Acoustic Virtual Reality as a Learning Framework for Built Environment Students

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Abstract

Virtual Reality (VR) technologies allow to experience the effects of different design configurations with strong immersion and are therefore also suitable to learn about different acoustic design configurations. The Eindhoven Acoustic Virtual Reality (EAVR) platform is a Unity application designed to experiment with different combinations of acoustic materials and room sizes while listening to these changes in real time. The application can be used with the Head Mounted Display (HMD) or from a computer screen. The scene acoustic properties can be edited and saved with observations on the current state, to be later recalled and compared while being in the room. The application makes use of a modified version of Resonance Audio, edited to make visible the absorption coefficients of the acoustic materials and the calculated reverberation time for educational purposes. The paper illustrates the design process leading to the first version of the application, and the main offered functionalities.

Keywords: room acoustics, immersive learning, virtual reality, spatial audio, built environment.

1 Introduction

Built environment students face high learning demands when starting university. Students are expected to learn quickly and effectively, amongst others, construction systems, building physics, and architectural design theory and practice. Poor room acoustic design yields a considerable impact on our daily life, and room acoustic design should therefore be addressed from the first years of training. Current consumer Virtual Reality (VR) systems support head and hand tracking, as well as room scale exploration. They allow the user to explore spaces while potentially listening to virtual reproductions for existing or imagined environments. However, there is shortage of technical solutions designed to facilitate the exploration of acoustic design principles in VR.

In this paper, a novel educational resource is presented, providing a high degree of immersion through VR while introducing the students to concepts related to acoustic design. For example speech intelligibility, which is influenced by room acoustics, can impact several activities in a given space, including typical class learning tasks like memorization and proofreading [1]. Speech intelligibility in an environment is mostly influenced the reverberation time and the ratio between the speech level and the background noise level at the listeners' position [2]. The speech intelligibility between a speaker and listener can be quantitatively measured or described through the speech transmission index (STI), where a value above 0.75 indicates excellent speech intelligibility and a value below 0.3 indicates nearly unintelligible speech [3]. Therefore our goal is to let students explore the audible differences of different room sizes and materials, and the related reverberation time, with respect to a given simulated speech source and listener position. To achieve this task we started from a simple shoe-box simulation, which is presented in this paper, and later introduced new features, such as the capability to import user-generated geometrical models at run-time.

The paper is structured as follows: Section 2 covers VR technologies applied to the field Architecture, Engineering, and Construction (AEC) for training and learning. Section 3 describes existing VR technologies designed with the intent to evaluate virtual acoustic environments, for research and education. Section 4 presents the design process for our solution, spanning from the design requirements to its development. Section 5 describes the main functionalities of the application developed, named Eindhoven Acoustic Virtual Reality (EAVR). Section 6 proposes an evaluation strategy, Section 7 presents challenges and future steps, and Section 8 concludes the paper.

2 Virtual Reality for Education in Architecture Engineering and Construction

Education in Architecture Engineering and Construction (AEC) often partly relies on Project Based Learning (PBL), situating exercises in plausible or real scenarios, created within the design studio paradigm. Virtual reality technology for education in construction and architecture has been studied in [4], [5], [6], [7], and [8]. Wang et al. [4] reviewed in detail 66 papers on the use of VR technologies for education and training, identifying five main technology categories: desktop VR, immersive VR, 3D game-based VR, building information modeling VR, and augmented reality. The authors found that VR applications are mostly used in architectural visualization and design education, construction safety training, equipment and operational task training, and structural analysis education. Following their review, the authors revealed five future directions for VR-related education in construction engineering: (i) integrations with emerging education paradigms; (ii) improvement of VR-related educational kits; (iii) VR-enhanced online education; (iv) hybrid visualization approaches for ubiquitous learning activities, (v) rapid as-built scene generation for virtual training. Therefore, the development strategy adopted for our tool should consider these promising directions.

3 Existing Acoustic VR Solutions

A growing number of systems allow to construct an acoustic scene with controlled conditions and reproduce it to the listener for experimental observations with scientific and educational intents. Virtual Acoustics (VA) by RTWH [9] is a real-time auralization framework that allows very fine control on spatial audio rendering implementations. The code is in C++, primarily targeting Windows platforms, and it also offers a package to use the C++ VA interfaces from the game engine Unity, through a series of C bindings that can be easily attached to GameObjects, the base class for all entities in the Unity scene. The framework also offers the opportunity to implement a custom real time auralization algorithm.

VA can in principle be used in partnership with the Sketchup plugin and C++ application RAVEN [10, 11], also developed with educational intents by RTWH Aachen. Architectural design students are often asked to become familiar with the Sketchup modelling software and therefore RAVEN represents a valid solution to experiment with model design, assign materials, and generate in real time impulse responses that can be used for auralization purposes. RAVEN as a standalone version belongs to the category of desktop VR according to the categorization in [4], since direct use of HMD is not available. For the version currently available, only one source at a time can be auralized in real time and using the application on an arbitrary machine requires to obtain an educational license first. Furthermore, the auralization code is not modifiable by external parties.

EVERTims is an open-source framework for real-time auralization in architectural acoustics and virtual reality [12]. Arbitrary geometries and materials can be changed in real time, as well as the position of the source and the receiver. The Open Sound Control (OSC) protocol allows to broadcast in real time updates from the Blender modelling software to the auralization engine, built using the audio framework JUCE. HMDs can be used to navigate the scene in Blender. However, the solution was not available for Windows platform when the project presented in this paper started.

The open-source project Resonance Audio allows creation and control on complex virtual acoustic environments in real-time. The Resonance Audio Software Development Kit (SDK) [13] includes the C++ library, the MATLAB library for helper Digital Signal Processing (DSP) functions, and platform integrations for game engines and audio / video editing software. Major platforms are supported, with attention to efficient audio rendering; the techniques adopted include thread-safety, non-blocking APIs, minimum audio processing latency (no buffered processing of audio data, single-threaded audio processing pipeline) and a small binary footprint [14]. The room acoustics spatialization method in the Resonance Audio core library works through audio processing nodes in a graph, always updating when any change occurs, such as changing the listener and source position. The reflection and reverb processing units are part of this graph, and can be switched on and off together as a total "room effect". The early reflections are built using directional delays (one for each shoebox wall), attenuated according to the room materials, while the reverb, that is equipped with an onset compensator, is generated using the Spectral Magnitude Decay method [15]. This method enables synthesis of late reverberation based on the scene conditions, with controllable decay times as a function of frequency.

4 Design Process

This section explains the steps undertaken in the design of the Eindhoven Acoustic VR (EAVR) application, detailing motivation, user analysis, goals, and design requirements.

4.1. Motivation

We aimed to develop EAVR to facilitate more intuitive learning based on listening experience rather than just interpreting and applying calculation methods. Moreover, we wished to integrate existing teaching practices, such as the design studio approach, in the application workflow.

4.2. User analysis

The first year Bachelor project course in the Bachelor programme of the Department of the Built Environment, called BAU Studio, is an introduction to architectural design and construction. Students attending this course have little knowledge of 3D modelling, architectural design, and building physics, including acoustics. Thus, the tool should not require them to have existing technical experience in these field but rather introduce them to topics that will be part of their future studies in the Built Environment department.

4.3. Project Goal

The aim of the application is to allow the students to reflect on the impact of design choices on the acoustics of a place. The application should also help them learn about basic principles of room acoustic modelling and related technical terms.

4.4. Design Requirements

Based on our use case and the suggestions from the existing studies on the use of VR in learning and training for AEC, the following list of requirements was extracted.

Interactivity

Using Head Mounted Displays (HMDs) for VR in combination with head rotation tracking and headphones allows the complete virtual replacement of the visual and aural scene. Researchers seem to agree that realism and gamification can foster engagement and indirectly motivation, whilst cyber-sickness yields detrimental effects. Locomotion systems enable the exploration of the virtual space. They are crucial tools for the exploration of virtual architectures. Locomotion systems can be based on natural scale movement or movement mapping devices such as the virtual treadmill, the joystick, or other kinds of controllers.

Accessibility and Creativity Support

Students who want to experiment with 3D modelling design and how this translates to a virtual acoustic environment might find beneficial to quickly experience acoustic consequences of room size and material properties. Adopting a screen-based desktop interaction can yield increased accessibility with respect to HMD-based VR. On the other hand, the higher degree of immersion provided by the HMD and controller might be beneficial towards faster learning, while, in contrast, a more fatiguing experience.

Technical simplicity and coherence

The application should employ not too complex technical terms and introduce to the relationship between architectural design and acoustics. Typical architectural elements such as room, materials, walls, ceiling, floor, should be put in an intuitive perceivable connection with their acoustic properties. We aim to introduce the relationship between room volume, surface areas, absorption coefficients, and reverberation time, in a self-explanatory way, aiding the listening process with the display of the numerical data in the form of graphs or numerical values.

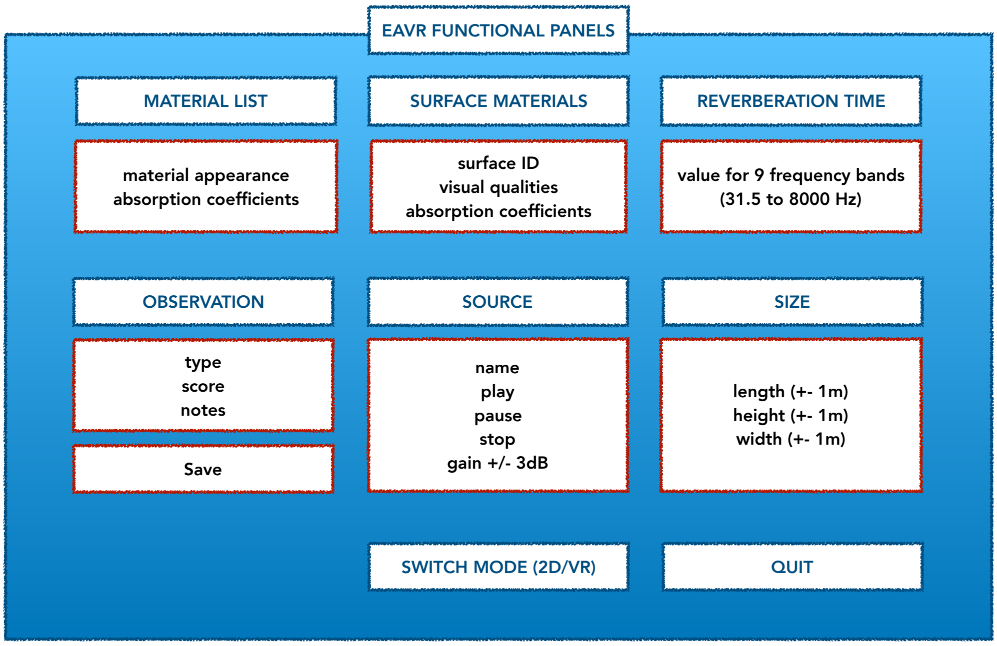

Figure 1: Simplified description of the functional panels in the EAVR graphical user interface

5 Proposed Solution: Eindhoven Acoustic Virtual Reality (EAVR)

The application design is based on the idea of changing the acoustic properties of the room through an intuitive interface available to the user both from a screen-based and HMD-based VR experience. The library Resonance Audio was chosen for: (i) being open-source software, thus allowing changes to the source code; (ii) being compatible with different platforms, including Windows, largely adopted in the Built Environment department; (iii) for offering efficient and fast audible updates at the changing of the room properties. For first year students approaching acoustics, the shoe-box approach implemented in Resonance Audio was considered suitable for offering a simple cause-effect development and thus it was adopted in the development of EAVR.

The main functionalities of the application can be divided in six groups plus a Quit and Switch mode. The six functional groups shown in Figure 1 represent all the controls that the user has on the virtual scene. In order to use the application, the user needs a personal computer with windows for the screen-based version, and, for the HMD-based version, a VR-enabled pc, the Oculus Touch Controller, and the Oculus Quest (+ link cable) or Rift HMD.

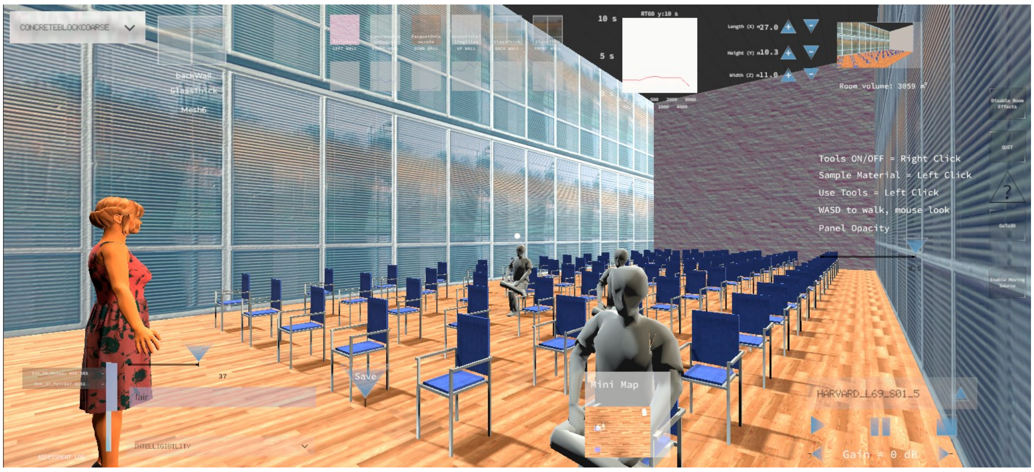

Figure 2: Appearance of the screen-based EAVR application

5.1. Workflow explanation

At startup the user can choose whether to use the application with the screen-based or HMD-based version. Once this choice is made, a room appears in the scene with default dimensions (17.3m, 5.3m, 8m). These dimensions, although slightly different because of architectural details, are based on the model of an existing shoe-box lecture hall in Bologna (hall c, volume of 850 m^3) acoustically measured and simulated, thus providing ground for comparison between the existing data and hypothetical solutions [16]. The source is represented by the avatar of a female speaker and is placed by default next to one of the narrow walls. When words from the Harvard speech corpus are selected, a list of words will be played back from the position of the speaker's head, oriented towards the audience. The source directivity is set as fixed within the application with a cardioid pattern based on voice directivity on the horizontal plane [17]. In the virtual room the user can interact with the room properties, for example selecting a wall and replacing the acoustic material or changing the room dimensions. This change might be more or less aurally perceivable, but still graphically visible. The new reverberation time appears as an overlay on the old one, which fades away. The user can also navigate the room through teleportation / thumbstick (HMD-based) or arrows (screen-based) and save own comments and a numerical value going from 0 to 100 to give a score to intelligibility and reverberation. The underlying idea is that perceived intelligibility score can be easily matched with STI quality ratings, for example mapping the 0-1 STI range to a 100-point scale to obtain the following scores: bad (<30); poor (>30, <45); fair (>45,<60); good(>60,<75); excellent (>75) [3].

5.2. Acoustic Materials List

This dropdown menu currently includes a list of the acoustic materials belonging to the Resonance Audio library. The original Resonance Audio library was edited to allow the retrieval of the absorption coefficients of acoustic materials and the calculated reverberation time so that they could be displayed as graphical information, and thus enhance the student's learning process. Every material in this list holds absorption values going from 0 to 1 for nine octave frequency bands (31.5 Hz to 8000 Hz). When the user selects the material, the corresponding curve is shown in a dedicated panel. This panel works as a sort of property inspector, showing also the last selected wall surface and its acoustic material (top left of Figure 2).

5.3. Surface Materials

This interface top area shows the 6 shoe-box material names and corresponding textures, and a graphic representation of the absorption curve for each surface. The absorption curve is retrieved directly from the walls of the Resonance Audio Room entity, thanks to a new function added in the original Resonance Audio code that extracts the absorption coefficient values for the queried materials.

5.4. Reverberation Time Display

This panel, visible on top-right in Figure 2, presents the reverberation time curve as calculated by the Resonance Audio library, and extracted through a new custom function, which follows the Eyring calculation method shown in the following equation

$$RT60_f = \frac{0.161V}{-S\ \ln(1-\bar{\alpha}_f) + 4m_f V} \tag{1}$$

where $RT60_f$ represents the reverberation time for each octave frequency band (31.5 Hz to 8000 Hz), V is the room volume (m^3), S is the total room surface area (m^2), $\bar{\alpha}_f$ is the average absorption coefficient for the frequency band in consideration, and m_f is the frequency dependent energy attenuation constant. With respect to this calculation, it is interesting to note that the values for m_f are derived from a table in [18] through extrapolation for lower frequencies. The adoption of this simplified calculation can be considered appropriate for the shoe-box case for a diffuse sound field in a relatively compact room.

5.5. Observation Panel

The observation panel (bottom left in Figure 2) allows the user to rate the scene numerically and through text judgements, for both intelligibility and perceived reverberation. Once an observation is saved through a button, it appears with the note details on the bottom left, available to be recalled at a later state just by clicking on it. The observations are saved in a JSON file and can be shared across users. The saved observations are accompanied by information that contains all the relevant data for the scene, such as the shoe-box dimension, the materials chosen, the listener and source position, allowing direct perceptual comparison between different scene states.

5.6. Source Control

This panel (bottom right in Figure 2) allows to select the input source from a series of predefined anechoic samples, which can be extended by the user upon choice. The audio file should be provided as mono, with any sampling rate allowed by Unity. The files are reproduced from a play button, overlaying sounds if this is pressed before the sample ends. Next to this there are the pause button and the stop button. Two arrows allow to increase or decrease the gain by 3dB.

5.7. Dimension Size

These controls (top right in Figure 2) allow to increase or decrease each room dimension by 1 meter independently: length, height, width. The change is reflected in the update of the room visual appearance and the Resonance Audio Room model, triggering the update for the reflections and reverb audio processing nodes as explained in Section 3.

5.8. Switch ad Quit

These buttons allow to switch between screen-based and HMD VR and quit the application. A slider helps setting the transparency of the functional panels with respect to the in-game scene. Current developments include a button to switch the reflection and reverb node on and off, and a button to display an interactive moving source.

6 Proposed Evaluation

A first round of testing has been conducted for the initial shoe-box prototype, which triggered some usability improvements and suggestions already implemented. For example, the possibility to navigate through teleportation in the HMD-based version to avoid motion sickness and the request for custom audio input. The testing of the new version of the application with the built environment students will be conducted in the future

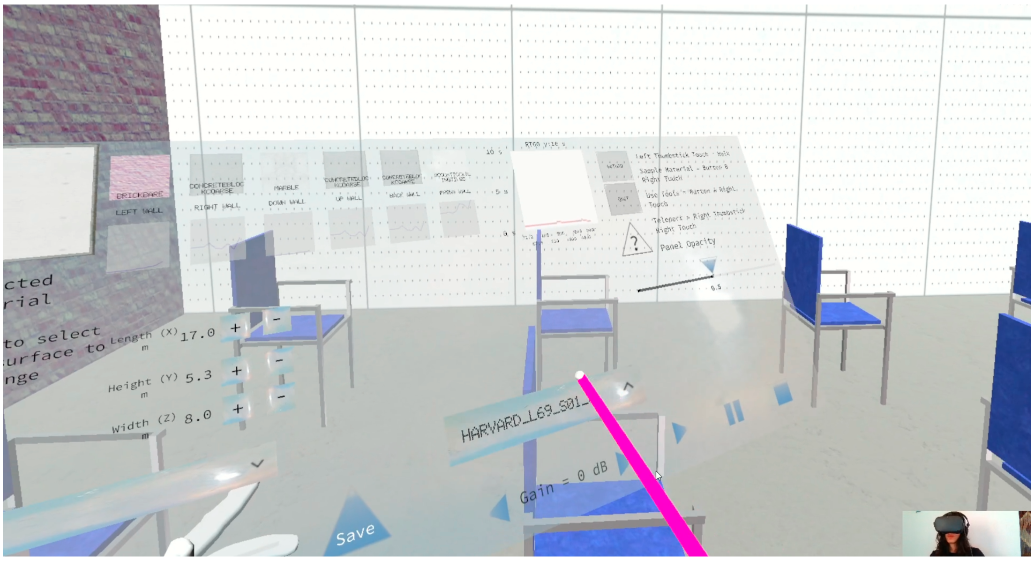

Figure 3: Appearance of the HMD-based EAVR application, showing the interface controls on a virtual tablet anchored on the left wrist.

months. The screen-based application should be launched by the students on their personal computer, while the HMD-version requires access to an Oculus Quest with link cable or Rift, left and right Touch controllers, and a VR-enabled laptop. Therefore, the evaluation with the VR hardware will be conducted in the laboratories of the university which offer these facilities, or remotely if other interested parties have the gear available.

Collaboration among students can be fostered through the exchange of the data saved, allowing for group comparison activity. A reflective questionnaire post experience can capture the technical challenge level, while specific questions on presence and immersion can help compare the screen and HMD versions of the educational tool and their potential role in aiding the learning process. Metrics aimed at capturing the student performance should be decided in agreement with the teachers. Fruitful exercises should aim at creating complex reasoning on the physics of sound in architectural spaces, even if digital: examples can be achieving a better sounding geometrical solution for a given set of materials, finding the worst sounding position in a given space and improve it, achieving the optimal reverberation time for a certain activity, and so on.

Finally, the application is based on the idea that changing the room model while observing audible and visual changes can generate new knowledge. In Figure 4 this circularity between observations and interaction is depicted: observing the current situation for the virtual environment might cause the will to change the properties of the room to achieve better intelligibility or experience unknown design solutions. Changes in the audible scene can be appreciated when changing head orientation, position in the room, or changing the room properties such as materials and size. It would be beneficial to capture how each of these variables and how the activity of storing and comparing room states impacts the learning process.

7 Challenges and Future Steps

Among the limitations of the simple shoe-box approach there is the problem that the reverberation time calculation used by Resonance Audio does not consider the audience or chair absorption, which should also be taken into account in the reverberation time estimation [19]. With this respect, a functionality which fills the floor area available with a fitting number of seats has been designed to give a sense of perspective and functionality to the virtual lecture room, otherwise very bare and looking empty. Future developments should explore the possibility to add dedicated absorption properties to the area filled with the audience chairs. Another limitation is that the Eyring calculation method should be applied when the absorbing power is almost uniformly distributed over all the room surfaces and the sound field is diffuse in a way that the results stay

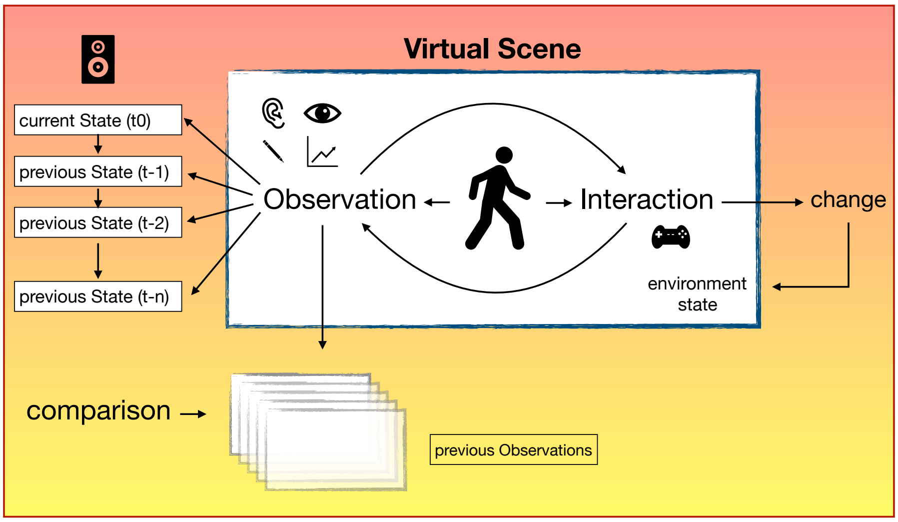

Figure 4: The Observation - Interaction activity enabled by the EAVR application

almost independent of the room's shape [19].

In the new version of the application, user defined models can be imported at runtime using the GL Transmission Format (glTF) format, that allows for interoperability between Sketchup and Unity. The Eyring formula can be easily applied to a number of surfaces higher than the standard six shoe-box surfaces. However, it is yet to be defined how to go from the fixed number of six early reflections to a more generalizable case for arbitrary geometries.

With respect to source directivities, Resonance Audio sources can be described with a value going from 0 (omni) to 1 (figure-of-eight) with additional control on directivity sharpness (1 to 10). According to the code documentation, a value of 0.5 will produce a cardioid pattern. Our application started from the case of a speaker in a lecture room, but in the future, different sound source types should be associated with their correspondent directivities and possibly a matching avatar to support enhanced realism.

8 Conclusions

This paper presented a technical solution aimed to allow built environment students experience acoustics in VR. Key aspects crucial to the development of virtual reality training for construction and engineering were identified and addressed during the design process. The current version of the application allows users to edit materials and size for a shoebox room and save their observations on intelligibility and reverberance. The system presented hereby is the initial demonstrative version for a single shoe-box-shaped room, that students can use to experience the impact of changes of materials and room size on its acoustics. Current development efforts are targeting a version that would better fit the students: they will import the space they have designed themselves and evaluate the acoustics in it. What is presented in this paper should thus be seen as a part of a bigger toolset.

Acknowledgements

This project has been funded through the BOOST innovation in education programme by Eindhoven University of Technology (boost.tue.nl).

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