Real-time building acoustics noise auralization and evaluation of human cognitive performance in virtual reality

Muhammad Imran, Anne Heimes and Michael Vorländer

Institute of Technical Acoustics, RWTH Aachen University, 52074 Aachen, Germany
E-Mail: mim@akustik.rwth-aachen.de

Introduction

There is concern about steadily growing high annoyance due to noise in private dwellings as well as in commercial work sites that leads to reduced power of concentration during physical or mental work [1,2]. Different surveys reveal that people are affected by noise caused by indoor activities. The studies show that people are also exposed to the noises from neighbours which causes consequences of disturbances in communication, physical or mental work imparities, and the disturbances in conversation in private dwellings as well as communication in office premises [3]. There exist different standards that describe the performance of buildings in terms of noise reduction and sound level reduction indices in the form of a single number value and/or frequency dependent insulation curve of the building construction separating the offices [6,7].

In this paper, we develop a real-time time building acoustic rendering framework based on ISO 12354 [8] and our previous work [4-6] with an extended approach that is used to construct sound insulation filters for binaural sound transmission between rooms separated by building elements. This approach made use of ISO 12354 for airborne sound transmission and focus on addressing the simplification that exist in our previous approach in order to develop accurate airborne sound transmission filters and represent a plausible real-time building acoustics auralization. For real-time auralization of complex buildings to a listener at some place in the building volume, we integrated the sound insulation rending model in VR using Unity 3D software as visual renderer. This framework allow the users to perform any task of daily life of work or learning under conditions of usual behaviour and movement. Therefore, it is intended to create more realistic noise perception tests in real-time virtual reality environment than simply asking for "annoyance" in questionnaires in listening tests [4].

Figure 1: Building of Institute of Technical Acoustics (ITA) as office environment for virtual reality visual rendering

curves, however, it can be assumed that these quantities are insufficient to describe the real situation for the perception of noise and its impact on the humans. Therefore, there is an opportunity in developing a real-time building acoustics auralization platform based on detailed models of ISO standards integrated with virtual reality (VR) systems, to accurately realize the perception and evaluation of noise effects on the daily work performance of the humans.

The basic principle of building acoustic auralization is to simulate the alteration of a sound signal from its source to the receiver via transmission through building structures [4-5]. The auralization of an office-to-office situation, where speech spoken in one office is transmitted through building structures to a neighbouring office, requires modelling sound propagation in both rooms, i.e. its generation and transmission form walls and the insulation characteristics of the direct and flanking walls between the offices. Both level and spectral characteristics of background speech highly depend on the

Building Acoustic Model and Auralization

To introduce more realism and contextual features into psychoacoustic experiments, the implementation of a real-time building acoustic auralization framework in 3D audio-visual technology is proposed. Generally there are three major parts of the framework and are described in this following section.

The framework includes the following major parts:

1. Prediction of sound insulation parameters and calculation of transmission paths according to [4-7].

2. Calculation of transfer functions between source and receiver rooms.
3. Implementation into VR and real time filter rendering

The general framework flow chart is given in Figure 2.

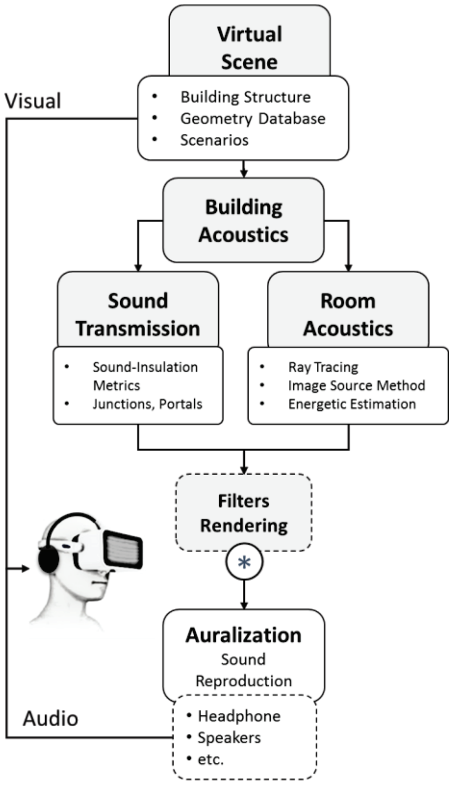

Figure 2: Building acoustic auralization process

Sound insulation model

The standardised sound level difference based on ISO standard, D_{nT}, expressed by the transmission coefficients $\tau_{ij} = 10^{-0.1R_{ij}}$ of all transmission paths between two rooms is given in Equation 1. Here, V is the volume of the receiving room and S_D the area of the separating element [8].

$$D_{nT} = -10\log\sum_{\forall ij}\tau_{ij} + 10\log\frac{0.32V}{S_D} \qquad (1)$$

The direct field can be assumed to decay as in free-field conditions, whilst the reverberant field is evenly distributed [9-10]. This phenomenon is shown through the classical sound field theory for sound propagation in rooms from Equation 2.

$$L_S = L_W + 10\log\left(\frac{Q_S}{4\pi r^2} + \frac{4}{A_S}\right) \qquad (2)$$

Equation 2 inherently incorporates the influence of the room reverberation, the directivity of the source, and the same balance between direct and reverberant energy as considered in approach [4,6].

Here, L_S is the sound pressure level, L_W is the sound power level, Q_S is source directivity normalised to 1 for the omnidirectional case, and A_S is equivalent absorption area of the source room.

The mean squared sound pressure at a point inside the source room in energetic notations is given by Equation 3, with $P_a = 10^{-12}10^{-0.1L_W}$ (source acoustic power in Watts).

$$p_S^2 = 400P_a\left(\frac{Q_S}{4\pi r^2} + \frac{4}{A_S}\right) \qquad (3)$$

The time domain representation of the above energetic form is represented in Equation 4.

$$p_S(t) = 20\sqrt{P_a}\cdot s(t) * \left(\sqrt{\frac{Q_S}{4\pi r_i^2}}\cdot\delta\left(t - \frac{r_i}{c}\right) + \sqrt{\frac{4}{A_S}}\cdot h_{S,i}(t)\right) \qquad (4)$$

with $s(t)$ as source room signal that is normalized in power and $h_s(t)$ as normalised impulse response of the source room in energy.

The incident sound power on a building element i in the source room with area S_i is a combination of the direct and the reverberant field [9-10]. The instantaneous incident sound power in time domain is calculated by the Equation 5. Here, F_i is represented by $\int_S \frac{Q_S}{4\pi r^2}|\cos\theta|dS$ and can be approximated as
$F_i \approx \frac{S_i Q_{S,i}}{4\pi R_i^2}|\cos\theta_i|$. This integral is numerically calculated by the adaptive Simpson's integration method.

$$W_{S,i}(t) = 20\sqrt{\frac{P_a}{\rho c}}\cdot s(t) * \left(\sqrt{\frac{F_i}{4\pi}}\cdot\delta\left(t - \frac{r_i}{c}\right) + \sqrt{\frac{S_i}{A_S}}\cdot h_{S,i}(t)\right) \qquad (5)$$

In Equation 5, $h_{S,i}$ is normalised room impulse response between the source location and the centre of element i. Similarly, the sound power transmitted from i^{th} element of the source room to j^{th} element of the receiver room for direct as well as flanking paths is defined by Equation 6.

$$W_{R,ij} = \frac{400P_a\cdot\tau_{ij}\cdot S_D}{\rho c\cdot S_i}\left(\frac{F_i}{4\pi} + \frac{S_i}{A_S}\right) \qquad (6)$$

The contribution of the ij path to the mean squared pressure in the receiving room is given by Equation 7.

$$p_{R,ij}^2 = 400\cdot W_{R,ij}\left(\frac{Q_j}{4\pi r_j^2} + \frac{4}{A_R}\right) \qquad (7)$$

Q_j represents the directivity of the radiating element j of the receiving room with an equivalent absorption area A_R, and r_j represents the distance between the acoustic centre of the radiating element j to the evaluation point (position of the receiver).

In our previous methods [4-6], the radiating elements in the receiving room are represented by single point sources located at the centre of the walls. In this improved model, each radiating element j is represented by a set of evenly distributed point sources on its surface. The acoustic power of the radiating element j is distributed homogeneously among point sources by a factor $2/N_j$. After calculating $h_{R,j}(t)$ as an energetically normalized impulse response of the receiving room for a radiating element j, the contribution of the transmission path ij to the instantaneous sound pressure is computed by Equation 8. Where, N_j is the total number of point sources used to approximate the radiation pattern of the element j and the factor 2 compensates for the point source radiation into a hemi-space. In this way, the wall radiation pattern is significantly improved.

$$p_{R,ij}(t) = \sqrt{\frac{P_a \tau_{ij} S_D \rho c_o}{S_i}} \cdot s(t) * \left(\sqrt{\frac{Q_j \cdot F_i}{16\pi^2 r_j^2}} \cdot \boldsymbol{HRIR}(\theta_j, \varphi_j) + \sqrt{\frac{Q_j \cdot S_i}{4\pi r_j^2 A_S}} \cdot \boldsymbol{h}_{S,i}\left(t - \frac{r_j}{c}\right) + \sqrt{\frac{F_i}{\pi A_R}} \cdot \boldsymbol{h}_{R,j}\left(t - \frac{r_i}{c}\right) + \sqrt{\frac{4S_i}{A_S A_R}} \cdot \left(\boldsymbol{h}_{S,i}(t) * \boldsymbol{h}_{R,j}(t)\right) \right) \qquad (8)$$

Here, all $h(t)$ are statistically valid for all points inside the room and, therefore, $h(t)$ could be synthesised before starting the auralization.

Implementation in virtual reality

A Unity-based framework of sound insulation is completed, evaluated and real-time performance of algorithm is tested including sound insulation filters between dwellings by flanking structures, HRTFs in the receiver room and reverberation of the receiver room. These filters are applied to two adjacent offices in the building [10].

The Auralization framework is used for cognitive performance test in complete VR. The ITA building is taken a case for validation of the improved techniques in the framework. ITA building is constructed in Unity 3D in order to test the improved method in virtual reality environment as shown in Figure 3. Two offices were selected as source and receiver room, the improved method is implemented and the results are shown in proceeding sections.

Psychoacoustic Evaluation

The objective of psychoacoustics experiment was to find correlation between the results of impact of background speech with different levels of sound intelligibility on the cognitive performance of humans, that are obtained in previous studies [3] and the results obtained while conducting the same experiment in VR environment based on our proposed framework. The research object of the psychoacoustics experiment in [3] was to see that whether reducing speech intelligibility due to frequency-specific sound insulation diminishes the potential negative impact of background speech on cognitive performance and subjective disturbance ratings was investigated in this experiment. The same experiment with the same procedure is conducted as described in [3] (referred for details), however, now this time in our study the experiment is carried out in proposed VR system. This experiment explored the impact of background speech differing in intelligibility and level on verbal serial

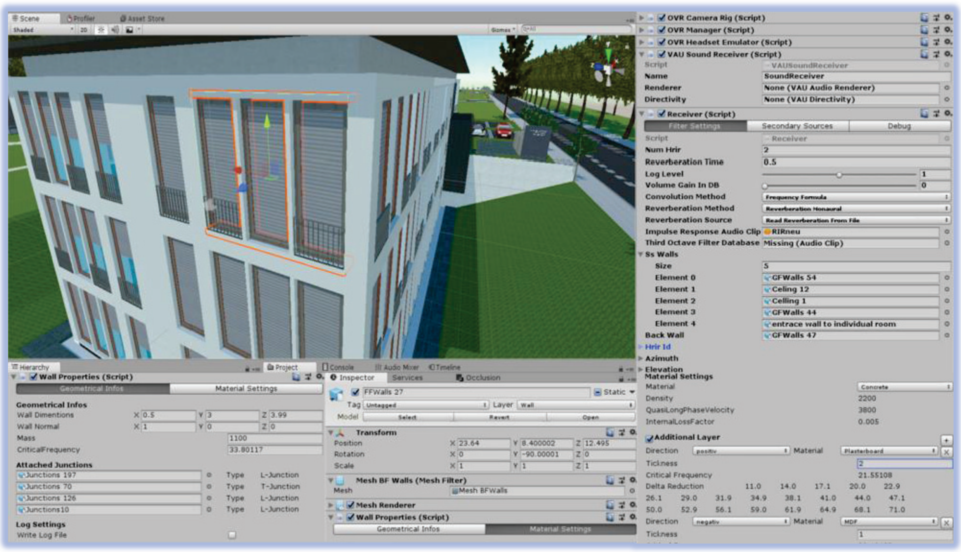

Figure 3: Unity 3D based software for real-time audio-visual rendering

recall and thus verbal short-term memory capacity. Since this task only requires successively presented digits to be recalled in the given order, no further processing or mental manipulation is needed apart from maintenance and recall. A total of 20 participants took part in experiment and were all native German speakers and reported normal hearing. As material to be serially remembered, the digits from 1 to 9 were successively presented visually in the middle of the screen in randomised order. Four sound conditions were included in the experiment: a speech signal at 55 dB(A) (S55), two auralised versions characterised by either good (S35_G) or bad intelligibility (S35_B) at 35 dB(A) and a silence condition represented by very soft pink noise (25 dB(A)).

The unity framework includes the following plugin [11-12]:

1. ISO: 12354-1 Model Plugin
2. Geometry Handling Plugin
   i. Ray Casting
   ii. Real-time source receiver detection
3. DAFF-HRTF Data Loading Plugin
4. FFT / iFFT DLLs (open Source from MIT USA)
5. Filter Construction and Convolution Plugin
6. Filter rendering Plugin (using VA plugin from ITA)

Results

The results of psychoacoustics experiment show that the serial recall performance affected by speech intelligibility as shown in Figure 4. In subjective disturbance rating results Figure 5, we can see a considerable differences between S55 and S35_G, however, a paired sample T-test confirmed that there are no significant differences between them. The significant difference found between S55 and PN_25 and between S55 and S35_B from one-factorial ANOVA (within-subjects, repeated measures) and is validated by a post-hoc paired sample T-test. It shows that the disturbance is independent of the level, however, intelligible speech disturbs more as its can been seen form the objective result in Figure 4 that show little difference between S35_B and PN_25.

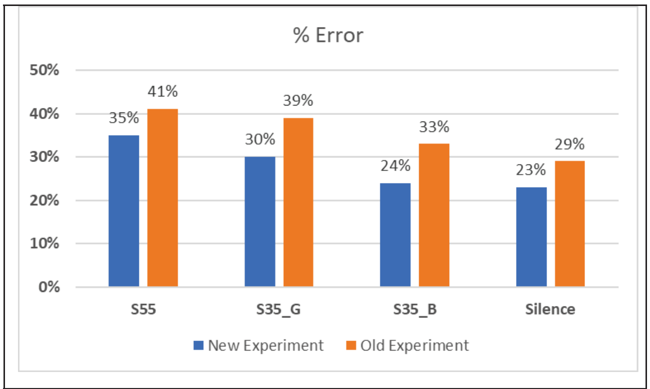

Figure 4: Error rating (%age)

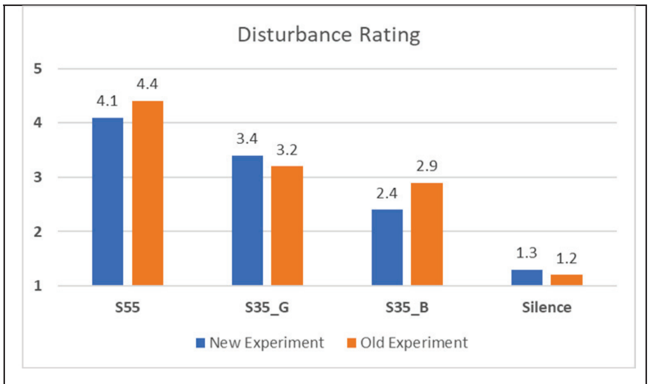

Figure 5: Subjective disturbance rating

Conclusion

The findings of this work is analogous to the results mentioned in [3]. From the results of both studies VR itself has no significant impact on serial recall task, therefore, VR can be used as a proper substitution of the real scenario for taking various psychoacoustic tests. The mean error rates for all four sound conditions were little less than that of for real case. This phenomenon could be explained by prompting the participants to be more aware of the VR situation and pay more attention during the test.

Outlook

The presented framework in this paper provides a platform for real-time auralization of sound insulation integrated with virtual reality in order to perform the psychoacoustic and cognitive tests to find out the influence of noise, speech and other stimuli on the performance of human beings during their daily work in built environments. Although the presented auralization framework incorporates many important room and building acoustic effects based on our extended approach, the psychoacoustic experiment conducted in this study was kept simple; i.e. static source and receiver in both source and receiver rooms. In future work, we are intended to conduct psychoacoustic experiments with dynamic auralization scenes where the users will be allow to perform any task of daily life of work or learning under conditions of usual behaviour and movement in order to find out the impact of noise on such task. In addition, the outdoor moving sound sources would be addressed to investigate the impact of intermittent noise effects of passing-by car, ambulance and police sirens etc.

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