is similar to the previous method, but the room's response is given by an integrated impulse response. As in the previous measurement, the room is excited with a sound signal, but in this case a sine sweep signal. The difference lies in the way this signal is captured, transformed into an impulse, and the RT calculated from the decay of this impulse. This mode of measuring is less influenced by background noise than the previous one [4]. Even so, the room must have little background noise; therefore, the measurements were taken in a furnished room without people. Dirac 3.1 software was used to take this measurement and process the data [13]. The equipment consisted of: (1) a omnidirectional source (distributes sound in the room); (2) a sound amplifier (connects the source to the audio interface); (3) audio interface (connects the sound amplifier to the portable computer); (4) 2238 sound level meter (receives the room's

Table 1
Absorption coefficients (α) of the materials in the classroom. The number following the description of the material refers to the reference from which α was taken for that material.

Frequency (Hz)	Brick wall [7]	Concrete [7]	Wood-paneled wall [8]	Parquet floor [9]	Hardwood floor [7]	Glass [9]	Plywood ceiling [9]	Doors and table [10]
125	0.02	0.01	0.15	0.04	0.09	0.04	0.25	0.20
250	0.02	0.01	0.25	0.04	0.08	0.04	0.30	0.15
500	0.03	0.01	0.12	0.06	0.08	0.03	0.30	0.10
1000	0.03	0.02	0.08	0.12	0.09	0.02	0.40	0.08
2000	0.03	0.02	0.08	0.10	0.10	0.02	0.55	0.09
4000	0.03	0.02	0.08	0.17	0.10	0.02	0.60	0.11

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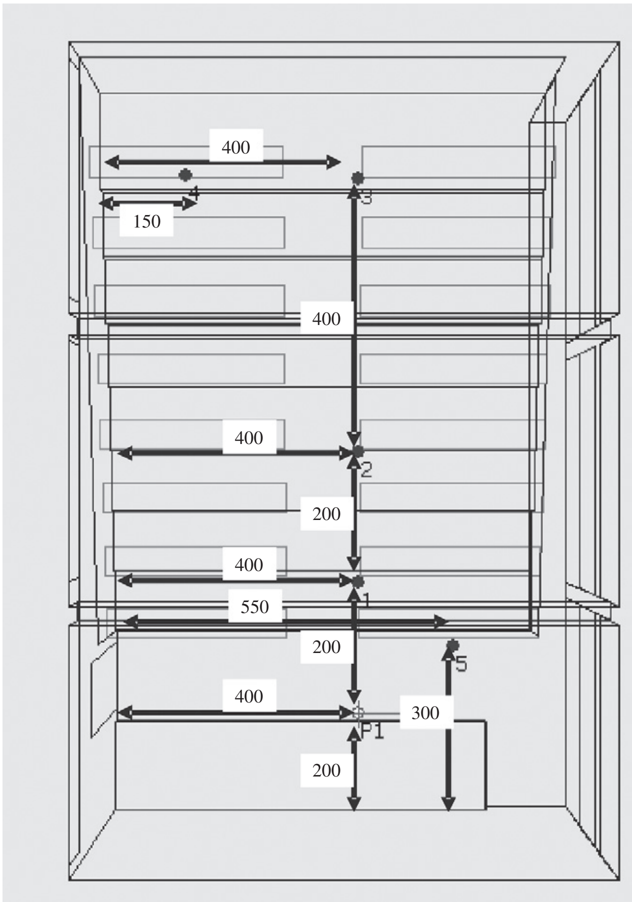

Fig. 1. Location of measurement points (1–5) and sound source (P1), on the floor plan, measured in cm.

response); and (5) portable computer with Dirac 3.1 software (generates the noise, receives the response of the sound level meter, and analyzes and stores the data) [13].

Changes were made in the wavelength, number of repetitions and intensity of the signal in order to obtain a more accurate measurement of the reverberation time. This precision is observed by means of the signal-to-noise ratio, which, according to the ISO 3382-1 standard [12], should be higher than 35 dB to calculate T20 and higher than 45 dB to calculate T30. If these signal-to-noise ratios are not reached, parameters T20 and T30 are considered inaccurate. The source and microphone were placed at the same measurement points as those used with the interrupted noise method.

2.3. Computer simulation using ODEON Version 9.0 software

The computer simulation was done using ODEON Version 9.0 software [14]. This software uses the hybrid method, which calculates the early reflections using a combination of the image source method and ray tracing, while the late reflections are calculated by a special ray tracing process generating diffuse secondary sources.

This simulation requires a three-dimensional model of the room. The model was built based on the room's construction elements, i.e., walls, floor, ceiling, windows and door, and the desks were modeled as horizontal surfaces with the height and dimensions of the desks in the classroom in question. The chairs were not included in the computer simulation model.

The ODEON software allows for several choices, i.e., the type of sound source – which, in this case, was Lambert omnidirectional surface sound-scattering. According to the Odeon 9.0 handbook, "If the Scattering Method is set to Lambert, all directions of 'late' reflections are calculated using the scattering coefficients assigned to the surfaces in the Materials List" [14]. Therefore, a scattering coefficient was attributed to each surface in the classroom. In this study, a scattering coefficient of 0.1 was applied to most of the room's surfaces, since they are characterized by few irregularities and large, flat dimensions. A scattering coefficient of 0.5 was applied only for the desks, considering they may contain smaller objects such as notebooks, books and pens, which were not considered in the 3D modeling [14]. Similar coefficients were used by Astolfi et al. [15] in their simulation of classrooms. The absorption coefficients of all the materials in the room must also be on hand. In addition, the sound source and receivers must be placed around the modeled room. These devices were located at the same points where the measurements were taken.

2.4. Calculation using classical formulas

The RT was calculated using Sabine, Eyring and Arau-Puchades' formulas (1) and (2).

Sabine's formula, which is the most traditional one for calculating reverberation time, was developed by Wallace Sabine in 1900. The formula is given below:

$$RT = \frac{0.161 \cdot V}{A + 4mV} \tag{1}$$

where

- V is the volume of the room.
- A is $\sum S \cdot \alpha$, S is the area of each material, and α is the absorption coefficient of these materials.
- $4mV$ corresponds to sound absorption by air, where V is the volume of the classroom and m is the absorption coefficient of air, expressed in Sabines/m.

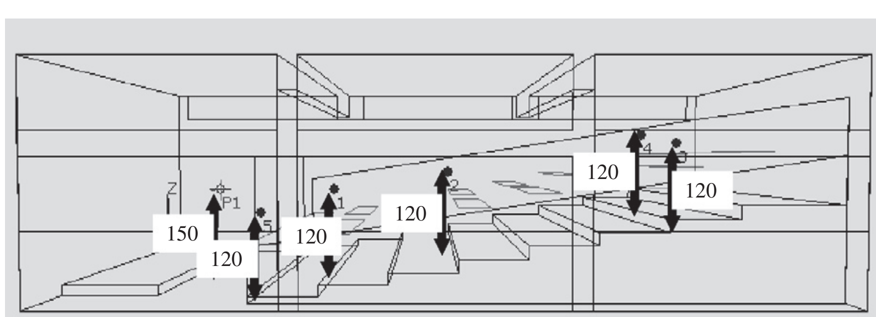

Fig. 2. Location of measurement points (1–5) and sound source (P1), on elevation, measured in cm.

In 1930, Carl Eyring proposed a modification of Sabine's formula. This modification would be suitable for rooms with a great deal of absorption, "dead" rooms, with $\overline{\alpha}$ higher than 0.5 [2]. Eyring's formula is as follows:

$$\mathrm{RT} = \frac{0.161 \cdot V}{-S \cdot \ln(1-\overline{\alpha}) + 4mV} \tag{2}$$

where

- V is the volume of the room.
- S is the sum of the areas of the materials in the room.
- ln is the neperian logarithm.
- $\overline{\alpha}$ is the mean absorption coefficient of all the materials: $\overline{\alpha} = \frac{1}{S}\sum_i S_i \cdot \alpha_i$.
- $4mV$ corresponds to sound absorption by air, where V is the volume of the room and m is the absorption coefficient of air, expressed in Sabines/m.

In an article published in the Journal Acustica in 1988, Arau-Puchades *apud* Neubauer and Kostek [1] proposed a formula for calculating the reverberation time of rooms with asymmetric distribution of absorption. This formula is given below:

$$\mathrm{RT} = \left[\frac{0.16V}{-S \cdot \ln(1-\alpha_x) + 4mV}\right]^{\frac{S_x}{S}} \cdot \left[\frac{0.16V}{-S.\ln(1-\alpha_y) + 4mV}\right]^{\frac{S_y}{S}} \cdot \left[\frac{0.16V}{-S \cdot \ln(1-\alpha_z) + 4mV}\right]^{\frac{S_z}{S}} \tag{3}$$

where

- The first portion corresponds to the absorption of the materials located parallel to the x axis, the second parallel to the y axis, and the third parallel to the z axis.
- $4mV$ corresponds to sound absorption by air, where V is the volume of the room and m is the absorption coefficient of air, expressed in Sabines/m.
- V is the volume.
- ln is the neperian logarithm.
- α_x is the arithmetic mean of the absorption coefficients of the surfaces of the floor (S_{x1}) and ceiling (S_{x2}), $\alpha_x = (\frac{\alpha_{x1}S_{x1}+\alpha_{x2}S_{x2}}{S_x})$; α_y and α_z are the arithmetic means of the absorption coefficients of the surfaces of the side, front and back walls, respectively.
- S is the sum of the areas of all the materials.
- S_x, S_y and S_z are the sums of the areas of the materials that are parallel to the x, y and z axes, respectively.

The ODEON Version 9.0 software calculates the room's RT using each of these formulas. The software calls this evaluation a quick estimate. These values were used in this work as the values calculated with the formulas of Sabine, Eyring and Arau-Puchades.

2.5. Statistical analysis

The RT values obtained by the various procedures described above were then subjected to a statistical analysis using the MINITAB 14 statistical package (Minitab Inc.). The data that presented repeatability – despite variation in the placement of the receptor point inside the room, which in this case were the simulated and measured values, were subjected to an analysis of variance (ANOVA) and to comparison by Tukey's method of multiple comparisons [16]. The values that did not show repeatability, i.e., the calculated values, were evaluated based on the confidence interval of the measured and simulated data. The formula used for the calculation of the confidence interval is described below [17].

$$IC = \bar{x} \pm E \tag{4}$$

where

- $\bar{x}$ is the sample mean, i.e.: $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_1$, where n is the number of repetitions and x represents the reverberation time values.
- $E = \frac{s}{\sqrt{n}}t$ where s is the sample standard deviation and t is the inverse of Student's t-distribution with a probability of 5% and $n-1$ degrees of freedom.

3. Results and discussion

The results presented here refer to the measurements, computer simulations and calculations, based on RT formulas, in a classroom.

The graph in Fig. 3 shows the results obtained by the two measuring methods and the computer simulation. This graph shows mean values, by frequency in octave band, and the standard deviation obtained by variations in RT according to the position of the microphone in the classroom.

The graph shows RT values in the range of 0.5–0.9 s, indicating higher RT values at low frequencies and lower values at high frequencies. At 500 Hz, the mean RT obtained was approximately 0.7 is the most traditional s. A closer examination of the graph reveals that the greatest similarity among the three methods occurred at a frequency of 500 Hz. Conversely, the most significant differences among the methods occurred at a frequency of 125 Hz. Moreover, at the latter frequency, note the high standard deviation from the values measured by the impulse response method.

Table 2 lists the values of reverberation time RT calculated by Sabine, Eyring and Arau-Puchades' formulas.

This table clearly shows that Eyring's formula yields the lowest reverberation time values and that Arau-Puchades' formula yields the highest. A frequency analysis indicated that the largest difference between the RT values calculated by means of the three formulas occurred at the medium and high frequencies.

3.1. Comparison of the methods

Tables 3 and 4 present the calculated values for the relative difference, in modules, of the various methods to determine the RT in comparison to the impulse response method (Table 3) and the interrupted noise method (Table 4). These tables present the relative differences for RT at the frequency of 500 Hz, for the mean RT at the octave-band frequencies of 500–2000 Hz, and for the mean RT at the octave-band frequencies of 125–4000 Hz. These values can be compared to the nominal accuracy established by the ISO 3382-2 standard (2008) as being equal to 10% for the Survey Method, which was adopted in this study.

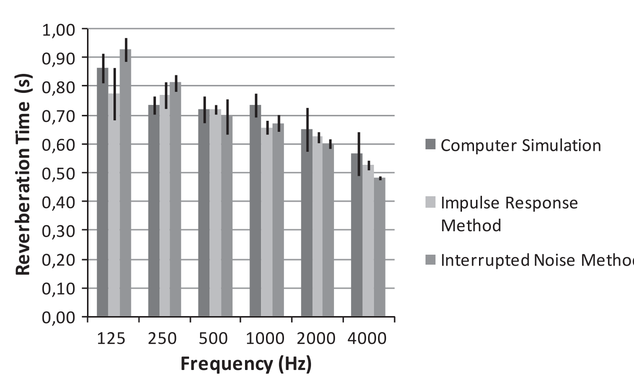

Fig. 3. RT graph obtained from measurements and computer simulations.

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Table 2
RT values, in seconds, obtained by calculations.

Frequency [Hz]	Sabine	Eyring	Arau-Puchades
125	0.89	0.84	0.93
250	0.79	0.73	0.78
500	0.78	0.72	0.85
1000	0.77	0.72	0.91
2000	0.62	0.56	0.76
4000	0.53	0.48	0.65

Table 3
Relative difference of the various methods to determine RT in relation to the impulse response method.

	500 Hz (%)	Mean 500–2000 Hz (%)	Mean 125–4000 Hz (%)
Sabine	8	8	7
Eyring	0	0	1
Arau-Puchades	18	26	20
Computational simulation	0	5	5
Interrupted noise method	3	1	3

Table 4
Relative difference of the various methods to determine RT in relation to the interrupted noise method.

	500 Hz (%)	Mean 500–2000 Hz (%)	Mean 125–4000 Hz (%)
Sabine	12	10	4
Eyring	3	1	4
Arau-Puchades	22	28	16
Computational simulation	4	7	2
Impulse response method	3	2	3

An analysis of Table 3 indicates that the lowest relative differences were found when comparing the RT values obtained by measurements using the impulse response method and the RT values obtained from calculations using Eyring's formula. Table 3 shows relative differences below 10% when comparing the RT values obtained by the two measuring methods and comparing the measured results against the simulated ones. An examination of the values of the relative difference for the results obtained with Sabine's formula reveals that these values are higher than the ones analyzed earlier, but still below 10%. However, in the same table, the values listed for the relative difference obtained by the Arau-Puchades formula are higher than 10%.

An examination of Table 4 indicates similarities with the information contained in Table 3. Note that the comparison of the interrupted noise method with Sabine's formula resulted in relative differences exceeding 10% for the RT values at 500 Hz. The relative difference for the mean RT at the octave-band frequencies of 500–2000 Hz was equal to the 10% established by the Survey Method according to the ISO 3382-2 standard. On the other hand, the mean RT at the frequencies of 125–4000 Hz showed a relative difference of 4%, which is lower than the 7% listed in Table 3 for the comparison of the measuring method and the calculation by Sabine's formula.

3.2. Statistical analysis of the data

The data obtained from the measurements and simulations were analyzed statistically, using the MINITAB 14 statistical package (Minitab Inc.).

The analysis involved the values of reverberation time at the frequency of 500 Hz, of the mean RT between the frequencies of 500, 1000 and 2000 Hz and the mean RT between the octave-band frequencies of 125–4000 Hz. Astolfi et al. [15] have also evaluated average RT in classrooms, across 500 Hz–2 kHz, and across 125 Hz–4 kHz.

The measurements and computer simulations yielded five values corresponding to the five points where microphones were located, generating repeatable data that were evaluated by analysis of variance (ANOVA). The calculated values did not show repeatability and were therefore evaluated based on the confidence interval of the previous data.

The graph in Fig. 4 below presents the calculated, measured and simulated values of reverberation time RT used for the statistical analysis of the data.

The application of the analysis of variance using the simulated RT data at the frequency of 500 Hz, the integrated impulse response measurement and the interrupted noise measurement resulted in a p value of 46%. Because the value of p is higher than 5%, the null hypothesis (H_0) that the values of reverberation time obtained by the three methods (simulation, integrated impulse response measurement and interrupted noise measurement) are statistically equal is accepted.

The analysis of variance of the mean RT values obtained at the frequencies of 500, 1000 and 2000 Hz resulted in a p value of 1.6%, i.e., lower than 5%. Thus, the null hypothesis (H_0) is rejected and the alternative hypothesis that at least one of the methods is different is accepted. To determine which of the methods is different, a multiple comparison was made using Tukey's multiple comparison method [17]. This comparison revealed a significant difference between the values obtained by computer simulation and by the interrupted noise method. In contrast, it was found that the values obtained by computer simulation and by the Integrated impulse response measurement did not differ significantly. In addition, the two methods of measurement generated statistically equal results.

The analysis of variance of the mean RT values obtained at the octave-band frequencies of 125–4000 Hz yielded a p value of 8.7%, indicating that that all the methods are statistically equal.

As for the values obtained by means of the RT calculation formulas, a comparison was made with the calculated confidence interval (Formula (4)) using the measured and simulated RT values.

Table 5 presents the confidence intervals of the RT values obtained by the two measuring methods and the computer simulation of the RT values at 500 Hz frequency, the mean RT at 500–2000 Hz octave-band frequencies, and the mean RT at 125–4000 Hz octave-band frequencies. This table also compares the

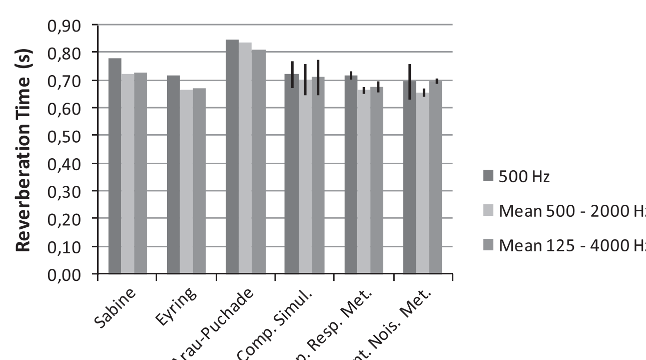

Fig. 4. Data used for the statistical analysis. Abbreviations: Comp. Simul. – computer simulation; Imp. Resp. Met. – impulse response method; Int. Nois. Met. – interrupted noise method.

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Table 5
Confidence interval of the RT obtained by computer simulation (Comp. Simul.), by the impulse response method (Imp. Resp. Met.) and by the interrupted noise method (Int. Nois. Met.). Comparison of the RT obtained by measurements and simulations of the RT obtained by calculations by formulas (= indicates within the confidence interval, while ≠ indicates outside the confidence interval).

	Confidence interval		Sabine	Eyring	Arau-Puchades
Comp. Simul. 500 Hz	0.67	0.79	=	=	≠
Imp. Resp. Met. 500 Hz	0.70	0.74	≠	=	≠
Int. Nois. Met. 500 Hz	0.63	0.76	≠	=	≠
Comp. Simul. 500, 1 K, 2 kHz	0.64	0.73	=	=	≠
Imp. Resp. Met. 500, 1 K, 2 kHz	0.66	0.68	≠	=	≠
Int. Nois. Met. 500, 1 K, 2 kHz	0.64	0.67	≠	=	≠
Comp. Simul. 125–4 kHz	0.68	0.74	=	=	≠
Imp. Resp. Met. 125–4 kHz	0.66	0.70	≠	=	≠
Int. Nois. Met. 125–4 kHz	0.69	0.71	≠	≠	≠

RT values calculated with the Sabine, Eyring and Arau-Puchades formulas and the confidence intervals (= indicates within the confidence interval, while ≠ indicates outside the confidence interval).

An analysis of the table reveals that most of the RT values calculated by Eyring's formula lie within the confidence intervals calculated for the measurement and computer simulation methods. The calculated value falls outside the confidence interval only when one compares the RT value calculated by this formula for the octave-band frequencies of 125–4000 Hz and the RT value in the same frequency range measured by the interrupted noise method.

A comparison of the RT values obtained by measurements and computer simulations against the RT values obtained with the Arau-Puchades formula indicates that in all the compared cases, methods and frequency ranges, the RT values calculated with this formula fall outside the confidence interval.

Astolfi et al. [15] evaluated eight classrooms with volumes ranging from 160 to 466 m^3, and found that "the Odeon 6.5 software and the Sabine formula yielded the most accurate results for RT in empty classrooms". A comparative analysis of the RT values obtained in this study using Sabine's formula and those obtained by computer simulation (Table 5) indicates that the values obtained by this formula fall within the confidence interval calculated by computer simulation. However, a comparison of the RT values calculated through this formula against the measured RT values indicates that the values calculated by the formula are outside the confidence interval of the measured RT.

Based on these data, it can be concluded that the most suitable formula for calculating the RT in this classroom is that of Eyring, while the least suitable formula to determine the RT in this room is that of Arau-Puchades.

4. Conclusions

The comparison of the results of the procedures to determine the RT based on the relative difference and on the statistical analysis clearly showed a statistical difference when the relative difference exceeded 5%. An example of this is the statistical difference between the data of mean RT at 500–2000 Hz octave-band frequencies measured by the interrupted noise method and the simulated RT data, which showed a relative difference of 7% between these methods. When the relative difference was compared with the calculated values and confidence interval between the mean and simulated RT values, a relative difference higher than or equal to 4% already yielded RT values outside the confidence interval.

The statistical analysis demonstrated that there is no significant difference between the two measurement methods, interrupted noise and integrated impulse response. These findings are in agreement with Astolfi et al. [15].

With regard to computer simulation using the Odeon software, there was no difference between this method and the two measuring methods when the RT was evaluated at the frequency of 500 Hz and the mean RT at octave-band frequencies of 125–4000 Hz. However, when the mean RT at 500, 1000, and 2000 Hz frequencies was evaluated, simulated values differed from the values measured by interrupted noise method.

According to Bork [18], the accuracy of the data simulated in the computer is in general influenced by and actually dependent on several parameters besides those directly considered by the software. A very relevant parameter for the precision of a computational simulation is the precision of the values attributed to the coefficients of absorption of the materials inside the room under study [15,19]. It is normally very difficult to identify the absorption coefficient of the materials in existing buildings. The values used in this work are standard ones and therefore do not take into account the wear and particularities of the materials in the room. According to Christensen [14], in addition to the coefficients of absorption, the imprecision of scattering coefficients inserted in computer simulations is one of the main sources of error.

In the present work, similarly to what was reported by Bistafa and Bradley [6], the reverberation times calculated by Sabine's formula were slightly longer than those calculated by Eyring's formula, but were still very similar, while Arau-Puchades' formula resulted in much longer reverberation times. The accuracy of the calculated values was much greater when the first two formulas were used, without the need to use more complex formulas such as that of Arau-Puchades.

Therefore, Arau-Puchades' formula proved to be the least suitable for calculating the RT of the room of this study. The values obtained with Eyring's formula were very similar to those obtained by the two measurements and by the computer simulation.

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