Evaluation of Stress in Response to Traffic Noise Using Virtual Reality

André Kruh-Elendt[1†], Christian Laufs[1], Jonas Heck[2], Janina Fels[2], Moritz Lippold[3], Christoph Klanten[3], and Andreas Herweg[1]

[1] *HEAD acoustics GmbH, 52134 Herzogenrath, Germany*

[2] *Institute for Hearing Technology and Acoustics (IHTA), RWTH Aachen University, 52074 Aachen, Germany*

[3] *Reicher Haase Assoziierte GmbH, 52066 Aachen, Germany*

[†] *Email: andre.kruh-elendt@head-acoustics.com*

Introduction

Road traffic noise is a key factor in the design of appealing living spaces and a major environmental stressor that can lead to a variety of health issues. Beyond hearing loss, long-term exposure to traffic noise is associated with multiple psychological and physiological adverse health effects, such as cardiovascular diseases, metabolic dysregulation, cognitive impairment and neurodegenerative disorders [1]. Tools for the simulation and auralization of traffic noise, which enable a perception-based prediction of its impact during early stages of the urban and traffic planning process are therefore of great value. The development of such tools is the main objective of the BaLSaM research project [2].

As part of the validation of these tools, a perception-based analysis of different simulated traffic noise scenarios using soundscape evaluations [3] in Virtual Reality (VR) is planned within the final stages of the project. In addition, physiological measurements will be performed and analyzed during various phases of the experiment. However, the development of perceptual VR experiments which deliver valid results bears a few key challenges to be considered.

On one side, while epidemiologic studies show the long-term health effects of exposure to traffic noise [4] and the underlying physiological reactions can be inferred, the direct measurement of physiological stress responses to noise during short-term laboratory experiments is not a trivial task. Other factors, such as additional stress from the experimental situation, might overlay the stress induced by the presented noise. Moreover, certain physiological response measurements are prone to produce artifacts due to participant motion, making them difficult to employ in interactive situations such as VR experiments. The acquisition of valid physiological data requires an adequate experimental design, taking into consideration baseline stress levels, measurement duration, and potential changes in stress levels during the course of the experiment [5].

On the other side, implementing a realistic and immersive VR environment in an interdisciplinary research project requires a suitable workflow which enables the integration of the components produced by different partners such as the traffic noise simulations, the modelled environments and the physiological measurement procedures. The purpose of this paper is to outline and assess possible solutions to these challenges in anticipation to the main validation experiment.

Method

Experimental Design

For the main study a perception-based experiment has been designed in order to validate the tools developed for traffic noise simulation. The design was based on a previous study by Laufs et al. [6], which showed a relationship between pure acoustic presentation of soundscape recordings containing traffic noise at different sound pressure levels and physiological reactions (in the form of skin conductance response). However, in contrast to [6], Electrocardiogram (ECG) recordings, using the sensor depicted in Figure 1, and derived Heart Rate Variability (HRV) was selected as a measure of stress response due to its robustness against motion artifacts in the more interactive VR setting. The duration of the HRV measurement phases was set to 5 minutes in order to obtain stable and reliable results [5].

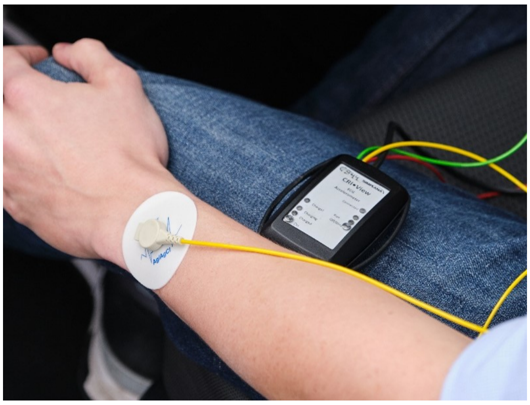

Figure 1: 3-Channel ECG sensor used for the measurement of HRV.

In addition, a perceptual evaluation of the simulated traffic noise scenes was included as part of the experiment based on the soundscape questionnaires and procedures standardized in ISO 12913 [3]. In accordance to the data collection method, a 3 minute exposure to the (virtual) soundscape before the activation of the respective questionnaire is required.

With this specifications in mind the phases of the experiment were structured as follows:

Instruction: The participant is introduced to the experimental procedure (outside of VR) and gives informed consent. The participant is then equipped with the ECG measurement sensors.

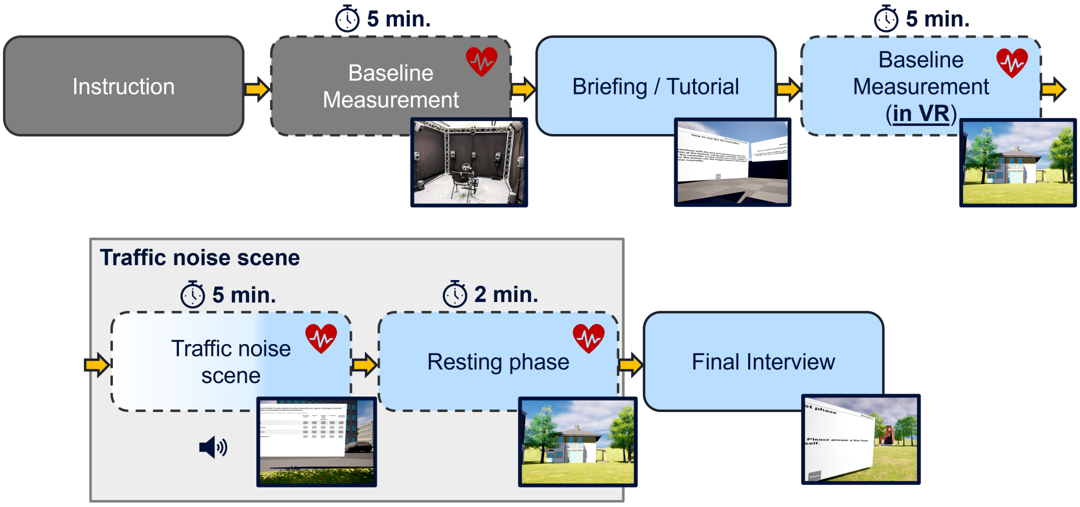

Figure 2: Overview of the main phases in the validation experiment design.

First baseline measurement: A first 5 minute HRV measurement is taken in the laboratory without any auditory or visual stimuli (i.e., outside of VR).

VR tutorial: The participant is equipped with a Head-Mounted Display (HMD) and headphones. A few tasks are then presented to familiarize the participant with the interactions and evaluation interfaces in VR.

Second baseline measurement: A second 5 minute HRV measurement is performed while the participant is in a quiet virtual environment resembling a park or backyard.

Traffic noise exposure: The participant is 'teleported' to a virtual urban scenario and exposed to a series of 5 minute long traffic scenes with varying characteristics (e.g., different sound pressure levels, traffic densities, etc.) The presentation order of the scenes is determined according to a reduced latin square design. The soundscape evaluation interface appears in front of the participant after 3 minutes. During each traffic noise exposure HRV data is recorded.

Rest period: After each traffic noise scene, the participant is 'teleported' back to a quiet virtual environment for a 2 minute rest period.

Final interview: After the last traffic scene, the participants are asked a series of questions about themselves and also with regard to their previous experience with interactive technologies and soundscape evaluation.

Virtual Reality Framework

In order to realize the experiment described above, a VR framework was developed and implemented using the Unreal Engine (UE). Its purpose is to provide a modular set of components that can be easily be adapted to the requirements of the experiments within the BaLSaM project, but also to future investigations in VR. The framework is an essential component in the integration of the different tools and outputs developed by the project partners.

The framework consists of the following components, as depicted in Figure 3:

Level: This is the basic component of the framework and is comprised of a series of actions and events which each participant has to fulfill to complete the experiment. Each of the VR experiment phases described above (e.g., the tutorial and each of the traffic noise scenes) are implemented as a level. Accordingly, the 3D virtual environment and access to other framework components are defined on a level by level basis. By using this approach, different partners in a project can work on individual levels at the same time without interfering with each other. Missing components, such as specific evaluation types, can be easily included later on.

Assets: This encompasses all the 3D models and textures used in the experiment. The assets are organized in a way that they can be easily accessed and loaded into the levels. Depending on the workflow within the project, assets (e.g., buildings and roads) can be generated by the respective partners for later use in VR.

Evaluation Manager: This module is responsible for the presentation of different evaluation interfaces or *steps* in a specified order and the collection of the participant's responses. In the BaLSaM project, the implemented steps include the soundscape questionnaires according to [3] and the final interview. The evaluation manager is implemented as a combination of blueprint objects and widget blueprints in UE and can be easily added to any level.

Sound Manager: This component is responsible for the playback of the required sounds inside each level. Within the sound manager, various audio players are defined which can interact with external rendering and playback software such as Digital Au-

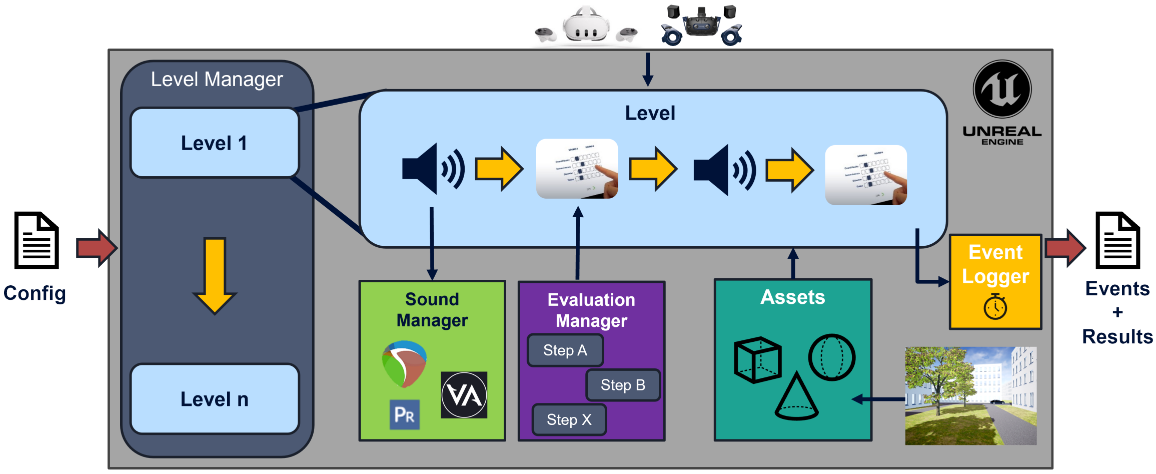

Figure 3: Overview of the main components of the Virtual Reality (VR) framework for audiovisual experiments developed in Unreal Engine (UE).

dio Workstations (DAWs) (e.g., Reaper [7]) or the Virtual Acoustics (VA) framework [8] developed by the Institute for Hearing Technology and Acoustics at RWTH Aachen University. Through this modularization, major changes in audio synthesis and reproduction can be realized without affecting the implementation inside the levels.

Event Logger: In order to synchronize the physiological data with the events in the VR environment, an event logger was implemented. It records the start and end times of each event in the experiment, such as the start of a level, the playback of a specific traffic noise scene or the activation of an evaluation interface. The event logger is implemented as a blueprint object in UE and can be easily accessed by levels and other framework components.

Level Manager: A key managing component inside the VR framework is the level manager. As the name suggests, its task is to manage the sequence and to ensure a smooth transition between the different levels (i.e., phases) of an audiovisual experiment. New or modified experiment designs can be created by recombining available levels through the configuration passed to the level manager.

Framework Game Instance: At the core of the framework is its persistent game instance. It is responsible for starting and finishing the experiment as well as loading all configuration settings from a given file. It also provides access to other framework components, thereby functioning as a central entrypoint.

In addition to these components a key feature of the framework is the ability to perform changes in the configuration of the experiment using a (JSON) configuration file and to export a all data (i.e., events and evaluation answers) in a structured format for further analysis.

Results

Following the implementation of the framework components described in the previous section, a preliminary experiment was carried out in order to evaluate the performance of the VR framework and to identify potential flaws in the experimental design. The experiment was conducted with $n = 12$ participants (9 male, 3 female; 85% in the age rage between 18 and 29 years) in the VR laboratory at HEAD acoustics in Herzogenrath. VR scenes were presented using an HTC Vive Pro 2 and ensuring a typically recommended framerate for VR applications of 90 FPS. In this preliminary trial HRV measurements were taken during the first and second baseline phases, as well as during the exposure to a virtual urban scenario with traffic noise. The HRV data was analyzed calculating the time domain parameter Root Mean Square of Successive Differences (RMSSD) as a measure of stress. Here, lower values are generally associated with a higher stress response. To enable an inter-individual comparison the data was standardized using a z-Score. A comparison of the baseline measurements taken outside and inside VR is depicted in Figure 4.

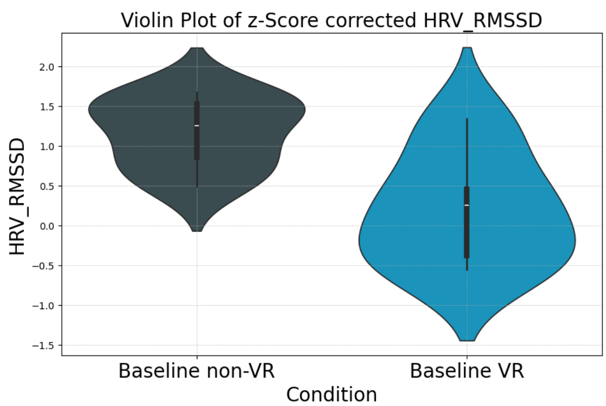

Figure 4: Comparison of HRV measurements during the first and second baseline phases. The violin plots show the distribution of z-Score corrected HRV values using RMSSD as a measure of stress.

The comparison shows that there is a significant difference in HRV values between the baseline measurement outside of VR ($M = 1.17, SD = 0.41$) and the baseline measurement in VR ($M = 0.21, SD = 0.65$);

$t(11) = 2.87, p = .021$, indicating that the VR environment itself can induce stress in the participants.

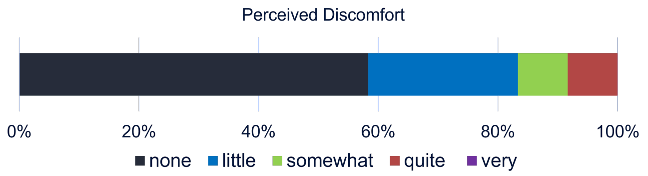

Figure 5: Perceived discomfort during the VR experiment.

According to the final interview, 83% of the participants reported having none or only little discomfort during the experiment with the remaining 17% reporting feeling somewhat or quite uncomfortable, as shown in Figure 5. Post-experimental discussions revealed that the perceived discomfort was mainly attributed to the annoying and repeating pattern of the presented traffic noise as well as some interactions with the evaluation interface.

Discussion

The results from this preliminary experiment highlight the importance of validating the tools and methodologies selected for perceptual experiments in VR. While the framework developed for the main study enabled an efficient configuration and performance of interactive audiovisual experiments in VR, participant reports suggest that the traffic noise simulations and the evaluation interfaces could be improved and thereby reduce the discomfort felt during the experiment even further.

More importantly, the comparison of stress response measurements taken inside and outside of the VR environment showed an increased stress reaction for the VR condition. This factor needs to be considered in the design of the main study to avoid confounding effects on the physiological data gathered during the exposure to the simulated traffic scenes. One approach to mitigate this effect could be the extension of the tutorial phase in VR to allow participants to become more familiar with the environment and the experimental procedure [9]. Another point to consider is the inclusion of background noise (e.g., wind and nature sounds) during the baseline measurement in VR, which might reduce the incongruence between the visual and auditory stimuli and thus the stress response. In addition, an extension of the rest period after each traffic scene and the analysis of changes in stress response across the length of the experiment could lead to more reliable intra-individual results.

Conclusion & Outlook

The preliminary experiment showed that the implemented VR framework is capable of integrating the different components required for the main experiment (e.g., the 3D environment models designed by urban planers and the simulated traffic scenes). A trial run with 12 participants was performed without major issues showing that HRV measurements can be taken and synchronized reliably and that perceptual responses can be gathered via soundscape evaluation interfaces within the virtual environment. The comparison of the baseline HRV measurements taken outside and inside of VR showed significant differences indicating that the VR environment itself can induce stress. This is an important finding for the design of the main study and suggests that the experimental design has to be adjusted to account for this effect. Once the necessary modifications have been implemented, the main BaLSaM study will be conducted with a larger group of participants.

Acknowledgements

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