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Learning Room Acoustics by Design: A Project-Based Experience*

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Optimizing room acoustics teaching for architects and building engineers is an unfinished business. Moreover, theoretical explanations about acoustic concepts hardly support the understanding of basic concepts of acoustics on these students. A basic BLA (Bipolar Laddering Assessment) experiment is presented with students showing that an active learning method can be accepted by them more easily when "sonification" is included in the course. This process, which converts data into non-speech audio to make acoustic concepts audible, is suggested as a possible solution for this problem. Additionally, the experiment indicates the basic guidelines for the improvement of a project-based pedagogy, which pretends to broaden architecture student's insight into acoustic problems.

Keywords: active learning; room acoustics; BLA; architectural education

1. Introduction

Carefully treating the acoustics in an interior space is absolutely necessary when designing auditoria, concert halls and theatres, where the enjoyment of the music and the sung voice must be of the highest quality. But acoustics is also necessary in more functional environments such as conference rooms, classrooms, train stations, airports, supermarkets, where the speech must be intelligible to understand the spoken message. The architecture and building engineering have the responsibility to design and build spaces that help to these purposes.

Against this necessity, it is commonly thought that the acoustic problems of building interiors are solved only by electroacoustics [1]. This concept is not only supported by the normal user of a building, but is also echoed in the conception of many architects and building engineers. They usually ignore that architecture modifies and conditions the perception of the sound that is propagating there. They usually suppose that an architectural interior sounds good by default and, as a consequence, they turn to electroacoustics when, once built, they encounter a very different reality. Moreover, the design of the space can also support or prohibit good electroacoustic solutions. The spatial envelope of an architectural interior, therefore, must be treated to direct, attenuate, accentuate or modulate the sound that one wants to hear there. This task is largely the responsibility of the architect and building engineer.

Despite the importance of the topic, acoustics education in the areas of Architecture and Construction Engineering is rather scarce. Little or nothing about acoustics is explained to future architects in the schools of architecture and building engineering.

This paper presents a study carried out at the Faculty of Architecture of the RWTH Aachen University. The objectives are to present and evaluate an acoustic educational experience for architects and building engineers. This educational experience proposes a different way of learning architectural acoustics based on the paradigm of Active Learning [2]. In particular, it focuses on project-based learning, where the student designs the space with the desired acoustics and then analyses the acoustic properties of its design to understand the acoustic behaviour of the architecture. This study evaluates student performance during an architectural acoustics course, analysing student satisfaction, performance and design results. Students are assessed against two types of teaching in acoustics: teaching through a design-based workshop (A) compared to teaching through a theoretical masterclass (B).

This study uses a mixed methodology. On the one hand, quantitative data are analysed to assess student outcomes, while qualitative data are collected to determine the reasons behind these outcomes. These methodologies are based on the research and publications of Fonseca, et al, on the introduction of new technologies in the Architecture curriculum [3–5]. These studies provide the appropriate framework and confirmation of a tested and reliable methodology.

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2. Framework

In architectural acoustics, concepts have generally been taught visually or verbally before they are experienced by listening. Murray Schafer argued that what we should use in acoustics, above all, is our ears [6]. The experience of a student of architecture and building engineering in explaining acoustic concepts is often quite confusing. The student lacks a basic knowledge of sound, so he or she does not know that:

- Sound can be examined according to its frequency
- Depending on its frequency sound can be perceived as high or low
- Sound can be examined according to its amplitude
- Depending on its amplitude sound can be loud or weak
- The decibel measures the sound pressure level referenced to the nominal threshold of human hearing on a logarithmic scale
- The physical characteristics of sound that determine the perception of timbre include spectrum and envelope
- etc.

All this basic knowledge is preliminary to any acoustic study. Therefore, to begin explaining concepts of architectural acoustics without understanding the above notions or having experienced them is a pedagogical error. This problem has already been described by [7, 8]. In these papers, the authors proposed to use the concept of "sonification" to teach acoustics and audio: "The term sonification refers to the process of converting data into non-speech audio, and is distinct from auralization in that the process does not aim to simulate an actual or imagined sound environment."

The teacher of acoustics can often find himself in the following situation: he explains that the brighter a room is, the more the high frequencies are accentuated. Simultaneously, the student does not associate this explanation with the practical consequence of it: when an orchestra plays in this room, the flutes and violins will sound louder and more strident than the double basses. Therefore, all music played there will be tinged with a sound more like that of a toy radio than that of a subwoofer. This is because the student of architecture and building engineering has never had contact with the fundamentals of sound science. He does not know what a high-pitched and low-pitched sound is. He also does not know that this distinction is closely related to the frequency of the sound and, therefore, those words sound strange to him in his vocabulary.

However, despite the limited understanding of sound, the architecture student has a tool at his disposal: the ability to draw and design architectural spaces [9–14]. This tool plays into his hands as long as he knows how to analyse what he has drawn. This student, generally, will not have the ability to define and speak about the sound of a space, but he will be able to transfer the space he or she perceives by his or her ears into to paper. Every architect should have the ability to draw the spatial idea contained in his imagination. Otherwise, he may never transmit his design proposal to a third party. Therefore, the teaching methodology of acoustics for students of architecture and building engineering is the opposite of what could be provided to a music student. If the latter can be directly explained the concepts of acoustics because he is familiar with the concepts of sound for years, the architect can only be taught acoustics if he is asked to reflect on the space he imagines and captures on paper.

This methodology is therefore based on the design of an architectural space based on a soundscape in order to analyse the acoustic properties of the designed space. In this context, experiences have already been made in the history of architecture and construction where sound was the generator of ideas. Iannis Xenakis, architect and composer, designed the main facade of the La Tourette monastery using stochastic methods similar to those used in his orchestral compositions [15, 16]. Renzo Piano designed the architectural stage for a piece of music by Luigi Nono and the spatial demands it required [17]. Stockhaussen and Fritz Bornemann designed a place where the spatiality of music was the central theme [18]. In addition, some research has been done on the close relationships between composers and architects [1, 19, 20].

In recent years, the influence of acoustics on students of architecture has been studied. Sheridan and van Lengen [21] studied an educational approach in which students experienced the properties of different spaces to make a proposal for architectural design. Michael Fowler teaches architecture students about the importance of sound in cities and encourages them to make urban proposals to generate particular acoustic conditions [22]. Other studies have highlighted the ability to draw intangible cultural heritage such as sound, popular stories or hiking trails [23, 24]. However, as far as can be known, none of the researches have tackled the teaching method on acoustics to architects and building engineers from design.

3. Materials and methods

3.1 Participants

Thirty-two subjects participated in the experiment. They were aged between 19 and 35 years old. All participants are architecture students, so they are considered trained participants [25]. 45.2% of the students worked during their architectural studies. Regarding their background education, 26.2% of them had no musical education; 61.3% of them had elementary musical education and 12.5% had professional musical education. All the participants took part firstly in option B (theoretical masterclass) and, afterwards, in option A (design-based workshop). Therefore, the two options were not randomized.

3.2 The design-based workshop

The experience consisted of two stages, which completely differ from a theoretical masterclass, to which the students are used to. While a theoretical masterclass superimposes the theory to the praxis, the design-based workshop flips this learning process.

The first session of the test consisted of the so-called *Listening-Design Test*. This was presented to the architectural students under the following conditions: a short duration soundtrack could be individually reproduced as many times as desired by the student. During the test (total: 45 minutes) they were allowed to sketch and draw the suggested architectural environment by the soundtrack on an A4 and A3 sheet of paper. On the A4 sheet, a ground plan and a section of the listened environment was required. They could draw them with a pencil and a ruler on a grid of 1 × 1 meter. This task lasted 15 minutes. On the A3 sheet, an axonometric military perspective of the listened environment was required. They could draw it with a pencil, a straight ruler and a square ruler. They could include geometry, materials, shadows, people, objects, vegetation, etc. in the drawing. They should also include a graphical scale, sound sources and listener positions. This task lasted 30 minutes. The soundtrack consisted of a sequence of sounds lasting 1 minute and 49 seconds. It contained the recording from a receiver point in a hall. The environment, where the sound sources and the receiver point were situated, was modelled in 3 dimensions in Sketchup and subsequently auralized [26] in RAVEN [27].

The soundtrack contained four sound sources and one fixed receiver. Two of the four sound sources (the guitar and the people talking and drinking) were static and the other two were dynamically moving (the steps on the staircase and the sneezing woman).

The second session consisted of the understanding of some concepts derived from the previous experience. This was conducted in small student groups (max. 10). They were introduced to the fundamentals of acoustics and were asked to investigate on the acoustic properties of their own designs done in the first session. In particular, the concept of Room Impulse Response, and Lateral Energy Fraction was explained to them [28]. Consequently, they were asked to analyse and correlate the Lateral Energy Fraction with the geometric properties of their drawings to clearly understand that there is a strong relation between the architectural design and the acoustical properties of that design.

3.3 BLA method (Bipolar Laddering Assessment)

By using complementary qualitative research, it is possible to obtain variables to study in future iterations and more detail for quantitative data [29].

Quantitative and qualitative approaches have been the main methods in the history of scientific research. On the one hand, quantitative research focuses on analysing the degree of association between quantified variables, as enacted by logical positivism; therefore, this method requires induction to understand the results of the research. Because this paradigm considers that the phenomena can be reduced to empirical indicators that represent reality, quantitative methods are considered to be objective [30].

On the other hand, qualitative research focuses on the detection and processing of intentions. Unlike quantitative methods, qualitative methods require deduction to interpret the results. The qualitative approach is subjective, because it assumes that reality is multifaceted and cannot be reduced to a universal indicator [31].

Qualitative methods are commonly used in usability studies and, inspired by experimental psychology and the hypothetical-deductive paradigm, deal with user samples that are relatively limited. However, the Socratic paradigm of post-modern psychology is also applicable and useful in usability studies because it targets details related to the User's eXperience (UX) with great reliability and reveals subtle information about the technological product studied [32]. Through qualitative methods, the aim is to explore users' wishes, needs and objectives.

The BLA method is based on positive and negative poles to define the strengths and weaknesses of the product. Once the element has been obtained, the laddering technique will be applied to define the details of the product. The purpose of a laddering interview is to reveal how the attributes of the product, the consequences of its use and the personal assessments of the product are related to the user's thinking. The characteristics obtained through the laddering application will define which specific factor will result in considering an element as a quality or a weakness. The BLA method consists of three steps, following the similar methodology of Fonseca, Redondo and Villagrasa [4] and [33, 34]:

Table 1. Positive common (PC), positive particular (PP), negative common (NC) and negative particular (NP) elements for option A (design-based workshop) and option B (theoretical masterclass)

E. Code	Description	Av. Score (Av)	Mention Index (MI) (%)
1PC (A)	It consists on learning by listening—learning by doing	8.55	(10) 31.25
2PC (A)	It is a practical work with sound	8.125	(8) 25
3PC (A)	It is an interesting introduction	9	(6) 18.75
4PC (A)	It is easy to understand	8.4	(5) 15.625
1PP (A)	It combines acoustics and space in graphic way	9	(1) 3.125
2PP (A)	It is a good method	10	(1) 3.125
	No answer		(1) 3.125
1NC (A)	There is not enough theoretical information	4.833	(12) 37.5
2NC (A)	Better organisation of the experiment	4.5	(12) 37.5
	No negative aspect		(7) 21.875
1NP (A)	Very subjective results obtained	4	(1) 3.125
1PC (B)	You learn lots of details about acoustics	7.5	(14) 43.75
2PC (B)	You know what to analyse beforehand	7.8	(5) 15.625
3PC (B)	It is an interesting method	8	(3) 9.375
1PP (B)	You use your knowledge to improve the design	7	(1) 3.125
	No answer		(9) 28.125
1NC (B)	Lack of practicity	5	(7) 21.875
2NC (B)	Difficult to follow	4.333	(6) 18.75
3NC (B)	It needs more time of explanation	6.333	(3) 9.375
4NC (B)	It can be boring	4.666	(3) 9.375
1NP (B)	You can forget the stuff you have learned in class really fast	4	(1) 3.125
	No answer		(12) 37.5

1. Elicitation of elements. The implementation of the test starts from a blank template for the positive (most favourable) and negative (less favourable) elements. The interviewer (in this case the professor) will ask the users (the student) to mention a positive and a negative aspect of the two types of learning methods (Option A and Option B). Thus, we are going to obtain two positive aspects and two negative aspects.
2. Marking of elements. Once the list of positive and negative elements is completed, the interviewer will ask the user to mark each one from 0 (lowest possible level of satisfaction) to 10 (maximum level of satisfaction);
3. Elements definition. Once the elements have been assessed, the qualitative phase starts. The interviewer asks for a justification of each one of the elements performing laddering technique. Why is it a positive element? Why this mark? The answer must be a specific explanation of the exact characteristics that make the mentioned element a strength or weakness of the product.

From the results obtained, the next step was to polarize the elements based on two criteria:

1. Positive (Px)/Negative (Nx): The student must differentiate the elements perceived between positive aspects of the experience that helped them to understand the music as satisfactory, and the negative aspects that were not satisfactory or simply need to be modified to be satisfactory;
2. Common Elements (xC)/Particular (xP): Finally, the positive and negative elements that were repeated in the students' answers (common points) and the responses that were only given by one of the students (particular

Table 2. Proposed common improvements (CI) and particular improvements (PI) for both positive and negative elements for common and particular items in option A (design-based workshop) and B recording (theoretical masterclass)

E. Code	Description	Mention Index (MI) (%)
1CI (A)	Devote more time in introducing more concepts and explanations	(12) 18.75
2CI (A)	Improve the planification of the course	(8) 12.5
3CI (A)	More exercises and practise would be wellcome	(2) 3.125
1PI (A)	Reduce the complexity of the topics	(1) 1.5625
	No answer	(41) 64.0625
1CI (B)	Combine theory and practice	(13) 20.3125
2CI (B)	Include more practical exercises	(12) 18.75
1PI (B)	Include more acoustic courses in architecture curriculum	(1) 1.5625
	No answer	(40) 62.5

Table 3. Particular questions of the experiment

Code	SD	Av. Score	SD
E1.1	Do you think "DESIGN-BASED WORKSHOP" method is useful to learn architectural acoustics?	5.31	1.17
E1.2	Was the workshop presentation good?	5	1.32
E1.3	Is the structure of the sessions appropriate?	5.13	1.25
E1.4	Is it easy to handle with the proposed exercises?	4.91	1.27
E2.1	Would you use this method to deep more into acoustic knowledge?	4.91	1.34
E2.2	Is the number of exercises related with the proposed time?	5.59	1.30
E2.3	Is it possible to solve the presented exercises?	5.78	1.11
E2.4	Is it easy to imagine spaces from a soundscape?	4.22	1.60
S1.1	Do you like this method?	5.16	1.49
S1.2	Do you feel comfortable working with this method?	4.94	1.56
S1.3	Is this method enhancing your acoustical knowledge?	5.125	1.32
S1.4	Is this method enhancing your spatial imagination?	5.125	1.13

points) were separated according to the coding scheme shown in Table 1 and 3.

The common elements that were mentioned at a higher rate are the most important aspects to use, improve, or modify (according to their positive or negative sign). The particular elements, due to their citation by only a single user, may be ruled out or treated in later stages for development.

Once the features mentioned by the students were identified and given values, the third step defined by the BLA initiated the qualitative stage in which the students described and provided solutions or improvements to each of their contributions in the format of an open interview.

Table 3 shows the main improvements or changes that the students proposed for both positive and negative elements.

Additionally, some particular questions were done to the students regarding "efficiency", "effectivity" and "satisfaction"

4. Discussion

At this point, it is possible to identify the most relevant items obtained from the BLA, which had high rates of citation, high scores or a combination of both. It is important to separate the types of results obtained. The first group belongs to option A (design-based workshop), and the second group to option B (theoretical masterclass). After the elicitation of the most relevant features of each of them, a comparison is going to be done.

Option A (design-based workshop). It is possible to highlight that this kind of teaching method is a good example of learning by doing procedure (MI: 31.25, Av: 8.55), it is considered as a good practical work with sound (MI: 25, Av: 8.125) and it seems to be a good introduction in the world of acoustics (MI: 18.75%, Av: 9). Additionally, it holds a good reputation as easy to understand (MI: 15.625%, Av: 8.4). In terms of the main negative comments, students clearly identified a lack of theoretical background in this kind of experience (MI: 37.5%, Av: 4.833), that was clearly related in the need of conceptual clarity in explanations (MI: 37.5%, Av: 4.5).

Option B (theoretical masterclass). Two main positive aspects were highlighted by students in this second method: the high level of details learned by this method (MI: 43.75%, Av: 7.5), and the clarity of concepts explained before the exercises are done (MI: 15.625%, Av: 7.8). Conversely, some negative comments were pointed out: the lack of practicity (MI: 21.875%, Av: 5) the difficulty to follow the masterclass (MI: 18.75%, Av: 4.333), and the need of more time of explanation (MI: 9.375%, Av: 6.333).

In summary, two clear opinions about the experiment were shown, which confirm the first question of the survey: Which method do you prefer, A or B? Most people (62.5%) agreed that option A was better than option B. The reasons for this answers were clearly explained in the rest of the survey. Although there was a high valuation of method A as an example of learning by doing procedure (MI: 31.25%, Av: 8.55), it was also certain that the level of theoretical background was worse in A than in B, as it is possible to see when comparing 1NC (A) with 1PC (B). This indicates that the design-based workshop implies a decreased amount of theoretical concepts. This could be a drawback for students who want to learn about acoustics. However, the survey reveals another feature that must be taken into account: almost one fifth of the students (MI: 18.75%) considered this method an interesting introduction acoustics in architecture with an excellent score (Av: 9) (3PC [A]). This shows the hidden potential of this method for architects and building engineers.

An overlook of the improvements suggested by the students and the limitations of the method, some modifications on it should be taken into account. Firstly, a better organization of the workshop regarding timing, tasks deliveries, and meeting planning should be done. Secondly, it seems crucial that this practical method 1CI (A) should be reinforced with some theoretical explanations: the practical teaching should not blind the clear view of acoustic concepts.

5. Conclusions

The present study concludes that a good acceptance of the project-based experience in the field of room and building acoustics learning has been recorded by the students. Moreover, they value specially the change of paradigm from passive learning to learning by listening. These results encourage us that the inclusion of this method for acoustics teaching can be valuable in architecture and building engineering curricula. However, some remarks must be considered in order to achieve better results. The clue of these improvements was demonstrated in the survey. In particular, this method needs a high level of organization to avoid the distraction of the student and, additionally, it should always be combined with theoretical explanations on acoustic concepts.

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