Investigating Low Frequency Sound from Traffic in a Living Room Lab

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Introduction

Today, more than 90 % of our time is spent indoors in our homes, at work or at leisure [1]. You could call us an indoor generation. Consequently, indoor environments have a substantial influence on our health and well-being. Our acoustic environment determines to a high degree our cognitive performance at our working places or the sleep quality in our homes. Research showed that dysfunctional acoustic indoor environments can lead to serious health effects like vertigo, sleep disturbance, stress, hypertension, and heart rhythm disorders.

Over the past decades, regulations and building codes have been established in order to protect people from the negative impact of acoustic environments. Most of these regulations have in common that they are expressed in terms of time-averaged energy-related measures such as sound pressure levels or reduction indices of walls. At the same time, we realized over the years the importance of the information content of sound for the human response. The conscious or unconscious interpretation of sound by our brains strongly affects the level of annoyance or stress as well as our cognitive performance to an extent that we can even be struggling with our daily tasks. Irrelevant speech in an open plan office, footsteps from neighbors above us or the sound of a dripping water tap can be stressful or distracting although the signals might exhibit low energy.

The solution cannot be to create perfectly silent indoor environments. Besides the circumstance that such solutions would be connected with high costs, if they are possible at all, the quality of such environments is not self-evident. We lack a sufficient understanding of how people perceive different acoustic indoor environments and how supportive acoustic indoor environments should sound like. Research is resource intensive as we have to investigate people's responses to a variety of acoustic environments. Field studies, for example by means of questionnaires, often turn out to be difficult to interpret as it is impossible to have control over all involved parameters. In addition, the design of environments by trial and error is costly and failures have negative consequences for those living or working in such environments.

In this paper, an alternative approach is chosen by creating virtual environments in which subjective and objective evaluations can be carried out. While, in other fields, an increasing virtualisation during the design process has been observed over the recent years, we are still at the very beginning of such a development when it comes to the acoustic design of indoor environments. What is needed is to create virtual environments that resemble acoustic indoor spaces sufficiently accurate when representing real life situations. Listening tests with human subjects could be carried out in these virtual environments and, in contrast to field studies, the spread of results would only depend on the variation in perception among the subjects.

In order to create an authentic virtual indoor sound environment, a Living Room Lab (LRL) was set up in the facilities of the Division of Applied Acoustics. Thereby, wave field synthesis is used to expose the window of the LRL to sound from virtual stationary or moving sound sources (e.g. passing-by vehicles) outside the LRL. The window then transmits sound to the inside of the LRL resulting in an indoor sound field similar to the one expected in reality. In a first experiment, electroencephalography (EEG) measurements following the oddball paradigm were carried out in order to demonstrate the approach for the case of stationary vehicle sound sources at different indoor sound pressure levels.

The Living Room Lab

A Living Room Lab (LRL) and a Sending Room (SR) were built into the sending and receiving room of a former transmission lab. This offers high sound insulation between both rooms as well as to the surrounding building. To increase the sound insulation further, both rooms are built in room in room design.

The LRL resembles a typical furnished living room (see Figure 1) with a length of 4.8 m, width of 3.73 m, and a visible height of 2.46 m.

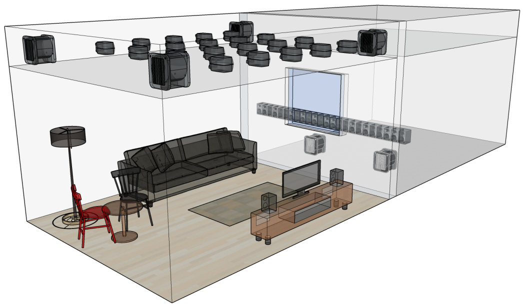

Figure 1: Sketch of Living Room Lab (LRL, left room) and Sending Room (SR, right room) with loudspeaker setup.

Both rooms are separated by a double wall consisting of three layers of gypsum boards on separate studs with a 150 mm mineral wool filled air gap as well as a standard window with good sound insulation. The resulting airborne sound insulation between SR and LRL as well as the sound insulation of the window as provided by the manufacturer (scaled by its surface contribution) are pre-

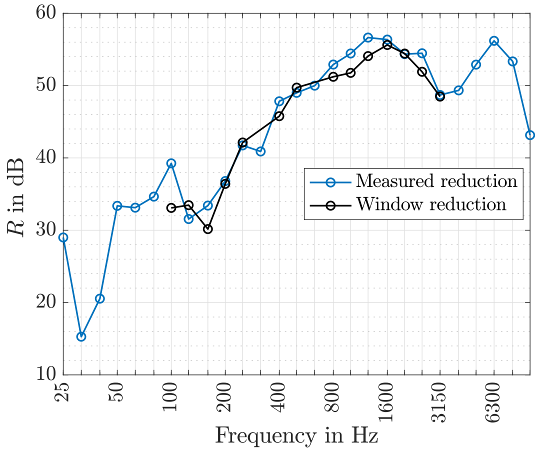

Figure 2: Measured air-borne sound insulation of the separating wall including window compared with the expected sound insulation of the window according to manufacturer.

sented in Figure 2. This comparison shows that, at least in the frequency range between 100 Hz and 3150 Hz, the sound insulation of the separating surface is determined by the sound insulation of the window.

In order to realistically reproduce different urban indoor soundscapes such as vehicle passages by means of wave field synthesis, 24 studio loudspeakers (Neumann KH80 DSP) as well as 2 subwoofers (Genelec 7050B) are placed in a linear array arrangement in front of the window in the sending room. Additionally, 20 studio loudspeakers (Genelec 8020A) and 4 subwoofers (Neumann KH805) are mounted in the suspended ceiling of the LRL to enable impact sound auralizations such as low-frequency sound caused by walking on e.g. lightweight floors [2].

Low Frequency Indoor Traffic Sound

European and Swedish policy endorses compact cities to stop urban sprawl and deliver prosperity and social cohesion. However, building new houses in urban areas is often hindered by the presence of road traffic noise. Therefore, the Swedish guideline values for road traffic noise were changed in 2017. Instead of an equivalent outdoor level $L_{\mathrm{Aeq,24h}}$ of 55 dB, 60 dB is now allowed and an unlimited outdoor level is allowed if the flat has a noise protected side at which the equivalent outdoor level does not exceed 55 dB. For smaller flats ($\leq$ 35 m^2), 65 dB are allowed. The argument for this change was that only the indoor levels are relevant for health and well-being of the people and that today's buildings have improved air-borne sound insulation in comparison to older buildings. However, this is only true in the medium and high frequency range. Due to physical limitations, it is difficult and costly to ensure improved sound insulation at low frequencies and modern wall designs hardly differ from older ones in terms of low frequency performance. This means that indoor environments are often exposed to low frequency sound from road traffic and especially from heavy vehicles if buildings are allowed in closer distance to roads.

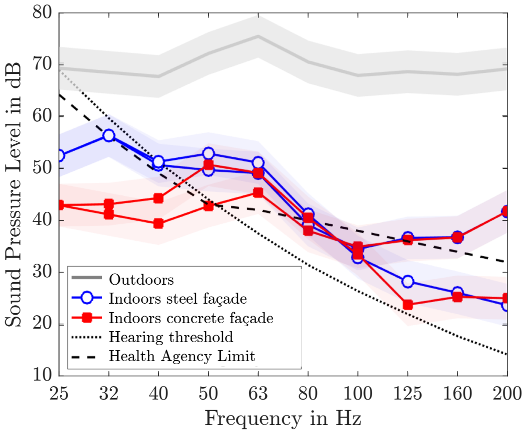

Figure 3: Peak sound pressure levels ($L_{\max}$ in dB) for a heavy vehicle (bus or truck) passing at 40 km/h with a distance of 12 m. Plotted are: the outdoor level, indoor levels with light façade construction ("steel façade"), with two different window types; the indoor level with heavy façade construction ("concrete façade"), with two different window types; the hearing threshold curve (according to ISO 226) and the Swedish Public Health Agency limit values for low frequency indoor noise (with an added data point at 25 Hz following Finnish regulations). The shaded areas at the curves represent the variation between individual vehicles (± one standard deviation according to the Nordic calculation model from 1996)

Based on a source and propagation model for road traffic noise (the Imagine source model and the Nordic calculation model from 1996) and real-life façade insulation values, indoor sound signals were calculated. The variation between individual vehicles was described using a probability distribution of the strength, with parameters determined by vehicle type and driving speed. In addition, the distance between the road and the façade was varied. Typical results of such studies are shown in Figure 3 in the form of peak values of the sound pressure levels for a case in Gothenburg.

Comparing the noise level outdoors with the indoor levels for the different façades and windows it becomes clear that the difference, and thus the sound insulation, tends to increase with frequency. The peak in the outdoor level around 60 Hz is due to engine noise and, since the sound insulation of the façade at that frequency is still relatively low, typically results in a frequency range around 50 - 60 Hz where the indoor noise level exceeds both the hearing threshold curve and the Swedish Public Health Agency's guideline values. This part of the sound can be assumed to be audible. The two curves that show an indoor level above the Public Health Agency's curve at 160 and 200 Hz are calculated for a normal window with ordinary but not poor sound insulation. This window can thus result in audible passages even at the upper part of the low-frequency range. The other two indoor noise level curves are for a special "soundproof" window where a very good sound insulation has been striven for.

An important factor for the degree of disturbance due to indoor traffic noise is the occurrence of audible passages. Audibility thereby partly depends on the traffic composition, e.g. the amount of heavy vehicles passing by, but also on the urban environment. Certain situations such as road slopes where the engine load of heavy vehicles increases, bus stops or traffic lights where heavy vehicles accelerate and urban canyons where a low frequency gain of 8 – 10 dB can occur are often particularly problematic. Assuming a usual mix of traffic, the outdoor equivalent free field level $L_{\mathrm{Aeq,24h}}$ for the case shown in Figure 3 is 63 dB. This meets today's Swedish noise requirements for smaller apartments up to 35 m^2. Indoors, the corresponding equivalent level from road traffic is estimated to be 22 dB – 28 dB and the maximum indoor level, L_{AFmax}, is estimated to be in the range 36 dB – 45 dB for the various façades. Thereby, the Swedish guideline values for both the equivalent indoor level (30 dB) and the maximum indoor level (45 dB) are fulfilled. However, especially at night most heavy vehicle passages are clearly audible and can hence be expected to be disruptive, even at low traffic flows. Residents may also feel a contradiction between the high sound insulation and the experience of many audible vehicle passages. Another important factor is that, due to the close spacing of the equal loudness contours in the low frequency region, the difference between an audible sound and a disturbing sound is smaller for sounds that are dominated by low frequencies hence only a minimal level increase may be required for a sound to change from being barely audible to being clearly disturbing. This illustrates the need to not only focus on energy related measures such as the equivalent sound pressure levels but also on time structure and subjective response.

Wavefield Synthesis

Wave Field Synthesis (WFS) is applied in order to create a virtual sound field in front of the window between the sending room and the LRL. Therefore, a linear loudspeaker array consisting of 24 studio loudspeakers and 2 subwoofers is placed along the separating partition as shown in Figure 1. The loudspeakers are controlled in phase and amplitude in a way that the incoming sound field from e.g. a point source in front of a building is projected as plane waves on the surface plane of the window. This was implemented for both stationary and moving sources following the methods described in [3].

For this setup, transfer functions between each loudspeaker and different microphone positions inside the LRL as well as in front of the window in the sending room were measured. This allows for computational analyses of generated WFS signals prior to the experiment and thereby for a careful design of the interior sound field. Figure 4 shows the measured transfer functions between a microphone position in the LRL and a position directly in front of the window in the sending room. These measurements also characterize the sound reduction through the window and wall shown in Figure 2. Additionally, binaural room impulse responses from each loudspeaker to a KEMAR artificial head placed at a typical listening position in the LRL were measured for 360 different head orientations in 1° steps. This allows to perceptually evaluate generated WFS signals by means of a dynamic headphone based auralization.

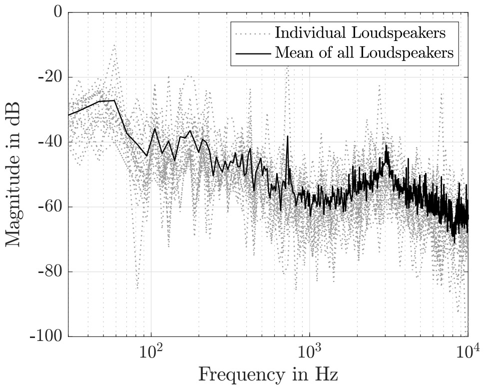

Figure 4: Measured transfer functions between the exterior side of the window and a listening position on the sofa.

When simulating pass-by noise from traffic, either recordings or synthetic sounds can be used. In both cases, a stationary source signal is needed since the motion of the source is part of the WFS. Although based on stationary source signals, the WFS approach thereby includes both Doppler shift and distance dependence as illustrated in the simulation of a 500 Hz sine source passing by at 180 km/h shown in Figure 5.

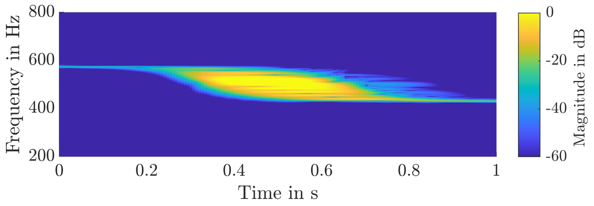

Figure 5: WFS result at listening position for 500 Hz sine source passing by at 180 km/h.

Examples for the typical time structure of the resulting indoor signal for heavy vehicle passages on a road parallel to the plane of the window as function of the distance between road and window are shown in Figure 6. Here, the shown indoor pressure signals were estimated by applying the described WFS approach for a moving sound source to a recording of stationary heavy vehicle engine noise, convolving the resulting loudspeaker signals with the measured transfer functions for each loudspeaker and summing up the results.

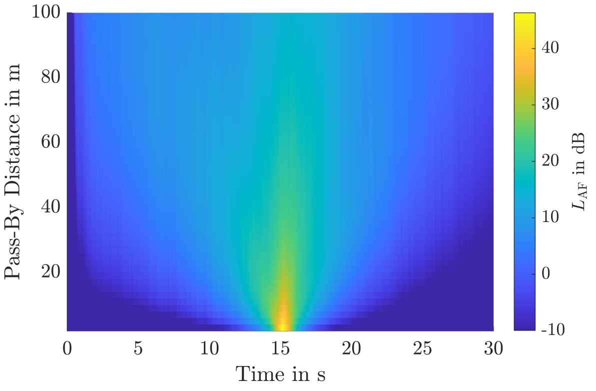

Figure 6: Predicted time structure of indoor pressure signal for heavy vehicle pass-by at 40 km/h as function of distance.

EEG Experiment

Electroencephalography (EEG) allows for recording electrical activity on the scalp and thereby observe a projection of the activity of the underlying brain layers on a macroscopic level. Although its spatial resolution is rather limited, a big advantage of EEG is its high time resolution which allows to monitor so called Event Related Potentials (ERPs). ERPs are frequently used in e.g. cognitive science when investigating processes in connection with events such as visual or auditory stimuli. Individual ERP components are named after their polarity and appearance in time related to the event, a comprehensive introduction describing different ERPs and their interpretation is given in [4]. A well described ERP is the P300, a positive pulse appearing around 300 ms after the event stimulus, which is often related to the process of decision making, evaluation or categorization. A typical method to evaluate the P300 component is the oddball paradigm which was used for this study as described in the following.

A participant was equipped with a wearable EEG headset and exposed to a sequence of repetitive visual stimuli in form of single letters (A to E) displayed on a computer screen. One specific letter was defined as target and the participant was instructed to press a button 1 if the currently shown letter is the target and a button 2 if the letter is no target. After a certain number of trials, the target letter was changed. Simultaneously, stationary motor noise at different levels was played back via the linear loudspeaker array in order to create different experiment conditions.

The raw EEG measurements were then low-pass filtered, baseline compensated and the moving window peak-to-peak amplitude method described in [4] was applied in order to reject artifacts such as eye blinks. Subtracting the preprocessed EEG signals of non-target stimuli from the signals measured for target stimuli reveals ERPs as shown on the left side of Figure 7. Analyzing the P300 amplitude and latency for all possible combinations of measured target- and non-target responses over all relevant EEG channels allows to evaluate the change in P300 distribution with respect to amplitude and latency for different indoor noise levels.

Results and Conclusions

The results shown in the right column of Figure 7 indicate that the presence and level of road traffic noise alters the distribution of the P300 component. Especially the P300 latency seems to be affected by the indoor traffic noise level. Sound levels very close to the hearing threshold seem to have a stronger impact on the latency than clearly audible but low levels. These results are, to a certain degree, consistent with findings of studies such as [5], where the effect of auditory oddball stimuli levels on the P300 component was investigated. However, reliable interpretations of these results with respect to the impact of traffic noise on cognitive performance are not possible since only the response of one subject was evaluated and stationary noise signals were used omitting time structure of vehicle passages. Nevertheless, this first experiment contributes to the design of further studies regarding the influence of road traffic noise on perceptual measures such as well-being and cognitive performance.

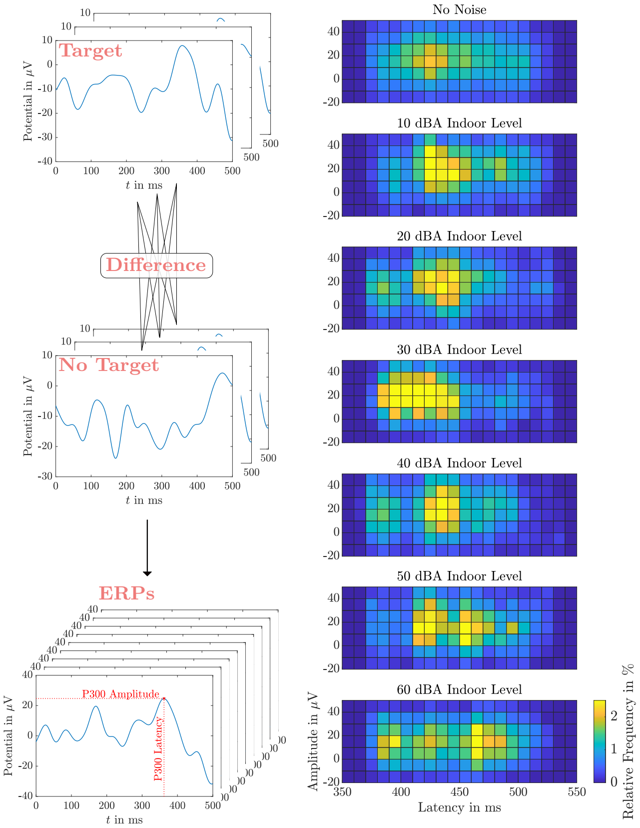

Figure 7: ERP evaluation procedure (left) and P300 amplitude and latency distribution for different indoor traffic noise levels (right).

This work demonstrated how to design and use virtual environments in the area of building acoustics with the objective to study the human response to urban indoor sound environments.

Acknowledgements

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