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INFLUENCE OF FACADE CHARACTERISTICS ON PERCEIVED ANNOYANCE FROM MOVING CARS IN URBAN LIVING ENVIRONMENTS

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ABSTRACT

Due to increased awareness of negative effects of noise exposure, distinct measures are applied to mitigate the sound immission from road traffic in urban areas. This includes strategic planning of road traffic, design of noise mitigating infrastructure, and efforts to reduce the sound emission of the sources. An increased effort has also been aimed at investigating how architectural features of urban areas, such as material properties and texture, affect perception of the local outdoor sound environment. This paper presents a psychoacoustic laboratory experiment investigating the effect of facade absorption and scattering properties on short-term noise annoyance from moving passenger car sounds in outdoor living environments. A virtual acoustic environment was designed based on a newly constructed housing area in Switzerland. Sound propagation was simulated with the ray tracing software ODEON. Car paths were modeled by spatially distributed source points along the roads for which multichannel impulse responses were ambisonically rendered for static receiver locations. The impulse responses were then converted to generic ones that allowed for a crossfading interpolation to estimate an impulse response for an arbitrary position between two source points. Subsequently, synthesized car emission signals were convolved with the position specific impulse responses to auralize moving cars. The sounds were reproduced via five satellite loudspeakers and two subwoofers in the laboratory. This paper presents the experimental results and discusses the possible influence of the facade's properties.

1. INTRODUCTION

Noise pollution is of concern in many cities and long term exposure to significant noise sources, such as road traffic, has been related to several health implications and disturbances [1]. This has brought increased attention to the importance of considering how noise can be mitigated within the urban layout, both in form of traditional measures such as noise barriers, but also with architectural design and planning ini-

tiatives. The propagation of sound within the urban environment is influenced, among other, by sound reflection from surfaces, diffraction at edges, scattering from rough surfaces and sound absorption by materials [2]. While those design parameters are widely considered within the field of architectural acoustics, it is more recent that their effect on the urban acoustic environment has been investigated with respect to eventual increase in sound pressure level (SPL) or change in acoustic perception of outdoor spaces.

Increased absorption has been shown to reduce the SPL in urban spaces such as street canyons [3, 4] and squares [5, 6]. Similarly, diffusely reflecting boundaries in a street canyon can lead to decrease in SPL [7] while studies have also shown non significant effect on SPL with increased scattering [4, 8]. On the other hand scattering, as well as absorption ability of facade material in an urban square can influence the acoustic characteristics of the space [9]. Similarly, use of moderate facade absorption has been found to increase the acoustic comfort in a courtyard situation [10]. This is in the context of a more subjective evaluation of the sound environment which has gained more attention over the last decades. Annoyance reactions have among other been used to evaluate various situations exposed to environmental sounds [11].

Road traffic noise is the main source of noise in many built-up environments, including residential areas. Although roads are usually treated as acoustic line sources for energy evaluations, the sonic experience at a receiver location during low traffic density phases is determined by single vehicle pass-by events. Changes in the reflection pattern due to a specific treatment of the facade surfaces are expected to be most easily heard in case of these single car passings.

With this background the present paper presents the results from a psychoacoustic laboratory experiment where annoyance reactions to car sounds in a neighborhood environment were investigated. Sound propagation from a moving car was simulated in a virtual room with distinct materials on building facades and pillars of overhead train lines. This enabled the investigation of different annoyance reactions to the

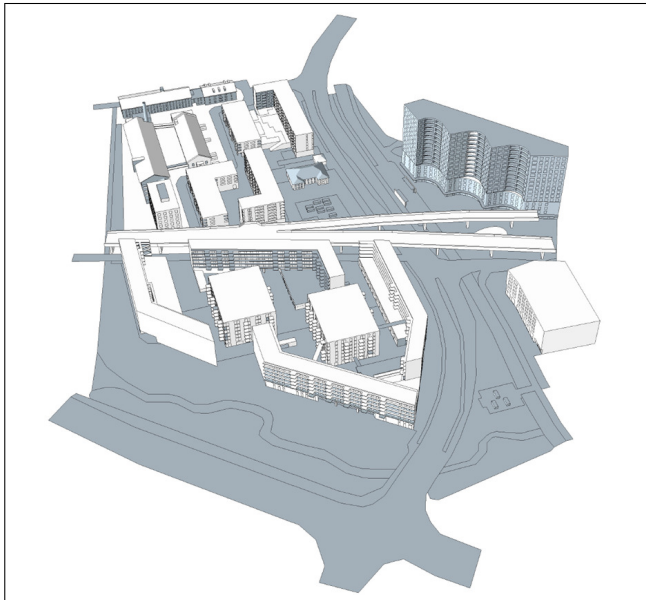


Figure 1. Overview of the reference neighborhood modeled in the Sketch up software environment.

applied building material.

2. SOUND SYNTHESIS AND REPRODUCTION

2.1 Reference neighborhood

The virtual room tested in the experiment was based on an existing, newly constructed neighborhood in Dübendorf, Switzerland. The neighborhood is constructed of several housing complexes, bounded by a relatively busy road and divided by a less busy road with an overhead train line. A geometric model of the neighborhood was created in the Sketch up Software environment (Trimble Inc., Sunnyvale, CA, USA), see Figure 1. Some simplifications were done. The terrain was assumed a flat plane, in reality there is a height difference of up to 3 m within the neighborhood. Similarly, an overhead tram track at the edge of the model was modeled flat although it does overlap in reality. Small ledges, mailboxes and doors were omitted, as well as blinds on windows and balconies. Finally, playground facilities were not modelled.

2.2 Simulation, auralization and signal processing

The Plugin SU2Odeon 2.00 was used to transfer the Sketchup model to the room acoustical software ODEON v. 15.15 (Odeon A/S, Kgs. Lyngby, Denmark). The 2D Surround sound option of ODEON was used to ambisonically render multichannel impulse responses, which were used in the post process to auralize the sound of a moving car.

As a room acoustical software, ODEON considers bounded/closed models. Thus, the neighborhood geometry was placed in a bounded box with fully absorptive surfaces towards the inside. This box represented the free field. Three receivers were placed at

different locations within the ODEON neighborhood model, see Figures 3 and 4, with various heights as will be described later. An array of omni-directional point sources was placed along two routes, representing the paths of the moving car. The sources were placed with 10 m intervals at 1 cm above ground, as placing them in plan with the road surface, which was preferred for post processing, caused problems when choosing the directivity of the receivers. The road surface closest to the sources was made fully absorptive in order to suppress a ground reflection that would cause unnatural time-dependent comb-filter / flanging effects. Indeed in nature these interference effects are very weak as the source has a substantial extension and is not concentrated at one point which is assumed in the simulation.

For the calculation setup in ODEON, the transition order was set to 0 (only using ray-based methods) with a number of late rays set to 8,000,000. A single point ambisonic impulse response (2D Surround sound) was generated for each source receiver relation. The speaker rig defined in the 2D Surround sound setup of ODEON was based on the setup of the listening test facility used in the experiment.

Necessary input for the auralization of a moving source is the audio signal emitted by the source and source position specific impulse responses h_i for the convolution operation. In simple geometries the source-receiver-impulse response can be quickly determined for any arbitrary source position. In this case, the impulse responses were obtained by an expensive propagation simulation and therefore they could be determined for a limited set of source locations only. This brought up the fundamental challenge of interpolation between the different source positions. One approach is to convolve individual emission signal segments with the representative impulse responses h_i and then cross-fade all snippets to obtain a smooth receiver signal [12]. Here, another approach was chosen where an interpolation between impulse responses h_i and h_{i+1} was determined in order to obtain an appropriate impulse response h_{i+f} ($f = 0 \dots 1$) for an arbitrary emission sample. This was achieved by an energy-conserving transformation of every impulse response h_i into a generic version h'_i that is composed of a direct sound component, the strongest reflection and a reverberant tail. The advantage of the generic versions is the fact that the three components can be aligned on the time axis with constant time delays. This allowed for a simple and straight-forward cross-fade interpolation between h'_i and h'_{i+1} to obtain h'_{i+f} without causing audible artefacts. As the suppression of information about the travel times makes the Doppler frequency shift vanish, this effect had to be included by manipulation of the emission signal based on information about the situation geometry.

Source signals for the virtual cars were synthesised by spectral modeling synthesis using the parametric

emission synthesis model described in [13]. For a selected car engine, tyre and road type, driving style and the respective driving speed, emission sound pressure signals were separately generated for tyre/road noise and propulsion noise. The synthesis model takes the radiation angle as an input parameter. As an interface to the omnidirectional source description, both source signal contributions were rendered for the time-dependent radiation direction pointing towards the receiver and summed up.

The 5-channel signals underwent further postprocessing before playback in the listening test facility. In order to have equal stimuli duration for all stimuli within each part of the experiment, 20-s and 15-s extracts were cut from signals related to Parts 1 and 2, respectively. This was done based on the L_{AF} and level-symmetrical to the maximum level (L_{AFmax}); i.e., around the L_{AFmax} . Furthermore, signals' spectral portions beyond 20 Hz and 10 kHz were filtered out. Finally, the signals of the five channels were allocated to the corresponding five satellite loudspeakers in the listening test facility and gated (i.e., faded in and out) with raised cosine ramps.

2.3 Listening test facility

The experiment was performed in AuraLab, the listening test facility of Empa Laboratory for Acoustics/Noise Control. AuraLab satisfies room acoustical requirements on background noise and reverberation time, which allows for high-quality audio reproduction. Furthermore, AuraLab has a separate listening and control room with the possibility of audio-visual supervision [10].

In the course of the experiment presented here, the floor was covered with additional porous absorbers. As shown in Figure 2, subjects were (individually) seated in the central listening spot with the test software in a screen in front of them. The sound was played back over five loudspeakers (KH 120 A, Georg Neumann GmbH, Berlin, Germany) in a 2D surround pentagon arrangement on the ear level at 2 m listening distance and over two subwoofers (KH 805, Georg Neumann GmbH, Berlin, Germany) [10]. This setup was chosen as ODEON can provide first-order ambisonics impulse responses for a 2D Surround sound setup [14].

3. EXPERIMENT

The experimental session consisted of two parts, part 1 and part 2, both in form of focused listening tests. Subjects did the tests individually. Before part 1, the subjects read information about the experiment and signed a consent form. Subsequently, the participants answered the first part of a questionnaire, where they were asked about their hearing and well-being. Finally, the subjects read information about part 1 of the experiment and were introduced to the listening



Figure 2. The experimental setup in AuraLab: the subject was seated in the central listening spot. The stimuli were played back through five satellite loudspeakers and two subwoofers.

test software designed for the experiment. After the subjects finished part 1, they were instructed to read the introduction to part 2. After finishing part 2 of the experiment, the subjects answered the second part of the questionnaire about their demographic data and living situation.

3.1 Design parameters

The same set of sound scenarios was used in both parts of the experiment, although with different stimuli durations. The following design parameters were varied: material of building facades and pillars of overhead train line (3 levels), driving path (2 levels) and observer position (3 levels). Three neighborhood models were constructed in ODEON: the reference model with original reflecting building facades and pillars of overhead train, one with increased absorption of the respective surfaces and one with increased scattering. The original surfaces were chosen from ODEON material library and were mainly constructed of smooth concrete, smooth painted or glazed concrete and smooth bricks. The absorption coefficients applied for increased absorption are listed in Table 1. For increased scattering, the scattering coefficient was set to 0.5, which accounts for the material roughness at mid frequencies (707 Hz). ODEON expands this scattering to other frequency bands by default [14].

Two car paths were defined: Car path 1 along the road bounding the neighborhood (50 km/h) and Car path 2 bounding and then entering the neighborhood (25 km/h). Three observer positions were chosen: Observer 1 highly exposed to Car path 1 looking towards the road, Observer 2 at a playground within a building complex, looking through an opening towards Car path 1 but rather shielded from Car path 2, and Observer 3 in a canyon like space, rather shielded from Car path 1 but highly exposed to and looking towards

| Frequency (Hz) | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|-------------------------|------|------|------|------|------|------|------|------|
| Absorption (α) | 0.25 | 0.25 | 0.55 | 0.85 | 0.90 | 0.80 | 0.75 | 0.75 |

Table 1. Frequency-dependent absorption coefficients of facades and overhead train line pillars for facade design with increased absorption.

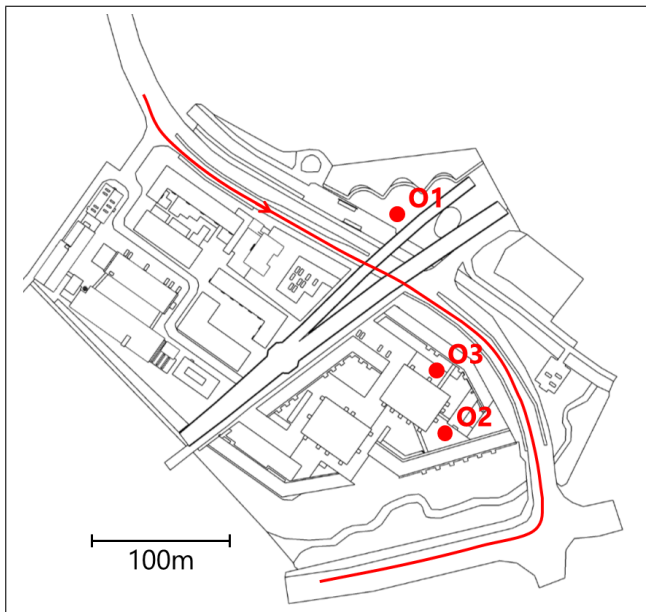


Figure 3. Car path 1 and the three observer positions: O1 (Observer 1), O2 (Observer 2) and O3 (Observer 3).

Car path 2. The Observer positions and car paths are illustrated in Figures 3 and 4. The height of the receiver representing the observers was 1.6 m above ground (ear height of a standing adult) for Observer 1 and Observer 3 and 1.2 m above ground (ear height of a sitting adult or standing child in the playground) for Observer 2. All in all, 15 sound scenarios were prepared from the combination of three facade types, two car paths, and three observer positions: $(3 \times 2 \times 3) - (1 \times 1 \times 3)$. No stimuli were prepared for the situation of Observer 1 responding to Car path 2 as it was very similar to the same observer responding to Car path 1.

3.2 Part 1

Part 1 initiated with two orienting and two training examples to familiarize with the sounds and the test software, before the main listening test started. In the main listening test, the subjects rated their level of annoyance to car sounds for the 15 stimuli described above. Each stimulus was 20-s long. During or after the playback of each stimulus, the subjects entered their ratings on an 11-point IC BEN scale considering the following question: “When you imagine that this is the sound situation in your outdoor living environment, what number from 0 to 10 represents best how much you would be bothered, disturbed or annoyed by it?” The subjects used a graphical interface of the test

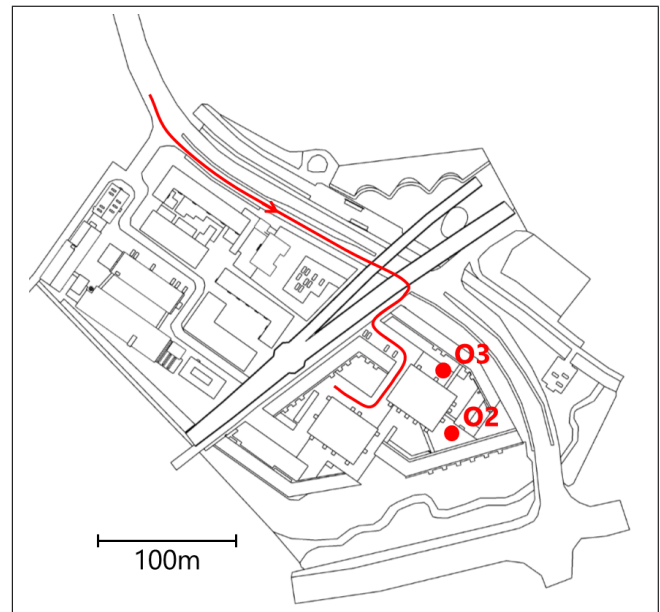


Figure 4. Car path 2 and the two observer positions: O2 (Observer 2) and O3 (Observer 3).

software to enter their annoyance ratings. The stimuli were played back one after another in a random order. After each stimulus was played back and the subject’s response was registered, the next stimulus played back automatically after a 2-s break.

3.3 Part 2

Part 2 of the experiment consisted only of a main listening test, as the subjects were already familiar with the sounds and the test software. The subjects had to choose the least and the most annoying / disturbing / bothering sounds among three sounds (A, B and C). Playback options for each sound were offered side by side in one page in the graphical interface. The subjects could listen to each sound (A, B, and C) twice and could choose which sound to play next, after the previous sound had finished playing back. The subjects were required to compare the three sounds considering the following: “Imagine that this is the sound situation in your outdoor living environment. Please choose the least annoying, disturbing or bothering and most annoying, disturbing or bothering sound.” After listening to each of the three sounds (A, B, and C) at least once and giving their feedback, the subjects could move further to the next page where three new sounds were presented. A total of five pages were tested, with the same fifteen stimuli as described above (5×3) . In part 2, each stimulus was 15-s long. The three stimuli (sound situations) offered on each page were in the

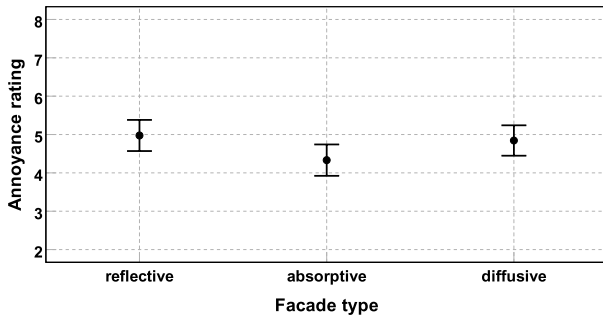


Figure 5. Results of part 1: mean acoustic comfort ratings across subjects and their 95% confidence intervals as a function of facade type.

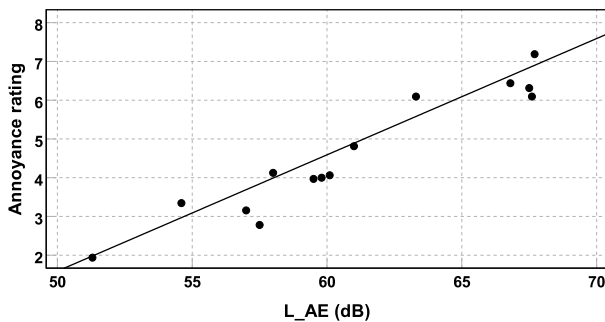


Figure 6. Results of part 1: mean acoustic comfort ratings across subjects as a function of L_{AE} .

same observer location with the same path. Only the material of the facade and the pillars of the overhead train line varied on each page. The order of pages and order of stimuli on each page were randomized.

3.4 Subjects

Thirty-two subjects (14 females and 18 males) participated in the experiment and finished both parts. All subjects declared having normal hearing (self judgment) and to feel well. They were aged between 19 and 62 yr (median 30.5 yr).

4. RESULTS

4.1 Part 1

Figure 5 shows mean annoyance ratings (on the 11-point ICBCEN scale) and their 95% confidence intervals as a function of facade type. The absorptive facade type tended to be associated with lower annoyance ratings than the two other facade types.

Figure 6 illustrates mean annoyance ratings as a function of stimulus' A-weighted sound exposure level L_{AE} . Annoyance rating correlated positively and significantly with L_{AE} ($r = 0.57, p < 0.01$). That is, annoyance increased with increasing L_{AE} .

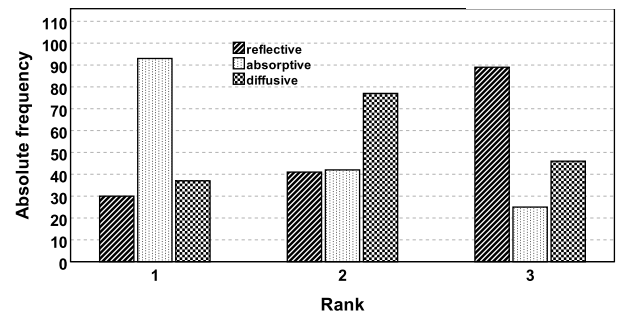


Figure 7. Results of part 2: counts of how many times each facade type was ranked as the least annoying (i.e., 1), the most annoying (i.e., 3) or was consequently ranked in between (i.e., 2).

4.2 Part 2

Figure 7 shows how often the stimuli associated with each facade type were ranked as the least or the most annoying stimuli in forced choices. The responses are coded as ranks 1, 2, and 3 from the least to the most annoying stimuli. The facade type had a significant effect on the annoyance ranking ($\chi^2(2) = 100.39, p < 0.001$). Stimuli corresponding to the absorptive and the reflective facade types were associated with the least and the most annoying rankings, respectively. The diffusive facade type was ranked in between.

5. DISCUSSION AND CONCLUSION

The annoyance reactions to car sounds from a moving car in a neighborhood environment were investigated in a two part psychoacoustic laboratory experiment. Three facade design parameters were investigated at three observer positions within the neighborhood. Of the three facade types, original (reflective), absorbing and scattering, the absorbing facade type was related with lower annoyance ratings. In Part 2 of the experiment the facade type had a significant effect on the annoyance ranking, where the absorptive facade was found to be the least annoying while the original facade was the most annoying. This result endorses the consideration of architectural features, such as facade properties, in relation to the urban sound environment.

The room acoustical software ODEON was used to simulate the sound propagation within the neighborhood layout. This was found beneficial as it allowed for a relatively effortless geometry input and assignment of material properties. Moreover, the 2D Surround option provided by ODEON could be used to ambisonically render multichannel impulse responses for each source-receiver relation. The area of the neighborhood simulated was quite large compared to normal room acoustical situations. This caused some problems at large source - receiver distances, where directional information in the multichannel IR was lost. This did not have effect on the stimuli of the experi-

ment presented here as the respective source - receiver distances were not too long, but should be taken into consideration for further applications.

The data from the experiment could be analyzed further, among other the effect of observer positions on annoyance ratings. The observers were placed in quite distinct situations within the neighborhood. The investigation of other architectural features such as material properties of ground surfaces and building placement as well as other observer positions could also be of interest in future experiments.

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