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Architectural acoustics and speech legibility in university environment – Case study

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ABSTRACT

Architecture solutions and acoustic sound filled parameters stay in close relation and mutually influence. Phenomenon is crucial in all education indoor environments, where legibility of speech must be provided. Thus, in presented research, issue was studied deeply with calculations and measurements for two selected rooms at one of the higher schools in Architecture Faculty in Poland (recently remodelled, end 2019). Studies goal was to diagnose problems, for students had difficulties in hearing and understanding. Conclusions where focused on possible solution scenarios, proven with computing and simulations. Aim of presented reach was: (1) to show mutual connection between architecture and acoustics, (2) diagnose the real-life problems, (3) propose re-modelling solution scenarios, which are applicable and can be presented to authorities.

1. Introduction

After remodelling (2017–2019) of University's building of Architecture Faculty in Poland, including classrooms serving as workshop studios and minor seminar and lecture rooms (to maximum 40 participants), it was observed that students complained on illegibility of speech and noise occurrence. They had problems with understanding Tutor but also peer-to-peer close communication was problematic. Several curriculum courses, were led by this article's Author in the building in years 2018–2020. They consisted mainly of design studios, requiring not only workshop space, but also enabling student presentations, mini-lectures and seminars, as well as discussion and introduction other active-learning tools. All these activities required fast and clear communication between all participants, at all times. In light of outlined problems and based on previous expertise in the field of architectural acoustics, i.e. papers: Jablonska [7], Trocka-Leszczynska, Jablonska [13], Jablonska Trocka-Leszczynska, Tarczewski [8], it was crucial to diagnose and address issues with illegibility of speech, occasional noise and 'to silent' presentations. Especially, that such problems were found at other universities: Yang D., Ming Mak [16] and it is safe to say, will be continued in future, due to lack of sufficient architect and acoustician co-operation during design process.

At a second glance, it was important to prevent negative effect of acoustical spatial performance directly to users well-being, comfort and safety Discroll [2]. Moreover, it was roughly assumed applicable norms and standards, i.e. American Standards no. 1910.95 (amended 2008, [9]), Polish Norms PN-B-02151–2 [11] or PN-B-02151–4 [10] were not fulfilled. Thus, further investigation was engaged in order to plan, test and present optimal and confirmed solutions to the faculties' authorities. Than a number of calculations [1, 12] and measurements was performed in order to re-design space and propose economical refurbishment scenarios. To make this article feasible and useful to wide audience, presented content was intended and formulated to be as universal as possible and finished with synthetic conclusions and guidelines.

2. Aim and scope

In light of problems outlined in the introduction, three goals of study were formulated, with first one of a general character (1) to show mutual connection between architecture and acoustics. As it was previously confirmed a vast number of professional practice and scientific research are led separately for acoustics and architecture, without highlighting their links and intersections. Thus, here it will be revealed and stressed. Second, non-less important goal was to (2) diagnose the real-life problem, which occurred in aforementioned environment and effected disadvantageously university educational process. Third aim (3) was focused on

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proposing solution scenarios of aforementioned issues, which can be further on presented to authorities and then, hopefully, implemented in particular rooms and spaces alike. The final and practical goal will be support and improvement of: speech legibility, acoustic background, sound absorbance and overall "sound-comfort" in rooms designated for education. In order to implement the final aim, at the end of article, there is a summary stressing the universal parts of presented study.

3. Method and research conduction

This research are within line of the author's work and are a part of wider study and cycle of publications aiming at improving the comfort and acoustic safety of built environment's users, both external and internal, despite a region or culture. General investigation was divided and conducted in several parts, opened by broad literature overview and discussion (more data and explanation in previous Author's articles), followed by forming this study plan, consistent of: volume measurements, existing state diagnosis, simplification and optimization of considered problem, basic acoustic field parameters calculations, sanctioning measurements, than forming solution scenarios and their calculations, followed by conclusions. Research were carried out on two exemplary rooms, which where selected as the most typical, simple work spaces, representative for higher schools and serving their purpose sufficiently, meaning: students capacity – groups of 15 to 30 people or 20 to 40, proper architectural students workspace size (at least 100x70 cm per person) and tutors equipment: desk, whiteboard, projector and laptop – and following basic ergonomic assumptions, outlined by i.e. Charytonowicz [3], Deasy [4] or Gedliczka [5].

First volume measurements were performed, with the use of laser meter (Bosh GLM50 Professional), with function of perpendicular distance correction and immediate volume calculations based on ×, y, z dimensions. Minor irregularities in volume were simplified, in order to represent rooms to shoe-box configuration for calculations. Sound field testing was carried out *in situ* with The SVAN 979 Class 1 Sound & Vibration Analyser, certified and calibrated with the use of acoustic calibrator model SV 33B (calibration before and after measurements). Tests were derived during pandemic teaching gap (October 2020) – no students in the building – on Monday (external background noise regular) at between high traffic hours – 12.00 till 1p.m. It is worth noticing, that roads around building in question are rather of a low traffic, and inside there were only few staff members. During measurements in selected rooms and corridor outside them only one researcher was present. Background noise tested in rooms was below required L_{AeqnT} (benchmark equivalent sound level) 35 dB according to Polish Norm PN-B-02151–2 [11], and ranged between 26,0–37,0 dBA, which was stated as satisfactory.

Research focused on two main parameters, which are directly connected to speech intelligibility occurrence, i.e.: Reverberation Time (RT) 30 and 60 – measurements and calculation; acoustic absorption (A) – in calculation; in reference towards relevant frequencies (f) from 250 to 4000 Hz. RT30 tests *in situ* were conducted with an impact sound source of a spherical character. For data analyses there were applied several tools, for initial and final computing: on-line acoustic calculators: Mega-Acoustics.pl [1], The Rigips Saint-Gobain Calculator [12, 14], for formulas definition and calculations: The SVAN 979 Class 1 Sound & Vibration Analyser with dedicated software, Excel application, and at all times data were critically revised. For comparisons current norms and standards were applied American Standards no. 1910.95 [9], Polish Norms PN-B-02151–2 [11] or PN-B-02151–4 [10]. Conclusions were formed with the use of synthesis and their graphical representation was proposed in AutoCAD software.

4. Case study description and problem outline

Rooms (1 and 2) where selected as the most typical, standard on a rectangular plan with few windows (deeply mounted into the wall in wooden, decorative frames), one wooden doors (decorative) and simple basic furnishing (hard board desks, even plywood chairs, whiteboard, ventilation shaft, sink). Researcher was aiming at universality of this study. Hence, floors in this spaces are even and finished with resin, walls are mostly uniform (minor structural elements visibility), plastered and painted. Ceiling was finished analogically, yet there are flat, structural vaults noticeable from the inside. All rooms were kept in simple minimal and laboratory-like interior design style, allowing students to focus on work or lectures. Also such solution is highly economic (Fig. 1).

Rooms have following features: no. 1: floor – even; wall 1 – even with 4 double windows; wall 2 - even, indispensable visibility of structural element; wall 3 – almost even with door, ventilation shaft, sink, magnetic board hidden under the plaster (Fig. 1.) wall 4 - even, indispensable, visibility of structural element and flat whiteboard; ceiling - flat, structural vaults visible from the inside, ventilation shaft, spatial parameters: X = 12,0 m, Y = 7,5 m, Z = 4,0 m; no. 2: floor – even; wall 1 – even with 2 double windows; wall 2 – even; wall 3 – almost even with door, ventilation shaft, sink; wall 4 – even; ceiling - flat, structural vaults visible from the inside, ventilation shaft; spatial parameters: X = 7,0 m, Y = 7,5 m, Z = 4,0 m.

Based on measured dimensions and described structure and finishing, first calculations were made (author, based on: The Mega-

Fig. 1. Tested rooms, from left: 1 and 2.

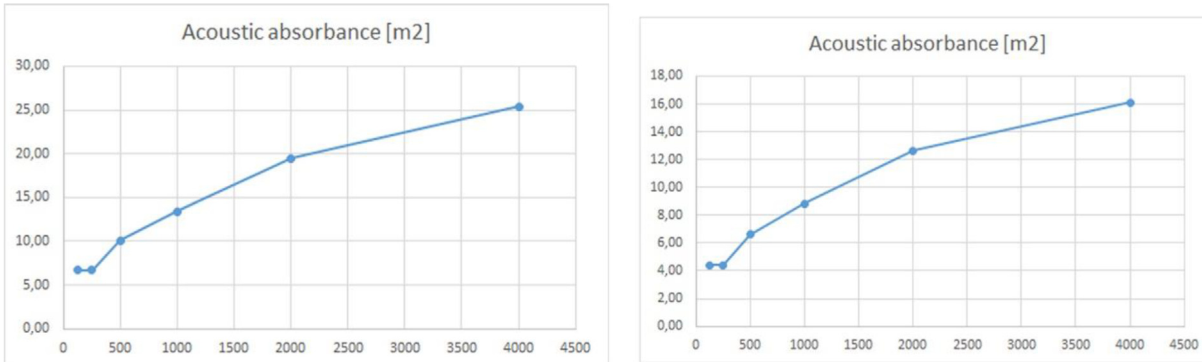


Fig. 2. Acoustic absorbance graph in function of frequency in tested rooms, from left: 1 and 2 – showing insufficient amount of sound absorbing materials.

Acoustics.pl 2020 [1], The Rigips Reverbetaion Time calculator [12,14]), assuming aforementioned interior data (without tables and benches) following results (Fig. 2):

- Room no. 1: A [m2] – *f* (Hz): 6.72 – 125 Hz; 6.72 – 250 Hz; 10.08 – 500 Hz; 13.44 – 1000 Hz; 19,50 – 2000 Hz; 25.44 – 4000 Hz; with average RT60 – 5.39 s
- Room no. 2: A [m2] – f (Hz): 4.42 – 125 Hz; 4.42 – 250 Hz; 6.63 – 500 Hz; 8.84 – 1000 Hz; 12.63 – 2000 Hz; 16.09 – 4000 Hz; with average RT60 – 4.80 s

Comparing sound meter test measurements of RT30 (average taken in 3 sets, due to aforementioned diversified background L_{Aeq}), room no. 1 – 2,29; *ergo* RT60 = 4,56 s and no. 2, RT30 = 1,88 s, *ergo* RT60 = 3,75 it is proven, that calculations are correct (the 0,73 s for room no. 1; and 0,33 s in no. 2) of difference is caused by furniture and small room irregularities and does not interfere with studies' goal).

Comparing them with polish norm PN-B-02151–4 [10] [– which is quite universal for room acoustics – recommendations for rooms designated for education between 120 m3 and 200 m3 – RT $\leq$ 0,6 s, while for rooms between 120 m3 and 500 m3 – RT $\leq$ 0,8 s. Also comparative A [m2] – acoustical absorbance was calculated based on norm PN-B-02151–4 A $\geq$ 0,6xS, where S [m2] – is surface of rooms plan, this:

- Room no. 1: comparative A [m2] – 54 m2
- Room no. 2: comparative A [m2] – 31,5 m2

Thus, it can be concluded that RT is few times to long, while acoustic absorbance is almost none. Such acoustic field parameters are responsible for problems with speech hearing and understanding, overlapping sounds and occurrence of reverberation noise, coming from people inside the rooms, outside and different other sources, i.e. installation (i.e. aforementioned shafts), traffic, etc.

5. Possible solutions

After diagnosing the problem and addressing specific room conditions, some economic remodelling proposal had to be formed. It seemed, that the easiest answer would be application of sufficient amount of absorbing material, taking into account existing conditions, user- and fire- safety requirements. So, selected product should be easy in installation, closed (no emission of fibres) and have proper for education object fire safety parameters – therefore a system was chosen from The Rigips Reverbetaion Time Calculator [12,14]. Therefore, solution scenarios were made, assuming previously, that ceilings should be left without remodelling – due to their original vault form and suspended light installation. Also floor (cleaning and specific upper finish) and white and magnetic board, cannot be covered with absorbent material. At the same time it seems as a bad idea to cover walls by the windows, for the bays are already deep, and thus screen natural light penetrating the rooms. In each room one selected back and side wall was theoretically covered with absorbent material. Calculation outcome was as following:

- Room no. 1: A [m2] – f (Hz): 29.96 – 125 Hz; 48.56 – 250 Hz; 48.04 – 500 Hz; 44.42 – 1000 Hz; 43.32 – 2000 Hz; 45.76 – 4000 Hz; with average RT60 – 1.27 s
- Room no. 2: A [m2] – f (Hz): 21.14 – 125 Hz; 34.34 – 250 Hz; 33.91 – 500 Hz; 31.28 – 1000 Hz; 30.23 – 2000 Hz; 31.49 – 4000 Hz; with average RT60 – 1,14 s

Although general acoustic conditions were much closer to required, yet in each of this scenarios optimal parameters could not be obtained and RT 60 was still too long. Next investigation was planned.

6. Conclusions – Selected scenario

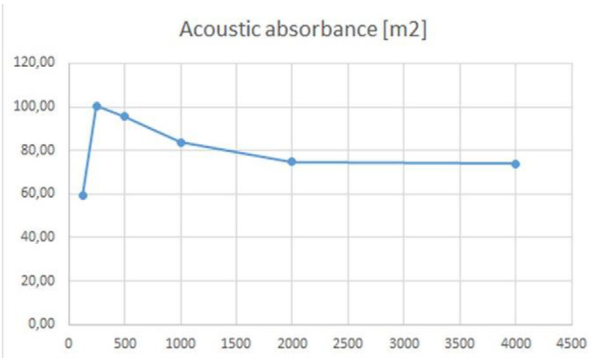
Based on previous unsatisfactory tests, optimal solutions were defined. Taking into account that in Room 1, the absorbent material must be applied only on ceiling (this time as a mandatory plan) and back wall, for lateral walls as aforementioned are covered with windows or magnetic board, while floor has to remain unchanged. From several scenarios only application of especially designed perforated plasterboard 12,5 mm thickness, perforated with square holes 12x12 mm in 25 mm distance and 50 mm of mineral wall acoustic insulation behind it (allowed to be tested by The Rigips Reverbetaion Time [14,12], has enabled following outcome (Fig. 3):

- Room no. 1: A [m2] – f (Hz): 59.16 – 125 Hz; 100.56 – 250 Hz; 95.64 – 500 Hz; 83.82– 1000 Hz; 74.70 – 2000 Hz; 73.74 – 4000 Hz; with average RT – 0.73 s

In room number 2 – renovation scenario was also focused on back wall and ceiling (without floor or window wall). Again testing calculations were carried out with the use of The Rigips Reverbetaion Time Calculator [14,12], and results were as follow (Fig. 3):

- Room no. 2: A [m2] – f (Hz): 50.76 – 125 Hz; 52.33 – 250 Hz; 51.82 – 500 Hz; 47.80 – 1000 Hz; 44.83 – 2000 Hz; 45.32 – 4000 Hz; with average RT – 0.69 s

Also comparative A [m2] 54 m2 for room no. 1 and 31 m2 for room no. 2 are fulfilled. Both results were described as good and sufficient. They were carried out for empty rooms without tables



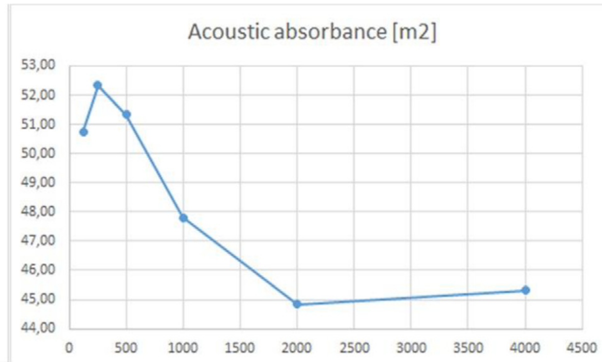


Fig. 3. Acoustic absorbance graph in function of frequency in tested rooms, from left: 1 and 2 – showing insufficient amount of sound absorbing materials.

of pupils, thus their presence will only improve general conditions. In room no. 1 – due to substantial volume and initial economic objections (existing laps and vaults), it is recommended that absorbing material suspended form ceiling should be places in form of geometric islands or other form of acoustic absorber. Such solution will provide more interesting spatial look of space, which is sought in architectural design classrooms (Fig. 4).

Based on proposed scenarios, solution and synthetic conclusions graphic representation was formed, which was based on simplified virtual model of room no. 1. Solution assumed, that based on aforementioned calculation and dew to aesthetic reasons, there is a possibility of creating suspended custom panels within the proposed system (Fig. 4).

Such solution will not only sufficiently increase speech legibility in both rooms, but also will significantly help to reduce background noise, coming from other rooms, while students will be again present in the building.

7. Summary

During conducted research all three initial aims were addressed. Mutual connection between geometrical, spatial and material solutions – belonging to architectural aspect of building design; and reverberation time with acoustic absorbance – from acoustic realm; was clearly shown and proved. Firstly, there was confirmed lack of sound filed consideration, which effected negatively inside speech legibility and users comfort. Secondly, manipulations of material solutions and their purpose placement, with use of existing or designed geometry, were used to reveal architecture and acoustic connections and possibilities of positive improvements both in space and auditory field parameters.

Second and third goal was reached, by calculations and measurements, as well as their repentance on planned scenarios. Author demonstrated quite simple, economic and applicable ways of development of architectural acoustics in case of education purposed rooms. The improvement was shown in respect of reverberation time, room absorbance and speech legibility achievement.

General summary from presented research project is focused on guides for design of spaces for education. It is stressed, that they all must be considered for acoustic performance during their architectural design, otherwise they will not serve their purpose. University halls, rooms and other education spaces ought to be planned and calculated according to conference halls standards, and agreeing with quoted in this article norm Polish Norm PN-B-02151–4 (2015), which states as follows:

- rooms under 120 m3 – RT $\leq$ 0,6 s,
- for rooms between 120 and 500 m3 – RT $\leq$ 0,8 s
- for rooms between 500 and 1000 m3– RT $\leq$ 1 s

Based on other studies and documents, i.e. Wuruk [15] or Iannace G., Sicurella F., Colamesta P., Gentilin M. [6], it can be specified, that this recommendations have universal character. Also, at every occasion it is necessary to calculate acoustic absorbance in room, according to norms and standards in particular region. Moreover, close co-operation between acousticians and architects is recommended for spaces where speech legibility and noise reduction is required, even at conceptual stage of design. In this way our environment will be humane and most of all will serve better education and communication.

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.

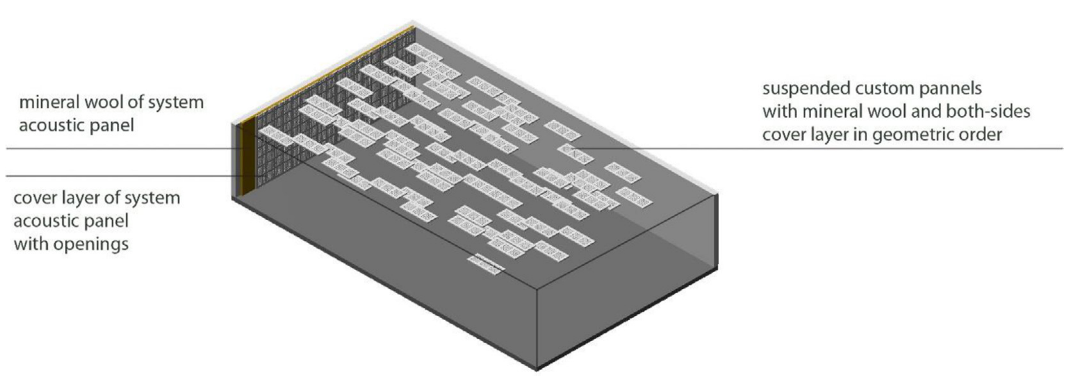


Fig. 4. Proposed acoustic adjustment solution presented on simplified virtual model of tested room 1 – axonometric 1:1:1 (scheme, no-scale).

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References

[1] Acoustic calculator, Mega-Acoustic.pl, https://www.mega-acoustic.pl/poradnik-akustyczny/kalkulator-akustyczny/ (Accessed on: 17.10.2020)
[2] Driscoll D. P. (2013) OSHA Technical Manual. United States Department of Labour. https://www.osha.gov/dts/osta/otm/new_noise/ (Accessed on: 11.09.2019)
[3] Charytonowicz J. Zasady kształtowania laboratoryjnych stanowisk pracy (self-translation: The rules for shaping laboratories' work places). Wrocław: Oficyna Wydawnicza Politechniki Wrocławskiej; 1994.
[4] Deasy C. M., Design Places for People. A Handbook of Human Behavior for Architects, Designers and Facility Managers., zebrane Lasswell T. E., Whitney Library of Design, Watson-Guptill Publications New York, New York 1985.
[5] Gedliczka A.: Atlas miar człowieka. Dane do projektowania i oceny ergonomicznej (self-translation: The atlas of human measures. Design data and ergonomics evaluation), CIOP Centralny Instytut ochrony pracy, Warszawa (2001)
[6] Iannace G., Sicurella F., Colamesta P., Gentilin M. (2018), Acoustic Project of a Conference Room of The Secondary School Venir (Delémont, Switzerland), in: Canadian Acoustics - Acoustique Canadienne 46(2), (accessed between August–October, pp. 31-38 2019)https://www.researchgate.net/publication/325976838_ACOUSTIC_PROJECT_OF_A_CONFERENCE_ROOM_OF_THE_SECONDARY_SCHOOL_VENIR_DELEMONT_SWITZERLAND (accessed between August–October, 2019)
[7] Jabłońska J. The role of acoustics in building clean urban and architectural environment. Builder 2020;276(7):44–6.
[8] Jabłońska J., Trocka-Leszczyńska E., Tarczewski R. (2019), Sound and form in public spaces of contemporary hotels, in: Advances in human factors, sustainable urban planning and infrastructure. Proceedings of the AHFE 2018 International Conference on Human Factors, Sustainable Urban Planning and Infrastructure, ed. Charytonowicz J., Falcão Ch., Springer 2019. pp. 216-225
[9] Occupational Safety and Health Standards no. 1910.95 (amended 2008) – Occupational noise exposure. OSHA. https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.95 (accessed between August–October, 2019)
[10] Polish Norm PN-B-02151-4 (2015) Building Acoustics. Protection from noise in buildings. Part 4: Requirements for reverberation conditions and speech intelligibility in rooms with guidelines for conducting research (self-translation from Polish), Polish Committee for Standardization (PKN), Poland 2015
[11] PN-B-02151-2 (2018) Polish norm, Building Acoustics. Protection form noise in building. Part 2: requirements on permissible sound level in room. (self-translation from Polish), Polish Committee for Standardization (PKN), Poland 2018
[12] Rigips Reverberation Time Calculator (based on PN-B-02151-4), (2020), https://poglos.rigips.pl/ (accessed between 2020.10.01-2020.10.20)
[13] Trocka-Leszczyńska E., Jabłońska J. (2021), Contemporary architectural design of offices in respect of acoustics, in: Applied Acoustics 2021, vol. 171, art. 107541, pp. 1-7
[14] The Rigips Saint-Gobain Calculator, for computing on line calculator was used provided by Rigips Saint-Gobain platform referring directly to Polish Standard: PN-B-02151-4, https://poglos.rigips.pl/ (accessed on 2020.06.16)
[15] Wuruk H. Jl. (2019), The Importance of Acoustic Design For Meeting Room, Office, Classroom, Auditorium Hall, School, Music Hall, in: Alta Integra, https://altaintegra.com/publications/articles/acoustic-design-and-function-room/ (accessed on 2020.10.19)
[16] Yang D., Ming Mak Ch. (2021), Effects of acoustical descriptions on speech intelligibility in Hong Kong classrooms, Applied Acoustics 171, art. no. 107678, pp. 1-8