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Acoustic Classroom: Using a virtual reality application to promote awareness for room acoustics in learning environments

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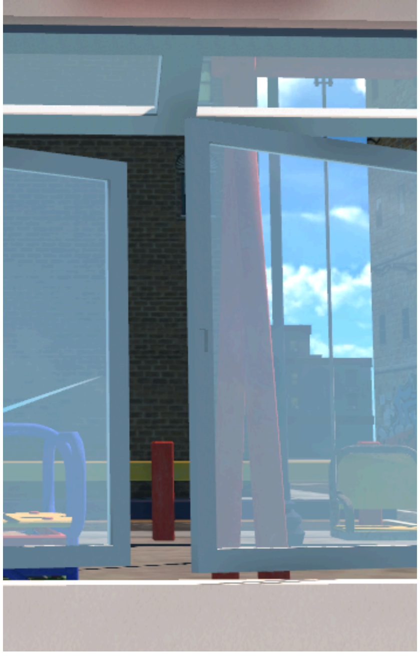
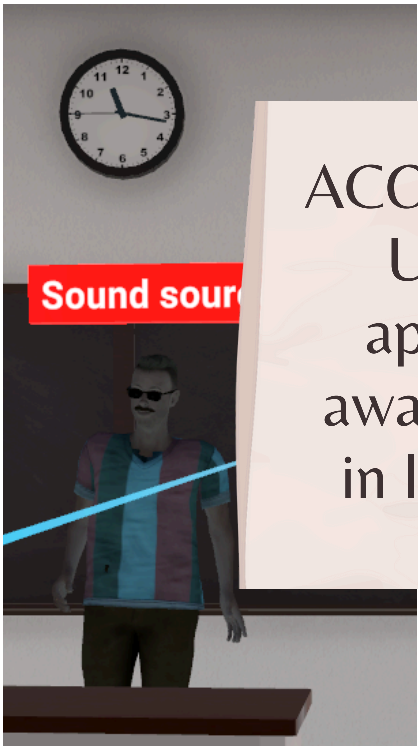
Abstract:

This thesis explores the application of virtual reality (VR) to enhance acoustic awareness among school teachers, focusing on the simulation of classroom acoustics within an interactive virtual environment (VE). By integrating insights from related research on acoustic simulation and VR's educational potential, this study developed and refined a VR prototype to provide an immersive learning experience for teachers. The initial prototype allowed users to experiment with various acoustic settings and materials, and feedback from this phase was used to improve the design and functionality in a subsequent prototype.
The effectiveness of the final prototype was evaluated through a series of tests conducted with school teachers. Results indicate that while the prototype succeeded in enhancing participants' understanding of acoustic principles, the small sample size and the preliminary nature of the evaluations limit the generalizability of these findings. Despite these limitations, the study demonstrates the potential of VR as a tool for education in acoustics, highlighting the need for further research with a larger participant pool. The results from a anticipated follow-up questionnaire are expected to provide additional insights into the long-term impact of the VR intervention on participants' acoustic awareness.





ACOUSTIC CLASSROOM: Using a virtual reality application to promote awareness about acoustics in learning environments

Acoustic Classroom: Using a virtual reality application to promote awareness for room acoustics in learning environments

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Contents

ABSTRACT

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1. INTRODUCTION

The perception of speech is significantly influenced by the acoustic characteristics of the environment [1, 2]. In a classroom setting, degraded speech intelligibility can have consequences for a child's learning [3]. The most important acoustic parameters affecting speech perception are reverberation time (RT) [2, 3] and background noise [2, 3]. Other parameters such as the level of the teacher's voice and the distance from the teacher also have an impact [2]. When the teacher speaks, the sound waves reflect off the surfaces in the classroom. The child will therefore hear some of the direct sound from the teacher, but also the reflected sound causing reverberation [3,4]. A long RT and reflections from background noise will decrease speech intelligibility in a classroom [3,5].

RT is of often determined by sending a noise burst or impulse into a room, and then analysing the energy decay curve of the recording [6]. One often used measure is the RT_{60}, which is the time from when the impulse stops, to the energy in the room has decreased by 60 dB [6]. RT_{60} can also be estimated by the following formula [4]:

$$RT_{60} = \frac{0.161V}{\sum S\alpha}$$

In this equation "V" is the volume of the room, "S" is the surface area, and "α" is the absorption coeffecient at any frequency for each of the materials of the surfaces. Understanding this, the RT_{60} of a given room can be changed by either reducing the size of the room, or increasing the sum of the absorption coefficients [4]. Thereby, changing the materials in a classroom to be more sound-absorbing, is a efficient way to improve acoustic [3,4]. In Denmark, there have been maximum RT_{60} standards in renovated schools since 2008, with 0.6 seconds RT_{60} in renovated schools and 0.9 seconds RT_{60} in older schools [7]. Nevertheless, a study by Crandell Smaldino (2000) suggests that the RT should be 0.4 to 0.6 or under [2].

Classrooms will often be prone to background noises such as playgrounds, traffic, and internal noises within the building [2,3]. Background noise in a classroom will often vary a lot over time, so it is difficult to describe it with a single number. However, a study by Crandell Smaldino (1995) found an unoccupied classroom to have a noise level of 51 dBA [8]. Because of the loud background noise, the teacher will have to speak louder to achieve an appropriate signal-to-noise ratio (SNR).

These factors cause children to have to use more cognitive resources to compensate for the signal distortion of background noise and reverberation [9]. Especially, hearing-impaired (HI) individuals have difficulties understanding speech in noisy and reverberant environments [2]. A normal-hearing (NH) individual will have no problem understanding speech until the SNR hits 0 dB, however, a HI individual will require around 4–12 dB, and an additional 3–6 dB in rooms with moderate levels of reverberation [2].

Because of these difficulties, it is essential to raise awareness about the importance of good acoustics in a learning environment. A full renovation of the classroom is not necessary for the improvement of acoustics, as the addition of sound-absorbing materials, such as curtains or carpets, can have a significant effect [4]. Experiencing how these modifications can improve acoustics in real-time, might help raising awareness about classroom acoustics. Virtual Reality (VR) is a technology that can provide an immersive and ecologically valid environment [10]. VR has successfully been used in other research to promote awareness about topics such as climate change [11,12].

Raising awareness about acoustics requires a virtual environment (VE) to faithfully replicate a real-world auditory experience. Therefore, it's crucial to simulate sound behavior accurately. This involves capturing how sound is perceived by the human ear in three-dimensional space and considering the acoustic characteristics of a classroom.

When pinpointing a sound source in three-dimensional space, it involves hearing its angular position (both azimuth and elevation) as well as its distance from the listener [13]. Before reaching the eardrums, sound waves undergo diffraction by features such as the torso, shoulders, head, and pinnae, thereby altering the sound spectrum [14]. Sound localization by the human auditory system relies on these cues including the diffraction of sound waves, interaural time differences (ITD), and interaural level differences (ILD) [13, 15]. However, this modification of sound waves can be intricate and varies significantly from person to person [14]. Individual-specific cues for direction are often encapsulated in what's known as a Head-Related Transfer Function (HRTF) [16]. For utmost accuracy, the HRTF data is typically captured through its equivalent Head-Related Impulse Response (HRIR), necessitating measurement for each listener [14, 16].

In modeling the acoustics of a real-world setting, a prevalent approach involves utilizing recorded Room Impulse Responses (RIRs), which are then combined with an original signal through convolution [17]. Nonetheless, this method has its limitations as RIRs only encapsulate the specific characteristics of the room and the setup of the source and receiver [18]. Consequently, to anticipate the acoustic properties of any given room and the positioning of sources and receivers, alternative room modeling techniques are needed [18]. These methods enable the synthesis of RIRs tailored to arbitrary configurations. Among the most utilized techniques for real-time applications are ray-based methods based on geometrical acoustics (GA) [18]. In GA, accurate representation of each geometric element's material is crucial, involving parameters such as scattering coefficient (i.e., the amount of sound deflected away from specular reflection) [19], and absorption coefficient (representing the amount of sound absorbed by the material) [20]. Several sound engines are available for implementing room modeling effectively for VR [21].

This paper explores the potential of developing a realistic interactive audio-visual virtual environment (VE), with the purpose of raising awareness about acoustics in school classrooms. This includes implementing a interactive 3D scene in VR, auralization of recorded audio, and the simulation of a hearing loss.

2. RELATED RESEARCH

2.1 Improving acoustics in classrooms

In a study conducted by Abraham et al. (2021) [4], the researchers examined methods for reducing the reverberation time (RT_{60}) in classrooms through the implementation of straightforward and practical acoustic modifications. In various classrooms, they installed heavy curtains that extended to the floor and spread thick carpets across the unoccupied areas. The incorporation of these readily accessible materials resulted in a significant reduction of the average RT_{60} from 4.37 seconds (i.e., in an empty classroom devoid of curtains, carpets, or furniture) to 0.74 seconds (i.e., with the addition of curtains, carpet, furniture, and students) [4]. The findings of this study demonstrate the feasibility of decreasing RT_{60} using simple interventions. For the prototype discussed in this paper, the primary objective is to simulate the enhanced acoustics provided by such materials in real-time within a VE.

2.2 Promoting awareness using virtual reality

As described in section 1, VR has been effectively utilized in prior research to promote awareness. As an example, a study by S. P. Thoma et al. (2023) [12], a immersive virtual environment was implemented as a tool to promote the abstract nature of environmental change [12]. The succes of these environments was tracked by an increase in pro-environmental attitudes among the participants [12]. By immersing the user directly in any environment VR seems to be a promising tool for promoting awareness. Implementing VR can however be complex, and the level of realism achieved can vary a lot. When a high realism is achieved VR is useful for simulating real-life situation [10]. In the case of this paper, the user can be immersed directly in a school environment with bad speech intelligibility. Furthermore, VR brings the ability to manipulate the acoustic characteristics of environments in ways that are impractical in the physical realm, thereby providing a platform for enhancing understanding of the acoustic challenges in a learning environment, and means to optimize it.

2.3 Sound engines for immersive audio in virtual reality

To effectively promote awareness about acoustics, the acoustic simulation should be realistic and adaptive. In order to generate lifelike auditory experiences within VR, integration of third-party acoustic plugins is often required. Steam Audio[1] is a plugin for game engines which facilitates the emulation of physical environments through ray-based GA [21]. Steam Audio is a intermediary solution between game audio design and physically precise modeling, and has proven its capability in delivering reasonably accurate acoustic simulations [22]. Studies, such as [23], have effectively used Steam Audio for the simulation of authentic acoustics. Conversely, Wwise[2], a middleware solution, offers a variety of plugins tailored for auralization purposes. In a comparative study conducted by Firat et al. [21], Steam Audio, however, exhibited closer adherence to real-world air absorption characteristics. While certain alternatives delve deeper into architectural acoustics, their suitability for game audio tasks—essential for VR development—remains limited [21]. Although other tools for acoustic simuation might be more precise, Steam Audio emerges as a good choice for straightforward yet ecologically valid auralization, thus justifying its utilization for sound rendering in the prototype presented in this paper.

2.4 Individualized vs non-individualized HRTFs

As mentioned in Section 1, it is essential that the prototype in this paper renders the sound using HRTFs. However, the task to craft individualized HRTFs for each user presents challenges [14]. Brungard et al. (2017) conducted a study wherein both normal-hearing and hearing-impaired participants attempted noise localization utilizing non-individualized HRTFs and free-field speakers [24]. Despite a slightly heightened sensitivity among hearing-impaired subjects towards individual HRTF variations, the study found that employing non-individualized HRTFs should be feasible [24]. Other research also consider the viability of generic HRTFs due to the impracticalities associated with recording HRIRs. [14, 15, 24]. Considering the constraints surrounding personalized HRTFs, the prototype presented in this paper will use a generic HRTF from Steam Audio.

[1] https://valvesoftware.github.io/steam-audio/
[2] https://www.audiokinetic.com/en/wwise/overview/

3. REQUIREMENT SPECIFICATIONS

Based on the introduction (see section 1) and related research (see section 2), a list of specifications required for the design of the prototype has been made. The requirement specification can be seen below:

- A VE with a classroom setting where background noise and reverberation decreases speech intelligibility.
- The ability to start different sound sources, such as a teacher speaking, internal noises, and background noise.
- The ability to change and add somple sound-absorbing materials to improve the acoustics in the VE in real-time.
- Implementation of Steam Audio for auralization of dry audio (i.e., speech, music etc.). Including HRTFs and ray-based GA.
- A hearing loss simulator for the user to experience an estimation of the decreased speech intelligibility of a HI individual in an reverberant environment.

4. INITIAL PROTOTYPE

4.1 Design

As presented in Section 1, optimal acoustics are paramount in a learning environment. Thus, the scenario depicted in the prototype includes a classroom setting. An overview of the entire classroom scene is depicted in Figure 1. The project is designed to run on a Meta Quest 2 VR headset[3].

Figure 1: An overview of the scene in the initial prototype.

[3]https://meta.com

4.1.1 *Sound*

The scene encompasses sound sources including a teacher, children, and a speaker to simulate internal noise within the classroom (see Figure 2 and 3), alongside a playground outside to replicate background noise (see Figure 4). A monologue for the teacher was recorded in an anechoic chamber by a SM7B microphone, while the audio for the children and the playground was downloaded royalty free from Splice[4].

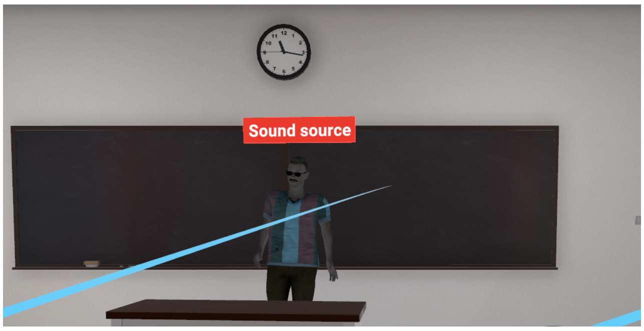


Figure 2: A screenshot of the teacher speaking in the scene.

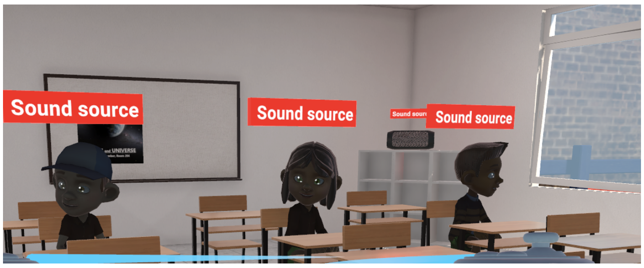


Figure 3: A screenshot of the children and the speaker in the initial prototype.

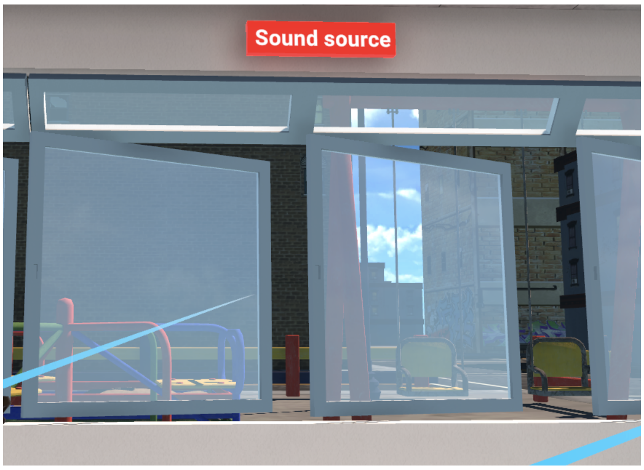


Figure 4: A screenshot of the playground sound source in the initial prototype.

As an additional feature, the users are able to hear themselves within the room, by pressing and holding down the

[4]https://splice.com/home

secondary button on one of the controllers. This will activate the microphone in the Meta Quest 2 headset, and send the audio signal out into the sound environment. Moreover, a range of ambisonic audio was incorporated, sourced from a study by Joerg Matthias Buchholz and Adam Weisser (2019) [25]. This addition aimed to enhance the perception of background noise in the environment. Additionally, sounds of footsteps on various materials were included to provide users with auditory feedback regarding the acoustics as they navigate the space.

4.1.2 Materials

For the different surfaces in the room (i.e., walls, floor and ceiling). Different sound absorbing materials was made available to add to the scene during runtime inspired by [4] (see section 2.1). To begin with, the four walls has a plaster surface (i.e., cement). While the floor and the ceiling has a surface of tiles (i.e., ceramic). All of these are highly reflective surfaces with low absorption coefficients. As a result, the initial sound environment has a high RT_{60}. However, for the walls it will be possible for the user to add a curtain or to add sound absorbing sound panels. While for the floor it will be possible to change the surface to a wood material, or to add a carpet of wool. For the ceiling it will also be possible to change the surface to a wood material, but also to sound absorbing panels of fibreglass.

4.1.3 Interactions

In the simulated environment, users have the ability to manipulate various elements, such as starting and stopping different sound sources (like the teacher or children) and changing the materials of surfaces to affect the acoustics. They can also add or remove furniture within the room. To interact with objects, a ray interactor tool is provided, allowing users to point at items and then use either the trigger or grab button on the controller to make selections. Once an interactive object is chosen, a menu pops up displaying different interaction options. To ensure ease of engagement, everything in the room is designed to be interactive, whether as a source of sound or as a material for modification. This approach simplifies the user's entry into interaction with the environment. Additionally, users can adjust a hearing loss simulator and activate the microphone of the device to hear themselves within the virtual space. To guide users through these interactions, instructional posters are positioned on the right wall of the environment, offering guidance on navigating the surroundings (see Figure 5).

4.2 Technical description

4.2.1 Virtual environment

The VE was developed using the Unity3D game engine[5]. To enhance the VE's interactivity and implement VR functionality, including ray interactions, the XR Interaction Toolkit by Unity was implemented. This toolkit provides comprehensive suite of resources, ensuring a smooth and

[5]https://unity.com

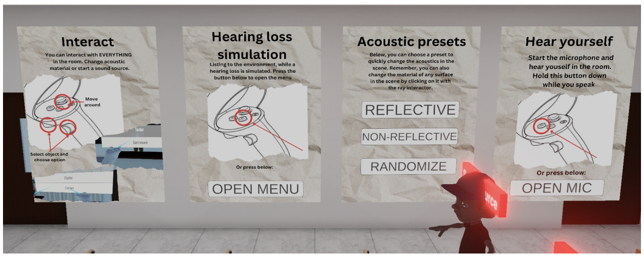


Figure 5: A screenshot of the posters introducing the interactions in the initial prototype.

engaging VR experience for users. To add lifelike characters and dynamic animations, the Adobe Mixamo[6] was used, leveraging its extensive library of 3D characters and animations.

4.2.2 Audio implementation and acoustic simulation

To manage audio within the environment, the FMOD middleware[7] was employed. FMOD organizes audio files into events, which are then grouped into a soundbank. This soundbank is exported for dynamic control through FMOD methods and components within the Unity platform. Within Unity, these events are linked to game objects, integrating the audio into the 3D scene. Integration with Steam Audio in FMOD allows for the implementation of GA[8] and Spatialization.

Implementing the ray-based GA technique in Unity requires surfaces to be tagged with specific geometric steam audio materials. These materials contain scattering and absorption coefficients for various frequency ranges (i.e., low, mid, high frequencies). When objects are tagged, they interact with sound by absorbing, reflecting, and transmitting it within the 3D scene. Steam Audio utilizes this material data to generate reflections based on the position and rotation of listeners (i.e., cameras).

The absorption coefficients for different materials are derived from the "Absorption Coefficient Database" provided by The Physikalisch-Technische Bundesanstalt (PTB), the national metrology institute of Germany[9]. These coefficients, along with the respective materials, are detailed in Table 5.2.

When using ray-based GA the two most influential parameters to control is the amount of rays spawned from a given sound source, and the amount of bounces each ray is allowed to do. Sending out more rays increases the quality of the RIR generated by the simulation, while increasing amount of bounces can help simulate a longer RT. However, increasing these parameters drastically increases the processing needed for the simulation. For this simulation to run smoothly standalone on a Meta Quest 2, it was found that 3500 rays and a maximum of 24 bounces results in a nice middleground between a valid simulation and a smoothly running application.

[6]https://www.mixamo.com/
[7]https://www.fmod.com
[8]https://valvesoftware.github.io/steam-audio/
[9]https://www.ptb.de/cms/ptb/fachabteilungen/abt1/fb-16/ag-163/absorption-coefficient-database.html

Material	Low	Mid	High
Plaster	0.12	0.06	0.04
Wood	0.2	0.15	0.06
Ceramic	0.01	0.01	0.02
Curtain	0.1	0.63	0.73
Carpet	0.06	0.37	0.65
Fibreglass	0.32	0.85	0.95

Table 1: All materials used in the initial prototype and their respective absorption coefficient for low, mid and high frequencies.

As mentioned in section 4.1.1, the user is able to activate the microphone of the headset, and pass the audio through the acoustic simulation. This is achieved by creating a programmer instrument in FMOD, and adding the Steam Audio plugin to this event. By calling a FMOD callback function within Unity, the audio data from the microphone, can be passed into the programmer instrument, at a given point in space of the scene. The outcome is auralization of the users own voice.

4.2.3 *Hearing loss simulation*

The hearing loss simulator developed for the prototype is grounded in the work of Mourgela et al. (2020) [26]. The described implementation was restructured in C++ to leverage the FMOD Plugin API [10] for exporting a dynamic library (i.e., plugin) tailored for FMOD, enabling integration into the Unity game engine. Additionally, the plugin was exported as a dynamic library for Android to operate independently on the Meta Quest 2 headset. The plugin was incorporated into the master bus in FMOD, influencing all audio post-aurilization. Various parameters from the plugin were made publicly accessible for dynamic control within the prototype (refer to Figure 6).

Figure 6: The implemented plugin within the FMOD middleware, featuring exposed parameters for dynamic control in a game engine.

In the plugin, the stereo signal from the master bus is split into left and right channels (representing each ear) before signal processing. The processing steps are depicted in a block diagram (see Figure 7).

Initially, the channel data undergoes audiogram matching. This is achieved using six Infinite Impulse Response (IIR) Notch filters, each attenuating specific frequency bands (250, 500, 1000, 2000, 4000, and 8000 Hz) to match the audiogram of mild, moderate, or severe hearing loss. After this step, the signal undergoes processing through a Gammatone Filterbank. This filterbank divides the signal into 32 bands spaced according to equivalent rectangular bandwidth (ERB), covering frequencies ranging from 20 Hz to 16000 Hz. The incorporation of the Gammatone Filterbank serves the purpose of aligning the band separation within the plugin with the natural separation observed in the human cochlea [26] (see section for 10.1.1 for details about implementation). The 32 bands is then split into two groups; high frequencies, and low frequencies.

The high-frequency signal then experiences spectral smearing, accomplished by multiplying each high frequency band with low-passed white noise. This produces a 'smeared' spectral representation, aiming to replicate the spectral smearing observed in individuals with decreased frequency selectivity [27] (see section 10.1.2 for more details). Subsequently, the high-frequency signal is then summed together and passed through a rapid loudness growth filter. This filter is implemented via an upwards expansion filter to increase the signal's dynamic range. This mimics the phenomenon of "compression loss", where a HI individual loses compression in the cochlear [28]. This causes loudness recruitment, where individuals with hearing impairment perceive a steeper growth of loudness with increasing sound levels above a certain threshold [26] (see section 10.1.3 for more information about implementation).

The low-frequency signal is also summed together and subjected solely to a temporal disruption filter, altering the temporal data by transforming the signal to the frequency domain using a Fast Fourier Transform (FFT). The phase of the signal in the frequency domain is then randomly shifted between $-\pi/2$ to $\pi/2$, while maintaining the magnitude. This process aims to recreate the loss of temporal resolution observed in individuals with hearing impairment [29] (see more in section 10.1.4).

As discussed in section 4.1.3, the hearing loss simulation can be controlled from the VE. Users can adjust the hearing loss for each ear using mild, moderate, or severe settings, thereby modifying the processing of either the left or right channel. The interface for this interaction is depicted in Figure 8.

[10] https://www.fmod.com/docs/2.00/api/plugin-api-dsp.html

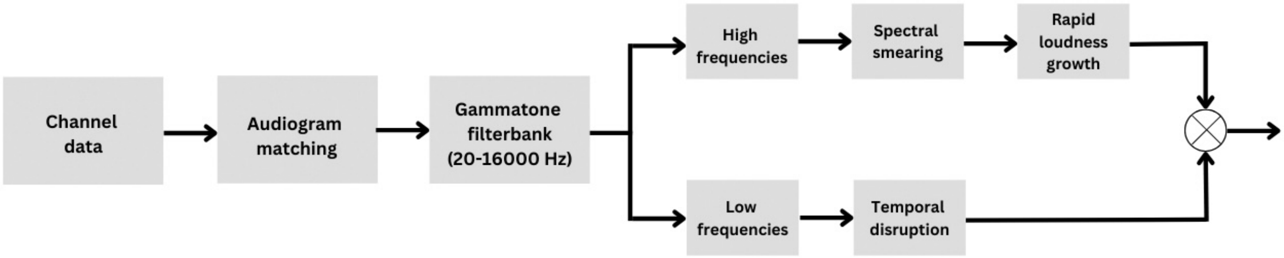


Figure 7: Block diagram illustrating the processing of each channel in the hearing loss simulator, preceded by stereo signal bifurcation.

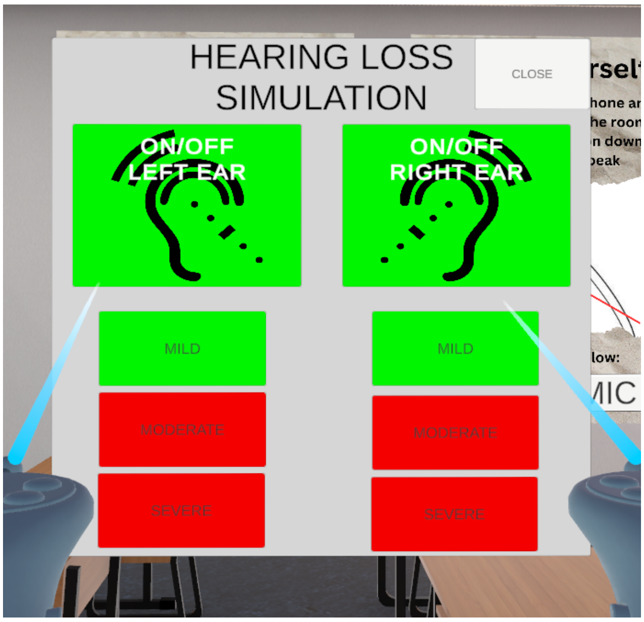


Figure 8: Interface for interaction with the hearing loss plugin developed for FMOD.

4.3 Evaluation

Following the implementation of the initial prototype, a usability test was conducted on four participants. Each participant was seated on a chair and asked to wear an Meta Quest 2 VR headset, along with a set of Audio-Technica ATH-M50X headphones. The aim of the test was to pinpoint any usability errors in the scene and to gather feedback on the realism of the sound and visuals. Prior to trying the application, participants received no instructions on how to navigate the scene. Instead, they were instructed to read the posters on the wall within the environment. There was no time limit, and participants were asked to use the scene until they felt they had exhausted all possible interaction types. After the test, participants were asked a short list of open-ended questions about their overall experience and any difficulties encountered while interacting with the environment.

4.3.1 Participants

All four participants had experience with VR development and were familiar with different interaction types in VR. None of the participants reported any hearing disabilities.

4.3.2 Results

Below is a list of the most significant feedback received from the test:

- Three out of four participants described feeling initially overwhelmed by the various interaction possibilities depicted on the posters. As a result, one participant suggested the need for a simpler tutorial guiding users through each interaction step by step.
- One participant felt that the curtains in the scene affected the acoustics too much compared to what was expected.
- The "close" button on the different menus was deemed too small and needed to be enlarged.
- One participant found it too easy to accidentally click outside the menus, triggering a new menu option unintentionally. Therefore, enlarging the menus was suggested to prevent this issue.
- Two out of four participants did not notice the playground as a sound source, resulting in them not starting it. Enhancing the visibility of the playground sound source was recommended.

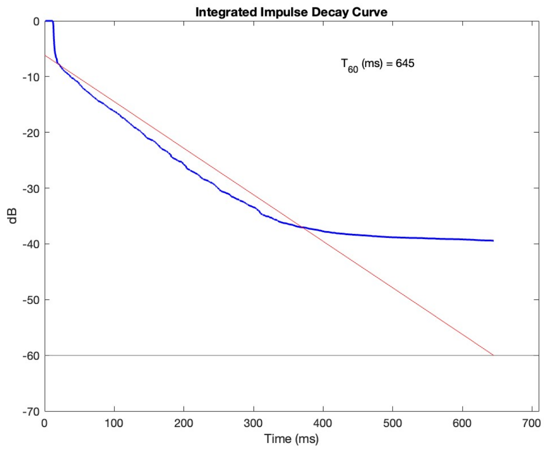
Despite these usability errors, the overall feedback regarding the realism of the sound and the visuals was positive. All participants were able to interact with the environment and change acoustic materials. Furthermore, all participants reported that they could clearly hear the change in acoustics when altering materials.

5. FINAL PROTOTYPE

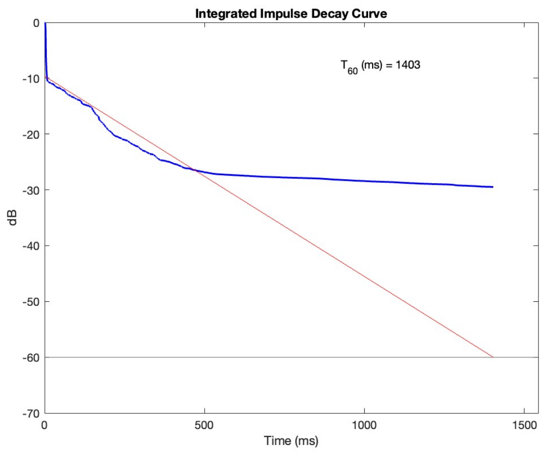
5.1 Usability optimization

Following insights derived from the usability test (see section 4.3.2), adjustments were made to refine the prototype. An initial tutorial was implemented to guide users through interacting with sound sources and materials. Within this tutorial, the teacher greets the user and directs them to add a curtain to one of the walls, followed by a guide to activate the playground sound source. The addition of instructions to initiate the playground sound source aimed to ensure that all participants noticed its presence. Moreover, the absorbance coefficient for the curtains was slightly reduced in response to user feedback indicating excessive sound absorption. Additionally, the "close" button on the menu was enlarged, and the overall size of the menus increased to reduce accidental clicks outside the menu area.

5.2 Real classroom comparison



(a) RT60 graph of the real classroom. RT60 = 0.65 s.



(b) RT60 graph of the virtual environment. RT60 = 1.4 s.

Figure 9: Comparison between the real and the simulated classroom.

In order to assess whether the acoustic simulation actually comes close to a real classroom, acoustic measurements of real classroom was made. The measured classroom is placed in the Harrestrup Å Skole[11] in Valby, Copenhagen (see classroom in Figure 10).

The RT60 of the classroom was measured by placing a microphone (i.e., a Neumann TLM103 condenser microphone) in the middle of the classroom, and sending out a impulse (i.e., a hand clap) close to it. The level of background noise was measured to be 22 dBA. It should be noted, that the recording of background noise, was made late in the day, when no children was present in the sorrounding areas of the classroom. Furthermore, the materials of the surfaces in the room was estimated. It seemed that the walls in the room was made out of concrete, while the floor had a linoleum surface and the ceiling had a surface of wood. Based on these estimation the starting point of the VE in the prototype was changed. As linoleum was not added to the environment yet, a material was generated with the absorption coefficients:

[11]https://harrestrup-aa-skole.aula.dk

Figure 10: The classroom from the Harrestrup Å Skole

Material	Low	Mid	High
Linoleum floor	0.03	0.035	0.05

Table 2: The absorption coefficients for the Linoleum floor

After these adjustments, the RT_{60} of the simulation was measured as well, by sending a impulse (i.e., hand clap) out in the environment, and recording the system audio. The results from the RT_{60} measurements can be seen in Figure: 9a and 9b.

As presented on the graphs, the VE has a over double as long RT_{60}, meaning the acoustics in the VE causes lower speech intelligibility than the real environment. Based on this, adjustments in the VE was made, so the RT60 of the VE comes closer the real classroom. The absorption coefficient of the linoleum material was increased to:

Material	Low	Mid	High
Linoleum floor	0.1	0.2	0.3

While the maximum amount of ray bounces in the simulation was decreased from 24 to 16 bounces. These minor changes caused the RT60 to become close to the real classroom (see figure 11)

6. FINAL EVALUATION

6.1 Methodology

After implementing the optimization noted in section 5, the VE underwent evaluation with three school teachers. Prior to engaging with the prototype, participants completed a pre-test questionnaire comprising three sections. The initial segment gathered demographic data regarding

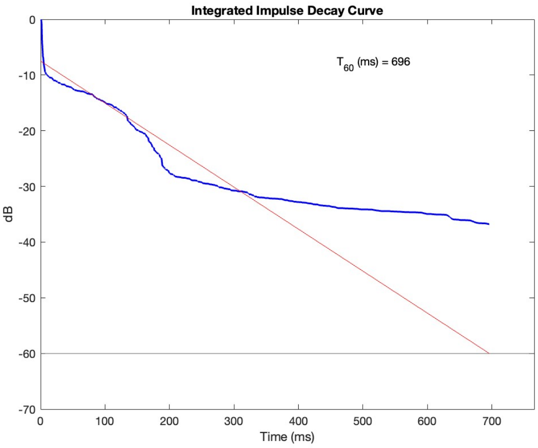


Figure 11: RT60 graph of the adjusted virtual environment. RT60 = 0.7 s.

VR experience and any hearing impairments. Following this, the questionnaire featured four Likert items for subjectively assessing classroom acoustics, referencing a study by Leśna et al. (2010) [30]. These items encompassed acoustic comfort, voice clarity, speech comprehension, and annoyance [30]. Additionally, two questions were appended to gauge acoustic awareness: one regarding the frequency with which teachers consider acoustics and another about whether they have ever taken measures to enhance acoustics in their classrooms. The final segment of the questionnaire consisted of a simulator sickness questionnaire (SSQ) [31], which will be repeated after trying the prototype to assess whether the VE causes any sickness.

After answering, the participants were introduced to the prototype, along with a small introduction to how to move and navigate the VE. They were also informed that everything in the environment is a simulation (i.e., both the ray-based GA, and the hearing loss simulation), and that it cannot be seen as a true replication of how acoustics or hearing loss sounds in the real world. See the full pre-test qustionaire in Appendix A.

After trying the prototype, the participant was asked a post-test questionnaire of also three segments. The initial segment was the SSQ, to assess sickness right after trying the prototype. The second segment comprises four Likert items to assess whether the participant was able to hear the difference in acoustics when changing materials, as well as whether the prototype gave the participant more insight into the effect of acoustics and how to improve it. Lastly, the participants answered the Igroup Presence Questionnaire (IPQ) consisting of 14 Likert items measuring spatial presence, involvement, and experienced realism in a VE [32]. See the full post-test questionnaire in Appendix B.

After answering the post-questionnaire, the participants' contact information was gathered, with the intent to send another short questionnaire two weeks after the test. This late questionnaire serves the purpose of measuring whether the participants have been more aware of acoustics in the weeks following the test. At the time of handing in this report, two weeks have yet to pass, and the result from this questionnaire will therefore not be included in this paper.

6.2 Demographics

Out of the 3 participants in the evaluation, none of them had any hearing impairment. The participants' ages ranged from 29 to 38 years, with an average age of 32.7 years. One participant had no prior experience with VR, while the two others had some little to moderate experience.

6.3 Results

6.3.1 SSQ scores

The cumulative scores from the SSQ were thoroughly analyzed. Both before and after the utilization of the prototype, there was no evidence suggesting an increase in symptoms such as nausea, oculomotor distress, or disorientation among the three participants.

6.3.2 Acoustic related items

As mentioned in Section 6.1, the pre-test questionnaire contained questions about the subjective acoustic experiences of the teachers within their respective classrooms. The results can be seen below in Table 3. Subsequent sections categorize and discuss the questions based on their thematic grouping, with a complete list of questions and their classifications available in the Appendix A and AppendixB.

Group	Mean	Min	Max
Acoustic comfort	3.7 ($\sigma = 0.47$)	3	4
Voice clarity	3.3 ($\sigma = 0.94$)	2	4
Speech comprehension	4 ($\sigma = 0.81$)	3	5
Annoyance	2.3 ($\sigma = 0.47$)	2	3
Acoustic awareness	2.7 ($\sigma = 0.47$)	2	3

Table 3: Acoustic scores based on Likert items assessing both subjective acoustic experiences and added questions regarding acoustic awareness

Generally, participants rated their subjective experience with classroom acoustics as above average, with acoustic comfort and voice clarity scoring above 3 on a scale of 5. Annoyance was rated lower at 2.3, while acoustic awareness averaged at 2.7, indicating some consideration of acoustics in their teaching environment. Moreover, all participants also responded "No" when asked if they had ever attempted to improve the acoustics in any of their classrooms.

Group	Mean	Min	Max
Perceived realism of sound	4.7 ($\sigma = 0.58$)	4	5
Acoustic adaptability	4 ($\sigma = 0$)	4	4

Table 4: The participants rating of the perceived realism of sound, and whether they were able to change the acoustics of the environment.

Table 4 reflects that the participants generally perceived the audio as quite realistic. Additionally, they were capable of noticing the changes in simulated acoustics when altering materials in the environment.

Group	Mean	Min	Max
Increased acoustic insight	4.3 $(\sigma = 0.47)$	4	5
Increased HI understanding	4 $(\sigma = 0)$	4	4

Table 5: The participants rating of whether they gained more insight about how to improve acoustics, and about whether the hearing loss simulation gave insight about how it especially effects HI individuals.

Table 5 demonstrates that the participants found the prototype insightful for learning how to modify acoustics effectively in real-world settings, and it helped increase their understanding of how hearing impairment affects speech intelligibility.

6.3.3 IPQ scores

Group	Mean	Min	Max
Total score	3.38 $(\sigma = 0.783)$	2.5	4.4
Spatial precense	4.27 $(\sigma = 0.231)$	4	4.4
Inolvement	2.58 $(\sigma = 0.144)$	2.5	2.75
Experienced realism	2.93 $(\sigma = 0.115)$	2.8	3.00

Table 6: IPQ Scores for all participants

The mean scores from the IPQ, as presented in Table 6, shows a moderate sense of presence across all participants, with scores generally hovering around 3.38 out of 5. This indicates that while participants felt a reasonable sense of presence in the virtual environment, there is room for improvement to enhance the immersive experience. Especially the involvement and experienced realism drags the average score of the IPQ down.

7. GENERAL DISCUSSION

The open design of the VE allowed participants to freely explore and interact with various acoustic settings and materials. This approach was intended to simulate real-world experimentation and learning. However, it also posed challenges in ensuring that all participants engaged with the essential features of the prototype, which ensures a comprehensive understanding of classroom acoustics. A more controlled testing environment could potentially focus participant interactions more directly on some predefined tasks, thereby yielding more quantifiable data and possibly clearer insights into specific learning outcomes. As an example, different controlled material settings in the prototype could be made, to ensure that every participant listened to the same type of acoustics throughout the experience. Future iterations of the prototype might benefit from a more hybrid approach, combining controlled settings with open-ended exploration.

The discrepancies found when comparing the RT_{60} between the simulated and actual classrooms indicate the prototype's current limitations in accurately modeling real-world acoustics. Although subsequent adjustments improved simulation, it seems that the GA, and the coefficients for the materials, are hard to rely on when comparing directly with the complex acoustic of a real-world classroom. However, a true replication of the acoustics might not be needed to promote awareness. The improvements in acoustic, the participant were able to perceive, when different sound absorbing to the prototype, seemed to have been enough to provide some valuable insight.

The IPQ scores indicate a moderate sense of presence and realism within the virtual environment, suggesting areas for improvement in user engagement and the immersive quality of the simulation (see Table 6). Enhancing graphical fidelity, interaction design, and auditory feedback could further increase realism and user involvement, thereby improving the overall educational impact of the prototype.

The methods employed to measure changes in acoustic awareness relied primarily on subjective assessments through Likert-scale items. While these instruments provide valuable insights into participants' perceptions, they may not fully capture the depth and complexity of acoustic awareness. Future research could incorporate more nuanced tools, such as behavioral observations or longitudinal studies, to measure how changes in awareness translate into everyday educational practices.

The very limited sample size of the evaluations constrains the generalizability of the findings. Larger-scale studies are required to validate these preliminary findings. Nevertheless, the prototype seemed to effectively provide the three participants with insight and knowledge about acoustics and how to improve it (see Table 5). However, translating this knowledge into actionable changes remains a challenge. The preliminary questionnaire also showed that the participants were already comfortable with the acoustic in their classroom, as they rated the acoustic comfort, voice clarity, and speech comprehension above average (see Table 3). This correlates well with the measured RT60 of only 0.65 s in one of their classrooms, which is only slightly above the suggested RT from [2] (see Figure 9a). It should also be mentioned, that the measurements of the RT_{60} from section 5.2, only can be understood as an estimation. A more trustworthy meaurement should use better equiptment (e.g., a omnidirectional sound source), and a impulse with more spectral data compared to a hand clap. Nevertheless, the teachers in the evaluation might already be quite comfortable with their acoustic environment, and therefore might not be keen to actually make improvements in their classrooms. However, the anticipated insights from the follow-up questionnaire are crucial for assessing the actual long-term impact of the prototype on participants' acoustic awareness. This data will inform whether the increased insight and knowledge observed immediately after the intervention translates into actual changes in perception and behavior regarding classroom acoustics.

8. CONCLUSION

This paper investigated, the use of VR to enhance acoustic awareness among teachers, by implementing a interactive VE that simulates classroom acoustics. Drawing on related research, the project designed an initial prototype that allowed users to experiment with various acoustic settings. Feedback from this phase informed significant refinements in a final prototype, which was then evaluated by school teachers.

The evaluations demonstrated that while the prototype effectively enhanced understanding of acoustic principles, the small sample size limits the generalizability of these findings. Furthermore, translating increased awareness into practical classroom changes might remain a challenge.

In summary, the results indicates the the VR prototype might be a tool to provide knowledge about acoustics, but further research with a larger participant pool is necessary to validate and expand these findings. The upcoming results from the follow-up questionnaire will provide additional insights into the sustained effects of the intervention on acoustic awareness.

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10. APPENDIX

10.1 A: Hearing loss simulation equations

10.1.1 Gammetone seperation

The gammatone seperation is executed by generating impulse responses from gammatone filters, normalizing them, and loading the into convolution processors.

Firstly, the center frequencies for the gammatone filters are calculated as:

$$cf = ERB(20.0, 16000.0, 32)$$

where ERB denotes the function that calculates Equivalent Rectangular Bandwidth frequencies logarithmically spaced between 20 Hz and 16000 Hz for 32 channels.

For each channel ch, an impulse response is generated by:

1. Initializing a signal $s[n]$ with an impulse at the origin:

   $$s[n] = \delta[n]$$

   where $\delta[n]$ is the Kronecker delta function, $\delta[0] = 1$ and $\delta[n] = 0$ for $n \neq 0$.

2. Applying a gammatone filter centered at $cf[ch]$:

   $$g[n] = G_{cf[ch]}(s[n])$$

   where $G_{cf[ch]}$ represents the gammatone filter operation.

3. Normalizing the filtered signal $g[n]$:

   $$g'[n] = \left(\frac{g[n] - min}{max - min}\right)$$

   where max and min are the maximum and minimum values of $g[n]$, respectively.

The normalized impulse responses are loaded into left and right convolution processors and gained a bit down:

$$L[ch] = g'[n] \times 0.8$$

$$R[ch] = g'[n] \times 0.8$$

where L and R denote the left and right channels respectively.

The processing $y_{ch}[n]$ for each channel ch is obtained by convoluting the input buffer $x[n]$ with the corresponding gammatone impulse response $g'_{ch}[n]$:

$$y_{ch}[n] = \sum_{k=0}^{N-1} x[k] \cdot g'_{ch}[n-k]$$

where N is the length of the impulse response and the summation extends over the entire length of $g'_{ch}[n]$.

10.1.2 Spectral smearing

To input to the spectral smearing processor is a buffer of high frequency bands from the previous gammatone filterbank sepearation, $x_{ch}[s]$, where ch represents the channel index and s represents the sample index. A noise buffer, $noise_{ch}[s]$, for each high frequency band is generated as:

$$noise_{ch}[s] = 0.5 \cdot (2 \cdot U(0,1) - 1)$$

where $U(0,1)$ represents a uniform distribution over [0, 1].

A lowpass filter, $F(\cdot)$, is applied to the noise buffer. The cutoff frequency of the lowpass controls the amount of smearing. Where a higher cutoff provides more smearing. In the case of this implementation, 100 Hz is low smearing, and 200 Hz is high smearing:

$$filtered\_noise_{ch}[s] = F(noise_{ch}[s])$$

The spectral smearing is performed by modifying the high frequency components of the audio buffer using the filtered noise (multiplying by 20 to account for loss from multiplying with the low-passed noise buffer):

$$x_{ch+11}[s] = 20 \cdot x_{ch}[s] \cdot filtered\_noise_{ch}[s]$$

10.1.3 Rapid Loudness Growth filter

The rapid loudness growth, is implemented as an expander, increasing the amplitude of the signal, when it reaches a certain threshold. The expander is configured with a threshold $T = -50$ dB and a ratio $r = 0.7$. The output $y[n]$ of the expander for an input signal $x[n]$ is described by the following equation:

$$y[n] = x[n] \cdot \left(1 + \frac{1-r}{r}\right), if|x[n]| < T$$

$$y[n] = x[n], if|x[n]| \geq T,$$

where:

- $|x[n]| < T$ indicates that the signal level is below the threshold, and the signal is expanded.
- $|x[n]| \geq T$ indicates that the signal level is above the threshold, and the signal remains unchanged.

10.1.4 Temporal disruption filter

The temporal disruption filter manipulates the channel data by altering the phase of its frequency components.

The input signal $x[n]$, where n is the sample index, is transformed into the frequency domain using Fast Fourier Transform:

$$X[k] = FFT(x[n])$$

where $X[k]$ represents the frequency components.

Each frequency component $X[k]$ is represented as $X[k] = A[k]e^{i\phi[k]}$, where $A[k]$ is the magnitude and $\phi[k]$ is the phase. The phase is then randomly altered:

$$\phi'[k] = \phi[k] - \theta[k]$$

where $\theta[k]$ is a random value between $-\frac{\pi}{2}$ and $\frac{\pi}{2}$.

The modified frequency components are converted back to the time domain using an inverse FFT:

$$y[n] = IFFT(A[k]e^{i\phi'[k]})$$

10.2 B: Pre-test questionnaire

Demographics:

- Hvor gammel er du?
- Hvor stor er din erfaring med Virtual Reality [*1-Ingen, 5-Meget stor*]
- Har du et høretab?
- Hvis ja, beskriv dit høretab nedenunder

Acoustic questions:

- **(Group: Acoustic awareness**) Hvor ofte tænker du på rummets akustik når du underviser? (Forklaring: Oplever du f.eks., at du nogle gange tænker; "I det her lokale er akustikken/lyden rigtig god!" eller omvendt "i det her lokale er akustikken/lyden dårlig" Akustik er bl.a. rumklang, men kan også være udefrakommende støj eller baggrundsstøj)[*1-Ingen, 5-Meget stor*]

- **(Group: Acoustic comfort**) Til hvilken grad føler du dig tilpas i klasselokalernes lydmiljø, når du underviser? (Forklaring: At føle sig tilpas i lydmiljøet, betyder at du ikke føler dig irriteret unødvendigt over for meget rumklang eller baggrundsstøj, når du underviser)[*1-Meget utilpas, 5-Meget tilpas*]

- **(Group: Voice clarity**) Hvor ofte er, oplever du at du er nødt til at hæve stemmen, på grund af lydmiljøet i klassen? (Forklaring: Har udefrakommende støj eller rumklang en sådan stor påvirkning, at du er nødt til at hæve stemmen, selvom dine elever er stille?)[*1-Aldrig, 5-Meget ofte*]

- **(Group: Speech comprehension**) Hvor ofte oplever du, at klasselokalets lydmiljø gør, at dine elever ikke kan forstå dig?(Forklaring: Har rumklang eller baggrundsstøj i klasselokalet en sådan stor påvirkning, at dine elever ikke forstår dig når du underviser.)[*1-Aldrig, 5-Meget ofte*]

- **(Group: Annoyance**) Hvor ofte føler du dig irriteret over klasselokalernes lydmiljø? (Betydning: Oplever du ofte, at du føler dig irriteret over lydmiljøet, når du underviser pga. meget rumklang og baggrundsstøj). [*1-Aldrig, 5-Meget ofte*]

- **(Group: Acoustic awareness)** Har du nogensinde gjort noget for at forbedre lydmiljøet eller akustikken i klasselokalerne?(Forklaring: Dette kan være at tilføje lyddæmpende materialer til lokalet såsom tæpper, gardiner eller enda sofaer og puder. Det kan også være blot at trække gardinerne for, så der er mindre baggrundsstøj) [*Ja eller nej*]
- **(Group: Acoustic awareness)** Hvis ja, forklar hvad du har gjort nedenunder

SSQ questionnaire:

- General? [*1-Ingen, 5-Meget*]
- Træthed? [*1-Ingen, 5-Meget*]
- Hovedpine? [*1-Ingen, 5-Meget*]
- Øjenbelastning? [*1-Ingen, 5-Meget*]
- Svært ved at fokusere? [*1-Ingen, 5-Meget*]
- Øget spyt? [*1-Ingen, 5-Meget*]
- Svedende? [*1-Ingen, 5-Meget*]
- Kvalme? [*1-Ingen, 5-Meget*]
- Svært ved at koncentrere sig? [*1-Ingen, 5-Meget*]
- Tungt hovede? [*1-Ingen, 5-Meget*]
- Sløret syn? [*1-Ingen, 5-Meget*]

- Svimmel med øjnene åbne? [*1-Ingen, 5-Meget*]
- Svimmel med øjnene lukkede? [*1-Ingen, 5-Meget*]
- Mavebevidsthed? [*1-Ingen, 5-Meget*]
- Bøvsende? [*1-Ingen, 5-Meget*]

10.3 C: Post-test questionaire

SSQ questionnaire:

Same as from pre-test questionnaire.

Acoustic questions:

- **(Group: Acoustic adaptability**) Til hvilken grad, føler du at du var i stand til at ændre lydmiljøet i det virtuelle klasselokale?(Forklaring: Ved at tilføje gardiner, eller ændre materialer, kunne du så høre en forskel i rumklang og baggrundsstøj)[*1-Lav grad, 5-Høj grad*]
- **(Group: Acoustic insight**) Til hvilken grad føler du, at det virtuelle klasselokale, gav dig et større indsigt i hvordan lydmiljøet i et klasselokale kan forbedres?[*1-Lav grad, 5-Høj grad*]
- **(Group: HI understanding**) Til hvilken grad følte du så, at høretabs simuleringen gav dig indsigt i en person med høretabs dårlige taleforståelse? [*1-Lav grad, 5-Høj grad*]
- **(Group: Perceived realism of sound**) Til hvilken grad, føler du at lydmiljøet blev påvirket på en realistisk måde? [*1-Lav grad, 5-Høj grad*]

IPQ:

- I den virtuelle verden havde jeg en fornemmelse af "at være der"[*1-Overhovedet ikke, 5-Rigtig meget*]
- På en eller anden måde følte jeg, at den virtuelle verden omgav mig [*1-Meget uenig, 5-Meget enig*]
- Jeg følte at jeg bare så billeder [*1-Meget uenig, 5-Meget enig*]
- Jeg følte mig ikke til stede i det virtuelle rum [*1-Følte mig ikke til stede, 5-Følte mig til stede*]
- Jeg havde en fornemmelse af at agere i det virtuelle rum, og ikke et sted udenfor rummet [*1-Meget uenig, 5-Meget enig*]
- Jeg havde en fornemmelse af at agere i det virtuelle rum, og ikke et sted udenfor rummet [*1-Meget uenig, 5-Meget enig*]
- Jeg følte mig til stede i det virtuelle rum [*1-Meget uenig, 5-Meget enig*]
- Hvor opmærksom var du på den virkelige verden omkring, mens du navigerede i den virtuelle verden? (dvs. lyde, rumtemperatur, andre mennesker osv.)? [*1-Overhovedet ikke opmærksom, 5-Ekstremt opmærksom*]
- Jeg var ikke opmærksom på mit virklige miljø [*1-Meget uenig, 5-Meget enig*]
- Jeg var stadig opmærksom på det virklige miljø [*1-Meget uenig, 5-Meget enig*]
- Jeg var fuldstændig betaget af den virtuelle verden [*1-Meget uenig, 5-Meget enig*]
- Hvor virkelig virkede den virtuelle verden for dig? [*1-Overhovedet ikke virkelig, 5-Fuldstændig virkelig*]
- Hvor meget var din oplevelse af den virtuelle verden, i overenstemmelse med din oplevelse af den virkelige verden? [*1-Ingen overensstemmelse, 5-Meget overensstemmelse*]

- Hvor virkelig virkede den virtuelle verden for dig? [*1-omtrent lige så virkelig som en forestillet verden, 5-kan ikke skelnes fra den virkelige verden*]

- Den virtuelle verden virkede ligeså vigtig som den virkelige verden [*1-Meget uenig, 5-Meget enig*]