Evaluation of audio-visual parameters in the perceived aircraft noise annoyance using virtual reality experiments

Sergiu Andrei Priboi

Delft University of Technology

TU Delft

Evaluation of audio-visual parameters in the perceived aircraft noise annoyance using virtual reality experiments

Thesis report

by

Sergiu Andrei Priboi

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on March 25, 2025 at 13:30 AM.

Supervisor:	Roberto Merino-Martinez
Project Duration:	May, 2024 - March, 2025
Faculty:	Faculty of Aerospace Engineering, Delft
Student number:	5000327

Cover: https://www.pexels.com/photo/low-angle-photo-of-airplane-flying-2510370/

TU Delft

Preface

This thesis represents a study towards the development of virtual reality environments in the field of aircraft psychoacoustic research. As more studies are performed towards understanding the effects that noise, especially the one produced by aerospace systems, have on the general population, it is of utmost importance to understand it thoroughly. To understand the influence of the audio-visual cues from the surrounding environment, of course, new tools have to be developed and integrated into the future studies. This work is focused on presenting the importance of the virtual reality technology in the field of psychoacoustics.

I consider that using virtual reality is just the starting point of a continuously growing and important field and can open new avenues for researchers to gather more relevant data towards understanding the effects that audio-visual cues have on the perceived annoyance.

Through this I want to extend my gratitude towards my supervisor Roberto Merino-Martinez for his ideas, interest and support throughout this period. I would also like to thank my good colleague Vlad Buzețelu, who helped me with great advice and offered valuable help during the experimental phase of this project. Lastly, I am grateful for all the people that have attended the experiment and gave their indispensable feedback.

Sergiu Andrei Priboi
Delft, March 2025

Summary

Noise pollution can lead to negative effects on the population, such as sleep disturbances, health issues, or psychosocial issues. As such, it is of utmost importance to understand the effects that the environment has on the perceived psychoacoustic annoyance, both from an acoustic as well as visual point of view.

This thesis presents a recently-introduced and built-upon method for exploring the field of psychoacoustics and the influence of audio-visual cues on the noise annoyance perception by the general population. This specifically focuses on addressing the impact of aircraft flyovers in different environments. The research employs a virtual reality application developed using the Unity Game Engine to facilitate the experimental assessment of the perceived aerospace noise, as well as the visual influence of the environment and the actual visual perception of the aircraft.

The developed application simulates an immersive realistic 360° environment, enabling participants to experience aircraft noise in different contextual settings. The audiovisual listening experiments involved 31 participants who rated their annoyance towards the sound created by an aircraft flyover on a 0 to 10 ICBEN scale. A total of 16 different scenes were used in the application, all of them divided into two sets of 8 scenes. Each participant had to grade one of these sets. Each scene presented the same aircraft rendering and sound signal, whereas the visual scene and the background noise differed in each of the scenes. The scenes where characterized by pair-wise visual attributes, such as urban - rural, sunny - cloudy, natural - artificial, city center - neutral city environment. The experiments were conducted in the Psychoacoustic Listening Laboratory (PALILA) inside the Aerospace Faculty at the Delft University of Technology.

The data analysis revealed that certain visual elements, such as rural or cloudy attributes significantly increase the annoyance perception of the participants, highlighting their importance in the surrounding environments. The visual factors were complemented in the analysis with psychoacoustic metrics, such as loudness, sharpness, tonality, etc., but a poor correlation with the annoyance ratings was found for them since the dominant sound source (the aircraft flyover) was kept constant throughout the different scenes. However, the signal-to-noise ratio showed more promising results with a better relationship observed with respect to the annoyance ratings.

Some key limitations were found during this research, such as the static visual background, the reliance on pre-recorded sounds, as well as a relatively small participant pool. As such, future research is recommended to include dynamic three-dimensional environments, tailored or auralized sounds, and a larger and more representative population of the participants. The scope of the application can also be extended to drones, wind turbines, as well as novel aerospace applications, such as hybrid aircraft designs or distributed electric propulsion aircraft.

Overall, this study proved the potential that virtual reality holds in the field of psychoacoustics. This not only enables a multidimensional analysis, but also opens new avenues towards a better understanding towards the environmental influence on noise annoyance by aerospace applications, as well as more immersive and realistic experiments.

Contents

1 Introduction

With the great and rapid development of the aeronautical industry, more attention is paid to the negative effects that its related noise emissions have on the population, especially on the communities around airports. These effects can range from smaller aspects, such as annoyance [1] and sleep disturbance [2], to higher risk health factors such as hypertension [3], cardiovascular diseases [4], or even psychosocial health [5]. Therefore, it is of utmost importance to study and understand the effects that noise and other stimuli have on the perception of aircraft.

There are numerous studies on the noise annoyance that transport generally produces [6], as well as studies on conventional aircraft and their influence on annoyance, such as a study on fourteen different aircraft sounds recorded around Munich airport [7]. Similar studies were also performed around Amsterdam Airport Schiphol with the intention of analyzing noise abatement procedures [8]. Lastly, studies such as the one by Miedema and Oudshoorn [9] show that aviation noise usually leads to the highest annoyance out of all modes of transportation, compared to railway and road transport.

However, in addition to the audio stimuli of conventional aircraft, two more topics are of high interest. First, the social acceptance of future aircraft configurations is currently an intriguing field to analyze [10], with studies on the noise produced by distributed electric propulsion aircraft and the annoyance created [11], the perception of drone aircraft and other types of Urban Air Mobility vehicles [12, 13], vertical take-off and landing aircraft [14], such as the Joby Aviation Aircraft [15]. Furthermore, the development of future aircraft is also leading to more intriguing designs such as the Flying-V [16], for which the shape may also play an important role in the perception that an observer may have on the annoyance coming from the produced noise. A study towards the fuselage design for internal aircraft noise of future aircraft designs is explained by Krakers [17]. Future considerations are analyzed as well for Urban Air Mobility and the noise annoyance that it may create [13]. As explained by Rizzi [18], experiments on the psychoacoustic annoyance can also lead to ”Perception-influenced design” (PID), where the perceived noise annoyance can positively influence the design of future aircraft.

Secondly, it has been described in numerous studies that the auditory factors are not the only influence on the perception of noise, and there can be several other non-auditory factors [19], that impact the noise perception in drones [20, 21, 14, 22], wind turbines [23, 24, 25] and other more general cases such as solely urban environments [26]. Therefore, factors such as visual representations of the noise producing object as in the study from Cox [27], the surrounding environment [28, 29], the time of day [30], and the background noise [31, 22] are shown to influence the perception of noise.

This thesis aims at answering the following research question: **What are the effects that visual perception has on listening experiments of aircraft noise?**. To answer this question, a tool has to be developed, consisting of a software application through which audio-visual experiments can be performed.

The visual representation of the sound emitters as well as the surrounding environment are implemented in the experiments through the development of a virtual reality (VR) application, that is able to simulate various environments, similar to past studies such as the ones performed by Torija [22] and Almoes [32], as well as other visual cues, such as time of day, color (greenery, cold/dark skies), etc. This environment is able to simulate both conventional and future aircraft configurations and is developed using Unity[1], an open-access game engine that allows the creation of VR applications with relative ease and offers a great support to numerous main-stream VR headsets, such as the Meta Quest 3[2] that will be used for the research.

The sound produced by the virtual emitter in each scene is based on an experimental recording of an aircraft flyover measured in previous researches [33]. In the final steps of the development, experiments were performed in the psychoacoustic listening laboratory (PALILA) at the faculty of Aerospace Engineering at TU Delft [34], and the effects that visual factors have on the perception of noise were recorded and analyzed. This research intends to open the way towards a further understanding of aircraft noise and its effects on the health and well-being of communities affected by this.

This thesis report is organized as follows: chapter 2, presenting the development of the VR application, chapter 3, explaining the experimental setup, chapter 4, presenting and discussing the results of the research and chapter 5, presenting the conclusion of the research and recommendations for the future.

[1] https://unity.com/solutions/vr
[2] https://blog.unity.com/engine-platform/get-started-developing-for-quest-3-with-unity

2 Development of the Virtual Reality Audio-Visual Environment

In the following chapter, the software application to be used in the audio-visual experiments is presented. This will focus on the reasoning behind the development of the environment, the application's scope and functionality, and the various elements that were implemented for this application.

2.1. Unity game engine

For this application, it was decided that the open-access Unity game engine represents the most suitable environment where the tool can be developed [35, 36]. This was chosen mainly due to its ease of use with virtual reality devices such as the Meta Quest 3. Furthermore, this engine also provides great usability when it comes to creating both suitable environments for this research, as well as easily manipulating background sounds, and the actual sound produced by the aircraft. Considering its relatively long lifespan, Unity has also gathered numerous tutorials, as well as considerable packages, both as 3D assets, and scripts, that present an easy and ready-to-use development kit for new users.

2.2. Main elements of the application

The application, or tool, to be used in this research will contain several main elements intended to give certain functionalities, such as: multiple scenes, the aircraft asset, the aircraft sound, the background sounds.

The scenes represent the environments that the user observes when running the application on the Meta Quest 3 VR headset. The main scenes represent the focus of the research, meaning a real-life environment, chosen based on several attributes that will be explained later, where the user is presented with an aircraft flyover. The second type of scenes is represented by menu items, where, in order, the participant is presented a tutorial on the functionality and scope of the application, a grading scene, where the participant can express their annoyance, and an end scene, where the participant can exit the application.

In this research, the use of VR was chosen as it allows for a quick and easy assessment of the annoyance in different scenarios. Using such an application opens the way for a lot of diversification regarding aircraft sounds, background noise, and background images. Moreover, rather than a static image on a monitor, the VR technology allows the user to move freely inside the scene. Although this movement is limited to one observer position in the 3D space, the user can look around the environment and perceive the data from the scene almost as if they were actually standing in the real-world location. As such, even from inside the laboratory, any participant can be transported to numerous locations around the globe, and in different scenarios regarding, the time of day, weather conditions, crowdedness, etc.

The aircraft render that is used in this application is based on a free asset[1], as seen in the background of Figure 2.2, that was downloaded from the Unity Asset store. The aircraft sound is represented by a plane flyover recorded by the Aircraft Noise and Climate Effects team for a previous research [33]. This sound is directly linked with the virtual plane ”flying over” the participant’s head, such that the sound can be ”emitted” by the plane and take into consideration its movement during the scene.

To bring another piece of realism to the scenes, background sounds were implemented that fitted with the elements presented in the scene (e.g. human voices, fountains, cars, nature sounds). These sounds were downloaded as royalty-free resources off the internet and reference links can be found for each sound in Appendix B.

2.3. Functionality

The Unity engine contains a scripting element, where custom functionalities can be implemented into the application. The scripting consists of C# pieces of code, that directly influence the behavior of assets, sounds, image backgrounds, scene functionality, and user interface (UI) elements, such as sliders and buttons.

Scripting using C# was mainly used in order to correctly parse through the scenes of the application. The menu to be used by the participant allowed them to either choose an annoyance rating and assess whether they saw the plane in the scene or not, or to access the previous room, and to continue with the following scene. This was performed based on a script, as the order in which the scenes were presented to each participant was randomized. The randomization of the scenes was done in order to avoid pattern learning effects from the participants that may complete several such experiments.

Each user has the option to re-assess any scene, using a button in the grading scene UI. In this case, a script keeps a log of where in the application the user currently is, and the randomized list of scenes. As such, the application knows what scene to render, based on the user’s choice.

Furthermore, the application also contains scripts for saving the outputs of each participant, as well as other useful data, such as the date and time of the experiment, and the participant number. Out of these pieces of data, the participant number was especially useful, as based on whether this number was odd or even, the participant was shown a different set of 8 scenes.

All data that was gathered during the experiment was automatically saved in a *.csv* file that was updated each time the application is started. As such, the application can be run for the whole experiment, without any interference. In order to have a safe back-up of the data, all the updated *.csv* files were downloaded from the VR headset to the laptop in PALILA.

The Meta Quest 3 VR headset and the controllers that have been used during this research are shown in Figure 2.1. The Meta Quest 3 is a standalone VR headset with $2064x2208$ pixels resolution per eye, a Snapdragon XR2 Gen 2 chip, and up to 120 Hz refresh rate. In addition to this headset, a pair of Sony WH-1000XM4 over-ear, closed-back headphones was installed, resulting in a deeper immersion of the participants in the scenes. The controllers are used to navigate through the menus and scenes, and to interact with the UI elements.

Figure 2.1: Meta Quest 3 VR headset and its controller. Picture taken inside PALILA [37].

[1] https://assetstore.unity.com/packages/3d/vehicles/air/planes-choppers-polypack-194946

2.4. Menus of the application

As specified before, the application consisted of several scenes. Each participant of the experiment was shown a set of 8 main scenes, each with a different real-world background. Moreover, they were shown an introduction scene (Figure 2.2), a grading scene (Figure 2.3), and an end scene (Figure 2.4).

In the introduction scene, the participant is shown a piece of text welcoming them to the experiment, then another window explaining how to use the UI elements of the application, and, lastly, lets the user explore a first VR scene, to get familiar with this technology in case they have never had any experience with it. The last part is of utmost importance, as for new users, using a VR headset can induce nausea, leading to issues regarding the participation of that person in the experiment.

Figure 2.2: Introduction scene of the application.

The main sub-scene of the application is the grading scene, where the participant is asked to rate the annoyance created by the aircraft flyover in the previous scene. Each participant was presented the following question: *”What grade from 0 to 10 best shows how much you would be bothered, disturbed, or annoyed by the sound of the aircraft in this scenario?”*. They then had to use a slider UI to set the grade based on an ICBEN 11-point scale from 0 (*not at all*) to 10 (*extremely*).

Another important element in this window is the second question: *”Did you see the plane?”* to which the participant can answer with ”Yes”, ”No”, or ”Not Sure”. The last choice was added in order to check whether the participant’s response was given after they have been paying full attention to the scene. In this context, it has to be noted that some of the scenes did not show a visible render of the aircraft.

Lastly, in this grading scene, there are two other buttons ”Previous Scene”, which was added in order to provide a second chance for the participant to reassess the annoyance that was caused by the flyover and ”Continue”, which proceeds to the following scene.

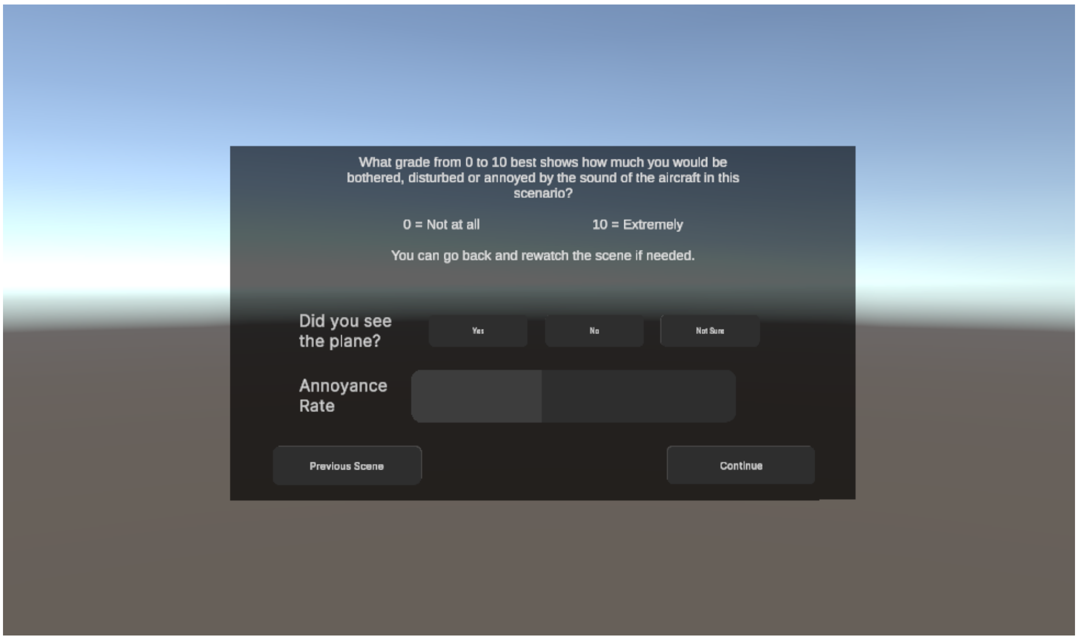


Figure 2.3: Grading scene of the application.

At the end of the experiment, the participant is shown a thank you message, followed by a button UI element, that exits the application and confirms to the participant that they can take off the VR headset.

Figure 2.4: End scene of the application.

2.5. Main scenes

As explained before, the main scenes of the application are represented by the real-world scenarios with the aircraft flyover. This section focuses on explaining how these scenes were set-up and the functionality of the menu present inside.

2.5.1. Scene menu

When a main scene starts, the user is presented with a menu, as seen in Figure 2.5, containing 4 buttons. The first button "Start Scene" initiates the aircraft flyover in the scene, by rendering both the airplane itself as well as the sound produced by it. The second button, "Reset Scene", shows the beginning of the scene before the aircraft with its sound is rendered. It has to be noted that when the scene is initialized, the only environment elements are the background sounds and the background image.

The third button, "Previous Scene" allows the participant to render the scene before, showing the grading scene related to the real-world scenario of the respective scene. This functionality allows the participant to reassess the previous scenarios based on the knowledge they gathered during the experiment. This can help, especially with the first few examples that a participant is shown, to better understand the reference to which they should compare the sounds, as such, improving the annoyance ratings provided for the first scenes.

The last button "Continue" renders the next scene in the order of the randomized list that is initiated at the start of the application. For a better understanding, each button has an explanatory text placed next to it, see Figure 2.5.

The window element can be bothering the participant by not allowing them to fully observe the complete scene and can interfere with the results of the experiment. As such, whenever the participant starts the scene, this window is automatically minimized, and is transformed in a translucent square. The window can then be maximized back again by either pressing the square element in the scene or by pressing a set button on the VR headset controller.

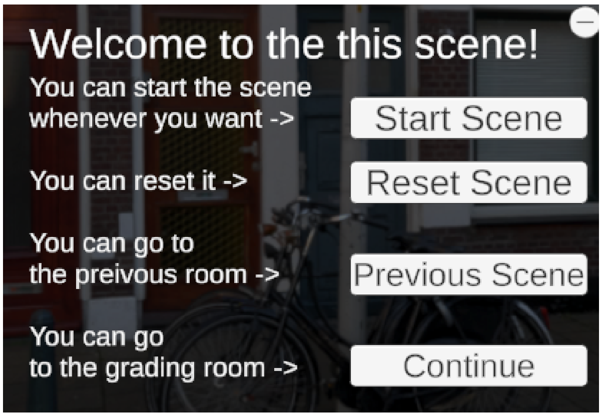


Figure 2.5: Menu inside main scenes.

2.5.2. Scene set-up

Each real-world scenario background is set by using 360° images that are downloaded of the internet. They are then rendered on a sphere element and placed as the foreground of the scene. As such, the participant can be immersed in a realistic environment, as seen in Figure 2.6. Example images of the rest of the scenes can be observed in Appendix C. However, this also introduces a limitation of the application, as the participant does not have the possibility of dynamic movement inside the scene. As such, a user can only experience the stationary location and the 360° movement of their head.

Figure 2.6: Screenshot from the Bucuresti Unirii Sunny scene

The scenes that were chosen for the experiment will be explained below and examples will be shown.

The division of the scenes into two groups was chosen, as for most participants, the VR headset represents a novel experience, which can induce fatigue to the eyes, overall tiredness, or even nausea. As such, it was decided that each user will only be shown 8 real-world scenes alongside the introduction, grading scenes and end scene. This was approximated to last between 15 and 20 minutes, allowing for a good assessment of the experiment, while maintaining a good state both mentally and physically.

The scenes were chosen such that they cover a wide range of attributes that were chosen based on literature [38]. For each attribute, a counter-attribute was chosen, such that the whole space of that specific aspect can be correctly analyzed. As such, the scenes can be defined as in Table 2.1. Moreover, representative screenshots of each scene can be found in Appendix C.

As some of the attributes are not full self explanatory, each of them will be defined below.

1. **Urban**: A scene that shows elements inside of cities, such as buildings, streets, cars, and people [28, 14, 22, 32];
2. **Rural**: A scene that shows mainly natural elements, outside of the city [29, 14, 32, 39];
3. **Sunny**: A scene where the sky is mostly clear and the sun can be observed [40, 41, 39];
4. **Cloudy**: A scene where the sky is very cloudy, leading to the plane being hidden behind the clouds [40, 41, 39];
5. **Natural**: A scene where most of the elements are natural, but not necessarily in a rural environment (Example: park inside of a city) [29, 39];
6. **Artificial**: A scene where most of the elements are man-made, but not necessarily inside of a city environment (Example: a beach containing restaurant, terraces etc.) [28, 14];
7. **Neutral City Environment**: A scene inside of a city, but in neutral, day-to-day locations, such as residential areas [29, 22];

8. **City Center**: A scene inside a city showing either locations from the city center or other recognizable attractions inside the city [28, 14, 22];

Table 2.1: Attributes and division of the scenes.

Scene Name	Urban/Rural	Sunny/Cloudy	Natural/Artificial	Neutral City Env./ City Center
Set 1				
Dutch Empty Street	Urban	Cloudy	Artificial	Neutral City Env.
Echo Building	Urban	Sunny	Artificial	City Center
Hague City Cloudy	Urban	Cloudy	Artificial	Neutral City Env.
Hague City Center Sunny	Urban	Sunny	Artificial	City Center
Scheveningen Day Grass Sun	Rural	Sunny	Natural	NaN
Hague City Center Sunny 2	Urban	Sunny	Artificial	City Center
Hague Park Kids Sunny	Urban	Sunny	Natural	Neutral City Env.
Bucharest Unirii Sunny	Urban	Sunny	Artificial	City Center
Set 2				
Timisoara Center Daylight	Urban	Cloudy	Artificial	City Center
Scheveningen Day Beach Cloudy	Rural	Cloudy	Artificial	NaN
Bowpub Sunny	Urban	Sunny	Artificial	City Center
Timisoara Parcul Civic Daylight	Urban	Sunny	Natural	Neutral City Env.
Colosseum Cloudy	Urban	Cloudy	Artificial	City Center
Scottish House Cloudy	Rural	Cloudy	Natural	NaN
Delft Center Sunny	Urban	Sunny	Artificial	Neutral City Env.
Delft Markt Sunny	Urban	Sunny	Artificial	City Center

As stated before, the aircraft is not shown in all scenes. This is done such that the user can have the same experience as in a real-world scenario. For example, whenever the sky is full of clouds, the visibility of the aircraft is limited and the sound produced is the only element certifying its visibility.

Table 2.2: Visibility of the aircraft in each scene

Scene Name	Existence of aircraft	Scene Name	Existence of aircraft
Dutch Empty Street	True	*Timisoara Center Daylight*	False
Echo Building	True	*Scheveningen Day Beach Cloudy*	False
Hague City Cloudy	False	*Bowpub Sunny*	True
Hague City Center Sunny	True	*Timisoara Parcul Civic Daylight*	False
Scheveningen Day Grass Sun	True	*Colosseum Cloudy*	False
Hague City Center Sunny 2	True	*Scottish House Cloudy*	True
Hague Park Kids Sunny	True	*Delft Center Sunny*	False
Bucharest Unirii Sunny	True	*Delft Markt Sunny*	True

In the cases where the aircraft was not shown, but the user communicated the opposite, their answer is considered to be rejected and not be used further in the analysis. In the cases where the plane was shown in the scene, but the user has not seen it, the answer is kept, as there is a possibility that indeed the user may have missed it in the specific scenario. The presence of the aircraft in each scenario is explained in Table 2.2.

2.6. Aircraft Sound

Several aircraft flyover recordings were provided by the ANCE team, however, it was decided that in all scenes, the same aircraft sound should be used, such that the research can focus mainly on the influence that the attributes of the environment have on the perceived noise annoyance. As such, one recording was used for all scenes.

The aircraft sound that is used in the application is produced by a CRJ-701 aircraft. The aircraft is equipped with two GE CF34-8C1 engines.

For an increased level of realism, the aircraft in each scene is considered as an audio source inside of Unity and the flyover recording is linked to it. Unity provides several settings that can influence the perceived sound. As such, all the sounds in the scenes, including the aircraft, are considered to be 3D sources that can be affected by spatial position and spread. Furthermore, Unity also provides a spread option, allowing the developer to set the range of maximum amplitude of any sound.

2.7. Background Sounds

Each scene contains one or several background sounds in accordance to the elements surrounding the user. These sounds range from recordings of general noise in residential areas, to people talking, fountains, wind, or even road traffic. They were added to provide another layer of realism to the scenes and help the participants get more immersed in the scene.

All sounds are linked to invisible spheres inside the scene, placed in the direction of the specific element. For example, if the scene shows a fountain on the left, a sphere will be placed in that direction, and its volume will be modified to sound as realistic as possible from that position. An example of this scenario can be observed in Figure 2.7. It has to be noted that here, the sphere mesh is shown and colored in red, such that it is obvious where the sound source is positioned for clarity reasons in this figure, but in practice they were not visible to the participants. The invisible spheres are used to give the scene a binaural feeling, such that the user can feel the sound and the direction it is coming from. In this case, if the sound is coming from a source placed to the left, the user's left ear will perceive an increased volume compared to its right. Furthermore, if the participant moves its head, the perceived sound will change accordingly. This process is completely managed by the Unity game engine and both stereo and mono sounds can be used.

Figure 2.7: Sphere where the background fountain noise source is attached. The sphere mesh and color are shown such that the reader can observe its position. The position of the user in the scene is shown by the 3-axes system.

In case a sound is considered to be just general noise in conformity with the environment, the invisible sphere will be placed in the same position as the head of the user in the environment. As such, the sound can be heard from all directions by the user. In this case, a stereo sound should be used, such that the background noise can be heard accordingly in both ears.

During the development of the application, the background sounds' sound pressure levels were modified based on personal experience and testing to give a natural feel to each element in the scene. To account for this, the background sounds were manually modified, using a MATLAB script, before the psychoacoustic analysis. All results were tabulated and saved in *.csv* files to be later used for the data analysis phase.

3

Experimental Setup

After its development, the application was used for the experimental part of the research. Over a duration of two weeks, 30 participants were invited to the PALILA laboratory, where they were asked to use the VR headset running the application. The data was then saved and later used in the analysis part in chapter 4. This chapter focuses on the main aspects of the experimental phase and the observations that were made during this time period.

3.1. Psychoacoustic listening laboratory (PALILA)

All experiments were performed inside the Psychoacoustic listening laboratory(PALILA) [37] at the Faculty of Aerospace Engineering of Delft University of Technology. This facility consists of a box-in-box structure, with interior dimensions of 2.32 m (length) x 2.32 m (width) x 2.04 m (height). It is constructed out of acoustic-absorbing foam panels that prevent sound reflection, creating an acoustically dead space, due to the 0.07 s reverberation time, where free-field sound propagation applies for frequencies higher or equal to 1600 Hz. Moreover, the room is isolated from any other external influence, having no window and no light penetrating it, and presents an A-weighted background noise level of only 13.4 dBA. As such, the participants can be fully immersed in the experiment and the only factors influencing them are the intended ones, presented during the experiment.

PALILA is equipped with a Dell Latitude 7340 touchscreen laptop, a pair of Sony WH-1000XM4 over-ear, closed-back headphones and the Meta Quest 3 VR headset with two controllers. The laboratory laptop is not directly used during the experiment, but was operated by one of the two conductors to the experiment at the end of each day to create back-ups of the data.

Figure 3.1 shows the set-up where the experiment was performed, as well as an example of how one participant was to be using the hardware.

3.2. Subjects

As stated in the introduction of this chapter, the experiment included 30 participants, with ages between 18 and 29 years, all being either students, or recently graduates of the Faculty of Aerospace Engineering, Nanobiology, or Computer Science. The participants had diverse educational backgrounds, with 6 of the participants having the highest level of education at high school, while the rest presented either a Bachelor's or Master's degree. Two of the participants reported that they have ”Some College, but No Degree”. Out of the 30 participants, 9 of them are employed, while the rest are students. The users' age distribution is plotted in Figure 3.2.

Figure 3.1: The set-up of the PALILA laboratory containing the VR headset, headphones, and laptop and an exemplification of how the participants used the hardware.

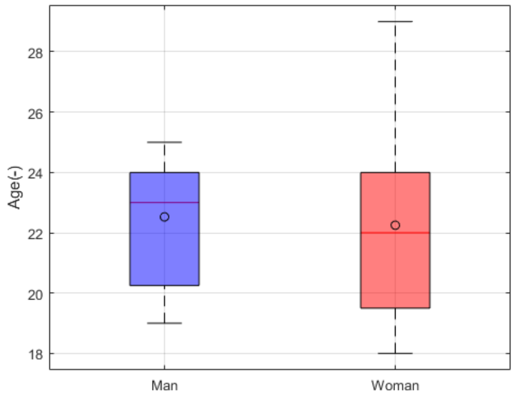


Figure 3.2: Box plot showing the distribution of the participants' age based on gender.

29 participants were affiliated with Delft University of Technology by either being students - active or recently graduates - or employees. Two participants have no affiliation with the university. Out of the 30 participants, three of them reported a mild cold, giving a score of either 1 or 2 on a 5-point scale, which was found to not influence the outcome of their responses.

Furthermore, no participants communicated utilizing hearing aids, and their hearing rating ranged from "good" to "excellent", with only one participant declaring they have a "fair" hearing rating. Two users reported having tinnitus, but they declared their hearing as being "Very Good". Lastly, none of the participants had ear diseases.

For the two sets of participants, a cross-correlation matrix was computed as the pair-wise correlation between the respective answers of different participants to the same scenarios as seen in Figure 3.3 and Figure 3.4.

It has to be noted that the even-player number set has one missing person, that was removed from the dataset immediately after the experiment, as they graded the annoyance of 7 out of 8 scenes with a 0-grade.

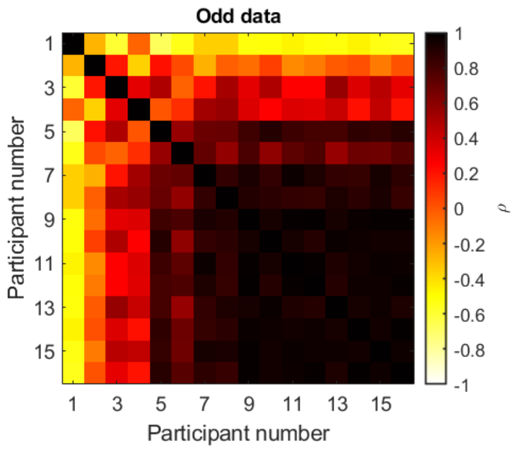


Figure 3.3: Cross-Correlation matrix between the responses of each pair of individual participants from the odd participant number set - showing the correlation coefficients (ρ).

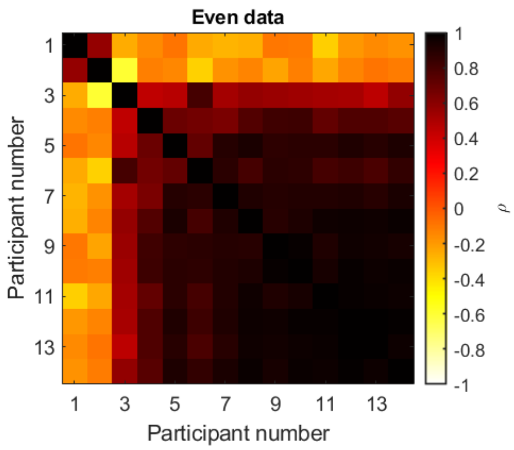


Figure 3.4: Cross-Correlation matrix between the responses of each pair of individual participants from the even participant number set - showing the correlation coefficients (ρ).

In these two figures, it is seen that participant number 1 from the odd data set and participants 1 and 2 from the even set present lower correlations compared to the rest of the participants, and as such, the mean correlation coefficients were computed along each row and tabulated in Table 3.1. Indeed, it is observed that the coefficient ρ of these participants are comparably lower than the others, presenting values close to 0, meaning no correlation. Furthermore, it is also seen that in the odd data set, the first participant had a negative correlation compared to the other values, the same as the first two participants in the even data set.

Table 3.1: Average correlation coefficients between the responses of each pair of individual participants from the odd and even participant data sets. The correlation coefficients from the participants that were removed from the analysis are bolded in the table.

Odd Data	Even Data
-0.3702	**-0.0570**
0.0099	**-0.0647**
0.3196	0.4345
0.2944	0.6120
0.6060	0.6987
0.4983	0.6619
0.6574	0.7011
0.6799	0.7305
0.7055	0.7357
0.6929	0.7521
0.6902	0.7108
0.6841	0.7469
0.6932	0.7379
0.6938	0.7520
0.7098	
0.6913	

Based on the information on the correlation coefficient of the participants' responses, an analysis was performed to check whether removing these participants' responses would affect the outcome of the responses. Indeed, it was observed, based on the new correlation coefficients computed, that the responses deviated from the initial analysis, and as such it was decided that any further result would be created without the three responses with a low correlation.

3.3. Experiment timeline

The experiments took place over a two week period, including 2 to 5 participants each day. The individual participants were welcomed and shortly briefed about the characteristics of the listening experiment. They were requested to read and sign an informed consent form, which was previously approved by the Human Research Ethics Committee from the Delft University of Technology (form number 3599). The experiments were performed at the same time as another MSc thesis experiment also related to aircraft noise annoyance and the participants were asked to perform both of them one after the other. Each session was planned to last 1 hour, with the first 20 to 25 minutes being planned for the other thesis experiment, while the following 20-25 minutes were planned for this research experiment. A 10 minute break was planned between the experiment, such that the participants were not experiencing fatigue and the experiment conductors could discuss any issues or feedback provided by the users. At the end of the experiment, each participant was asked again about any potential issues or feedback on the experiment and they were awarded a 10 Euros gift card to compensate for their time spent in the experiment.

All participants to the experiment were asked whether they felt any nausea or discomfort during the VR experiment, but none of them signaled any issues regarding this.

4
Results and Discussion

After the experiments have finished, the data gathered during the two weeks was saved on a personal computer and later used for further analysis. This analysis includes observations over the participants' responses pairwise cross-correlation, and box plots of the annoyance ratings based on the presented scenes, analysis of the influence of the attributes of each scene, and, lastly, a correlation computation between the average annoyance ratings and sound metrics of the background and aircraft noise. This chapter explains in detail the process, results, and findings of the data analysis part of this research.

4.1. Box Plots

Figure 4.1 shows the box plot for the complete dataset including all 16 scenes. As seen in the caption of the figure, this box plot shows the filtered dataset as explained earlier.

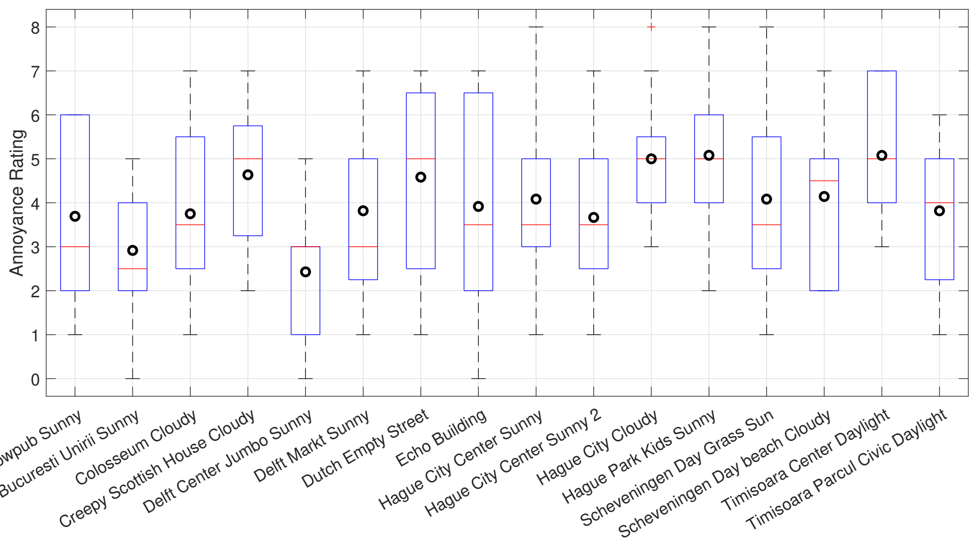


Figure 4.1: Box plot of complete dataset filtered based on the visibility of the plane filter.

From Figure 4.1 it can be seen that some scenes, such as ”Bowpub Sunny”, ”Dutch Empty Street”, ”Echo Building”, ”Hague City Center Sunny 2”, and ”Timisoara Parcul Civic Daylight” present a high variability in terms of the annoyance of the participants. Moreover, other scenes seem to present values that are more clustered together, with a low variability, such as ”Hague City Center Sunny”, ”Hague City Cloudy”, or ”Hague Park Kids Sunny”. The last major observation from this figure is the ”Delft Center Jumbo Sunny” scene, where the values seem to present the lowest trend considering the overall values, but the lowest median values are seen in ”Bucuresti Unirii Sunny”.

As seen in Figure 4.1, although useful, these data are not completely clear in the discussion regarding the attributes that the scenes were built upon. As such, the following four figures were also plotted, where the different attribute pairs are plotted. These box plots can enhance the understanding of the variability between scenes and specific attributes. Moreover, four other figures are plotted showing the average annoyance rating of each pair of attributes in the form of box plots.

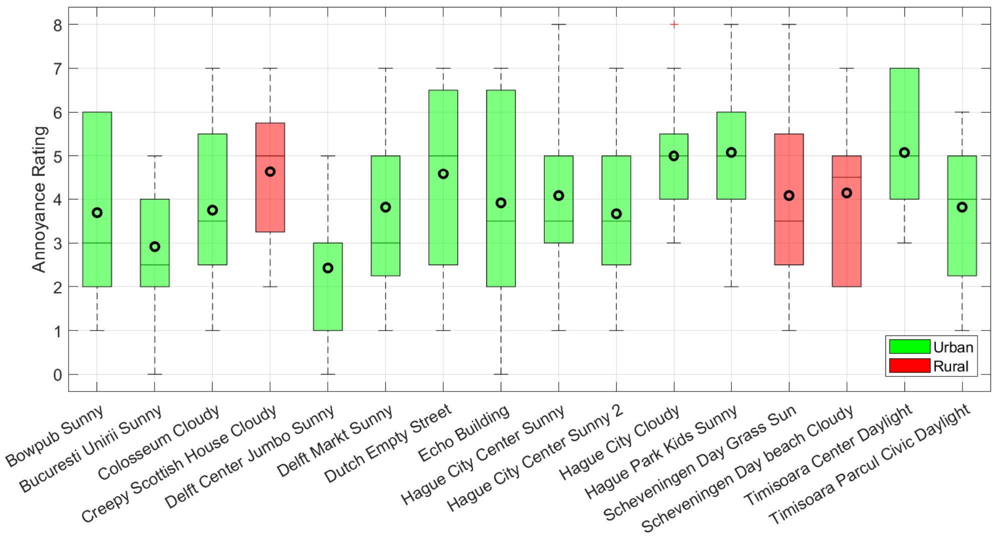


Figure 4.2: Box plot showing the urban and rural scene attributes.

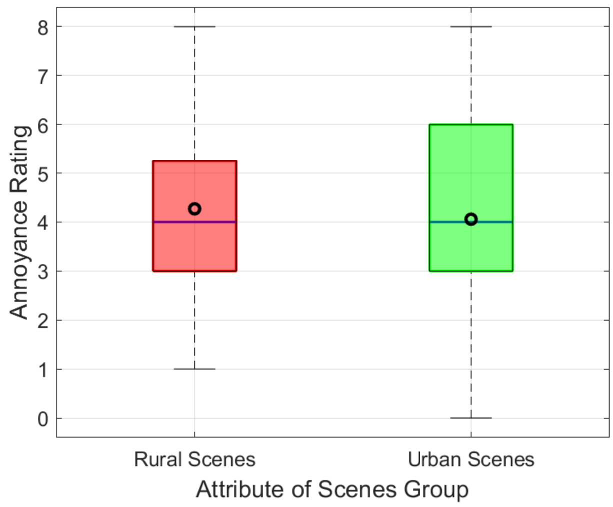


Figure 4.3: Box plot showing the mean annoyance ratings for the urban and rural scenes.

Three scenes out of 16 were considered to be *Rural*, where the first one shows a trend towards a higher annoyance, containing the highest median value of 5. The other two scenes have a lower trend, with the ”Scheveningen Day Grass Sun” having a median value of around 3.5. Comparing the values for the *rural* vs. *urban* values, it is observed that the differences are not major. However, considering the fact that the last two *rural* scenes are taken from relatively familiar environments for the participants that are living in the Netherlands, it may be the case that a purely *rural* scene, may induce a higher annoyance when it comes to the existence of a flyover in that environment.

Figure 4.3 shows that indeed, the median values of the annoyance ratings provided for the scenes defined as rural and urban are the same, with a value of 4 and the mean values are also close, with a value of around 4. However, it is observed that the urban scenes have a trend towards higher annoyance ratings, with the interquartile range (IQR) starting from the same annoyance rate of 3, but going up to 6. This hints to the fact that the annoyance trend is higher in urban scenes.

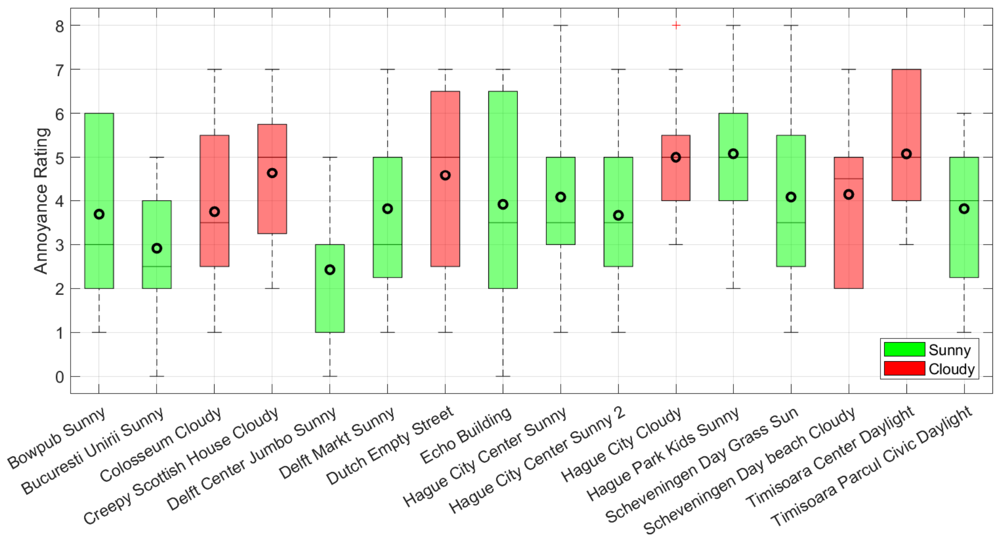


Figure 4.4: Box plot showing the sunny and cloudy scene attributes.

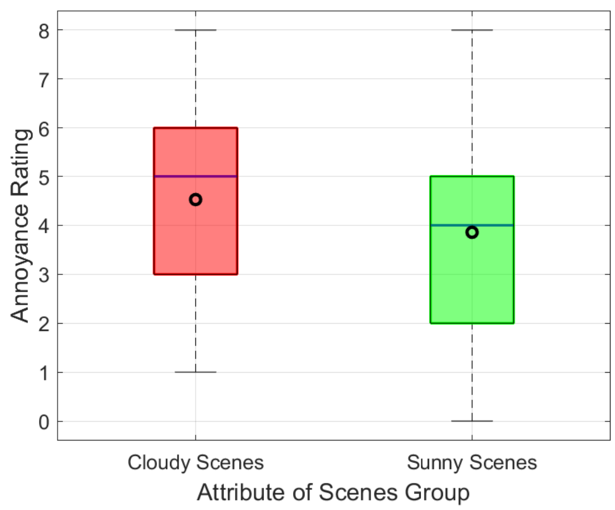


Figure 4.5: Box plot showing the mean annoyance ratings for the sunny and cloudy scenes.

The scenes where a cloudy environment was displayed seem to present generally higher mean and median values, with a trend towards higher annoyance. However, the ranges of the values seem to present high variability, with scenes, such as "Dutch Empty Street" having the values in the IQR ranging from 2.5 up to 6.5. Overall, it is seen that the cloudy environments present high median value, with 5 out of 6 scenes, having approximately a median value of 5. This is further supported by Figure 4.5 where it can be clearly seen that a higher overall annoyance was perceived in the cloudy scenes, with the IQR presenting values from 3 up to 6, a median value of 5, and the mean around 4.6, while the sunny scenes present values from 2 up to 5, with a median of 4 and a mean value slightly lower.

Sunny scenes, on the other hand, presented a lowered trend, with median values for the individual scenes generally closer to 3, and with minimum values down to even 0 (representing no annoyance). However, it is seen that in one of the scenes, ”Hague Park Kids Sunny”, the median value is 5, and most of the values are nested together around this value. This also presents a highest annoyance rating of 7, which is the maximum in the experiment. This information suggests a high general annoyance in this scene, differing from the trend of the *sunny* scenes.

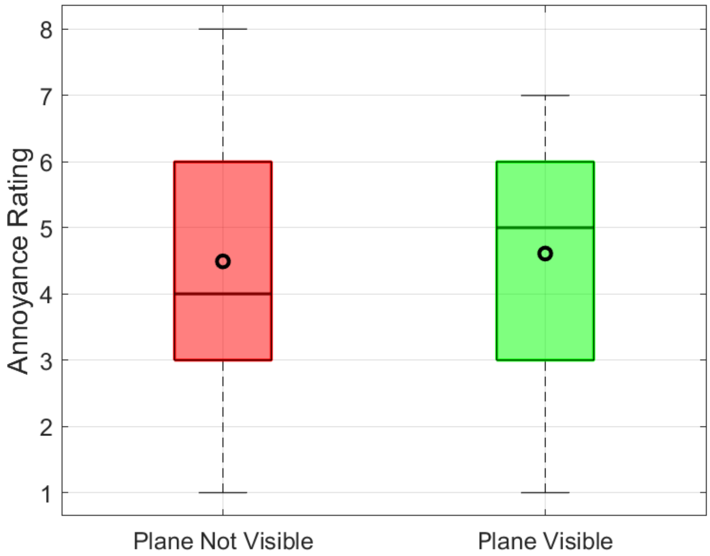


Figure 4.6: Box plot of the average annoyance ratings for the cloudy scenes where the aircraft was visible or not.

Figure 4.6 helps in the comparison between the *cloudy* scenes where the plane is visible and not visible respectively. From this plot, it is observed that when the plane is not visible, the median annoyance is 4, while for the cases when the aircraft is visible in the scene, the median annoyance rating increases by one, to a value of 5. However, the IQR values are seen to be placed between the same values of 3 and 6, and also the mean values are very similar, with a mean value of 4.49 for the cases where the plane is visible, and for the other case, a value of 4.6. This shows that when the plane is visible, there is a slightly higher annoyance reported in the cloudy scenes. This shows that the cloudy scenes where the plane is visible lead to an increased annoyance, but not by a meaningful value, as the percentage difference is only 2.4%.

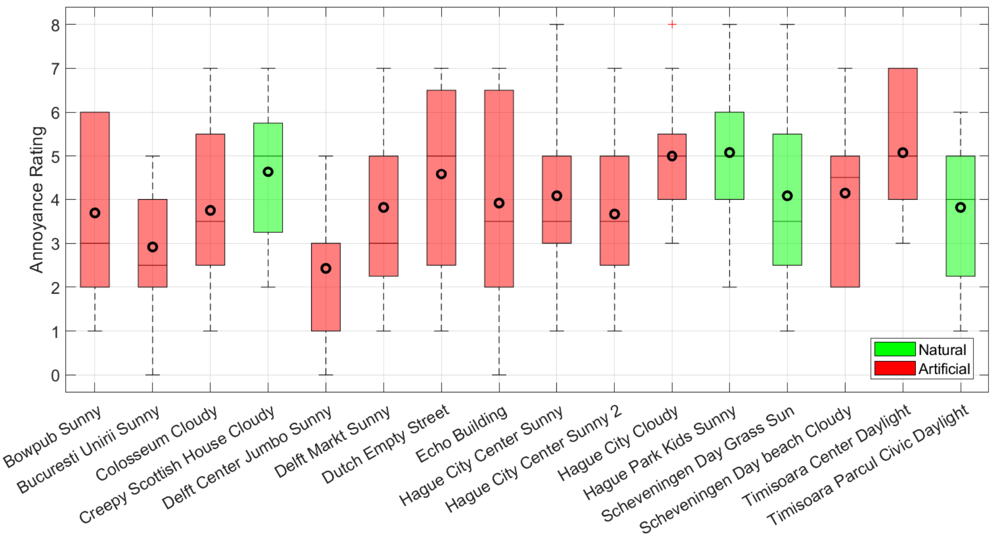


Figure 4.7: Box plot showing the natural and artificial scene attributes.

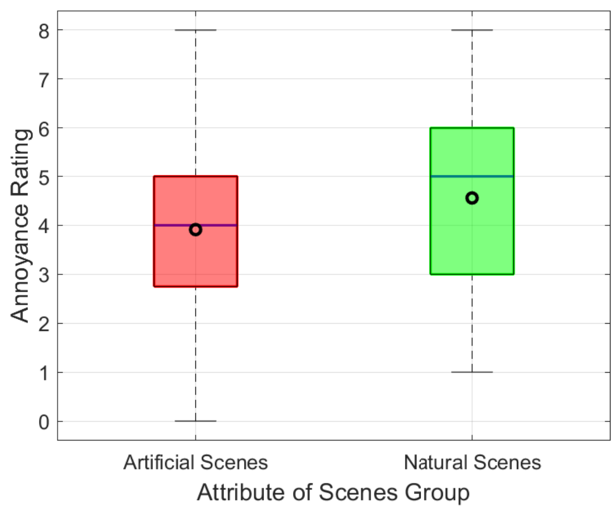


Figure 4.8: Box plot showing the mean annoyance ratings for the natural and artificial scenes.

Four scenes were considered to be *Natural*, while the others were *Artificial*. In Figure 4.7 it is seen that a trend is not immediately observed, as two scenes have a high median value of 5 while the other two have a median value of 3.5 and 4 respectively. Although having less data, it is seen in Figure 4.8 that the natural scenes present an overall higher annoyance trend, with the median value being 5 and the maximum for the IQR of the data going up to 6. Furthermore, the mean value for the natural scenes is also higher than the artificial ones, with a mean of around 4.6 compared to a mean of 4. This shows the presence of a higher annoyance in the natural scenes compared to the scenes with the artificial attribute. The higher annoyance recorded in the natural scenes may be explained by the disturbance of the peace associated with such environments, created by the presence of the aircraft flyover.

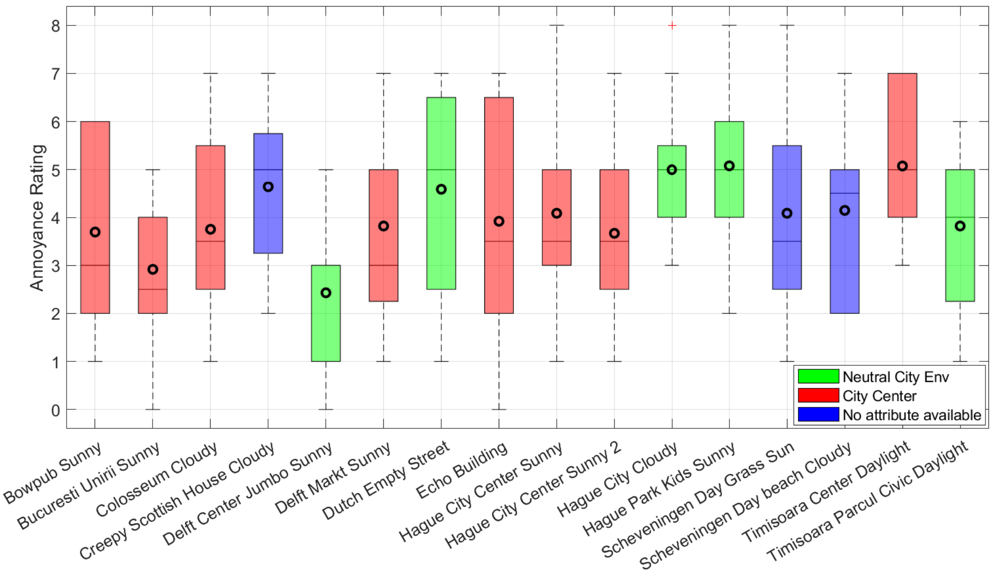


Figure 4.9: Box plot showing the *neutral city environment* and *city center* scene attributes.

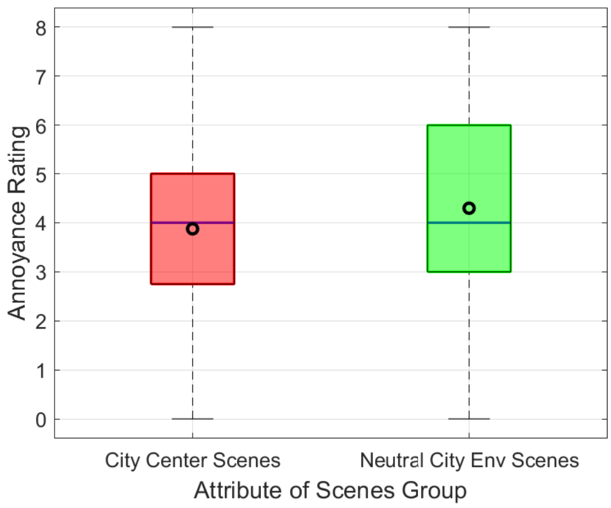


Figure 4.10: Box plot showing the mean annoyance ratings for the *neutral city environment* and *city center* scenes.

In Figure 4.9, three scenes, represented in blue, were not defined based on the *Neutral City Environment* or *City Center* attributes, as they could not be integrated into their definitions, as such, these scenes are not considered in the attributes discussion in this case.

In Figure 4.9, the scenes considered to be part of the *Neutral City Environment* and *City Center* attributes are shown. Here, it is seen again that a general trend is not observed for the *neutral city environment* attribute, with values of the median annoyance rating ranging from 3, to 5 and presenting both low and high variability. On the other hand, for the scenes defined as being part of the *city center* definition, it is observed that the median values are all gathered between 2.5 and 3.5, presenting a much lower variation, with the exception of ”Timisoara Center Daylight” which presented both a raised variation, with a high median value of 5.

However, looking at Figure 4.10, it is observed that although having the same median value, the overall trend of the scenes with the *neutral city environment* attribute is towards higher annoyance ratings, with the IQR of the data rising up to 6. This is further supported by their higher mean value of around 4.3, compared to 3.9 for the *city center* scenes.

Considering the results gathered from the box plots above, it is clear that the discussion should be extended towards understanding the trends specific to the scenes, and considering the combination of all the attributes. For a quick analysis of the attributes, the mean and median annoyance ratings from the scenes defined as specific attributes are tabulated in Table 4.1. It is clear that attributes such as *Rural*, *Natural*, *Neutral City Environment*, or *Cloudy* bring higher annoyance ratings, both in the mean and median values. On the other hand, attributes such as *Urban*, *Artificial*, *City Center*, or *Sunny* show a trend towards a lowered annoyance rating.

Based on this observation, it is clear that scenes that would combine attributes, such as *natural* and *cloudy* would be expected to show a strong trend towards high annoyance. Indeed, it is seen in ”Creepy Scottish House Cloudy” that the median value is the highest, being equal to 5, and the general trend is towards high annoyance.

However, it is seen that another scene, ”Timisoara Center Daylight” seems to be presenting the highest general annoyance out of all scenes, although being defined as only *cloudy* out of the ”high annoyance attributes list”. This scene presents as attributes the following: *urban*, *cloudy*, *artificial*, *city center*; the first three attributes were hypothesized to result in lower annoyance, based on the fact that they are considered to induce a generally neutral state, having no ”warm” attributes defined to them. However, it seems that these ”cold” attributes tend to increase the annoyance of the participants.

Other scenes, such as ”Creepy Scottish House”, ”Hague City Cloudy”, and ”Hague Park Kids Sunny” also present a median annoyance rating of 5, with the variation trending towards a high annoyance. These scenes do not all have a common attribute to them, but it seems that the combination of their attributes led to a higher annoyance rating compared to the others.

Table 4.1: Mean and median annoyance ratings specific to each scene attribute

Attribute	Mean	Median
Urban	4.0585	4
Rural	4.2703	4
Sunny	3.8582	4
Cloudy	4.527	5
Natural	4.5593	5
Artificial	3.9128	4
Neutral City Env	4.2973	4
City Center	3.8763	4

Table 4.1 shows the mean and median annoyance rating computed for each attribute. It is seen that for the first two attribute pairs (Urban-Rural and Natural-Artificial) the hypothesis stands correct, where the more ”positive” attribute led to a higher annoyance overall, with a difference of around 0.22 for the first pair and 0.64 for the second one. However, the other two pairs, seem to counteract this idea, as the city center attribute, led to a lowered annoyance and the sunny environments had the same effect.

This difference shows that some attributes that may be considered ”positive” do not necessarily lead to an increased annoyance when it comes to an aircraft flyover, and hints to the fact that a more in-depth analysis has to be performed to correctly asses the definitions of a negative or positive attribute.

Lastly, based on Table 4.1 it has to be noted that all the annoyance ratings fall in a close range to each other, with the highest difference between the means being 0.7. Moreover, only three of the 8 attributes have a median annoyance rating of 5, while all the others have a median annoyance rating of 4. This may lead to inaccuracies when it comes to further analyses.

These observations seem to indicate that, although relevant, the visual aspects of the scene are not the only indicator affecting the perceived overall annoyance in a scene and a deeper analysis has to be performed regarding the background and aircraft sounds in the scenes.

4.2. Analysis of background and aircraft sound

The other main aspect of the scenes used in this research experiment is represented by the background and aircraft sounds. An analysis of some sound quality metrics will be made for both the background and the aircraft and the numerical values will be further used to gather more relevant data regarding the annoyance created by the flyovers.

4.2.1. Sound Quality Metrics

Sound Quality Metrics (SQMs) are to be used in this application as these values better relate to the hearing sensation of human participants and spread over a larger scale. The SQMs considered in this scenario are the five most usual ones:

- Loudness (N): Subjective perception of sound magnitude, corresponding to the overall sound intensity [42].
- Tonality (K): Perceived intensity of the total unmasked energy of a sound [43, 44, 45].
- Sharpness (S): Perception of high-frequency content of a sound [46].
- Roughness (R): Unpleasant perception of complex sounds caused by differences higher than 15 Hz between two tones [47]
- Fluctuation Strength (FS): Perception of the difference in speed (less than 20 Hz) in complex sounds [48].

The above-defined SQMs are all computed using the open-source tool SQAT [49]. Furthermore, these SQMs are also combined based on models from Zwicker, More and Di, et al. to calculate global psychoacoustic annoyance (PA) metrics. All SQMs, alongside the psychoacoustic annoyance metrics, were calculated using the open-source MATLAB toolbox SQAT.

The psychoacoustic metrics were used to check the correlation to the participants' annoyance ratings for each scene to see whether the background, aircraft, or a combination of both had any effects on the perceived annoyance. The next subsection focuses on presenting and explaining the observations made regarding the correlations.

The background sounds Appendix A used in the application were all downloaded as license-free *.wav* files from the Pixabay website [1] and all were chosen to be stereo sounds. This sound reproduction method gives the impression of a fully immersed, three-dimensional audio perception. Stereophonic (stereo) sounds were used in the application's scenes as they were linked to static objects close to the user, or even placed in the same position as the user. As such, even if the sound was not moved far enough from the listener's position, they were still providing a full three dimensional impression, imitating reality.

It has to be noted that the aircraft sound that was recorded by the ANCE team is played as a monaural sound. This was done as the sound emitter, in this case the aircraft, was moving through the scene and was placed at a far distance from the observer.

Moreover, the SQAT analysis was performed on the background and aircraft sounds, as well as on the combination of both based on each scene. As stated before, the aircraft sound in each scene is played at the same volume and intensity each time, with an equivalent sound level $L_{\text{A,eq}} = 51.93dBA$ the only differences coming from the visual cues and the background sounds of each scene. As such, it was considered optimal to analyze both the combination of sounds, as well as the background and aircraft sounds by themselves.

4.2.2. Results of psychoacoustic metrics

The analysis consists of calculating the correlation between the average annoyance rating for a scene and the psychoacoustic metrics related to the scene's aircraft and background sounds.

Three analyses were computed for all the scenes. Firstly, the aircraft sound by itself, then the background sounds by themselves, and lastly a combination of both. For some of the metrics this was a

[1] https://pixabay.com/sound-effects/

matter of simple subtraction, but for the metrics that are measured in decibels (dB) the following formula was applied:

$$L = 10 \cdot log_{10}(10^{comb} - 10^{bgn}), \quad (4.1)$$

where *comb* is the decibel metric value of the combination of sounds and *bgn* is the decibel metric value of the background sounds.

The correlation coefficient matrix was computed using both a linear (Pearson) and two non-linear (Kendall and Spearman) correlations.

Unfortunately, the numerical values for this analysis show that there is no correlation between the sounds and the annoyance ratings in all the analyses. This was based on the correlation coefficients (ρ) that were in the range 0 - 0.35 and the high p-values over 0.05 of the metrics.

The poor correlation between the SQMs and the annoyance ratings of the scenes raised another analysis directly on the SQM values. The absence of any correlation between these data led to the idea that there is not actually much variability between the SQMs for each scene. As such, it was decided to calculate the variability and standard deviation for these values. Small variability and STD values were found for the SQMs, showing that the values were not changing drastically between the scenes. This can be explained through the fact that acoustically, the background noise, which is the only audio influence that changes throughout the scenes, has a much lower psychoacoustic footprint compared to the aircraft.

As such, it can be deduced that the aircraft noise was the main audio element in the psychoacoustic element. As this sound was not changing from scene to scene, almost all the variability in the SQMs was reduced drastically, with only very small variations arising from the background noise.

Table 4.2: Mean, standard deviation and variance of the annoyance ratings specific to each scene

Scene	Mean	Std	Variance
Bowpub Sunny	3.69	1.79	3.23
Bucuresti Unirii Sunny	2.92	1.50	2.26
Colosseum Cloudy	3.75	1.96	3.84
Creepy Scottish House Cloudy	4.64	1.63	2.65
Delft Center Jumbo Sunny	2.43	1.45	2.11
Delft Markt sunny	3.82	1.99	3.96
Dutch Empty Street	4.58	2.15	4.63
Echo Building	3.92	2.35	5.54
Hague City Center Sunny	4.08	1.83	3.35
Hague City Center Sunny 2	3.67	1.87	3.51
Hague City Cloudy	5.00	1.41	2.00
Hague Park Kids Sunny	5.08	1.47	2.16
Scheveningen Day Grass Sun	4.08	2.15	4.63
Scheveningen Day Beach Cloudy	4.14	1.70	2.90
Timisoara Center Daylight	5.07	1.55	2.41
Timisoara Parcul Civic Daylight	3.82	1.72	2.96

Table 4.2 presents the mean, standard deviation, and variance of the annoyance ratings for all scenes. The annoyance levels were generally rated low, with mean values ranging from 2.43 (Delft Center Jumbo Sunny) to 5.08 (Hague Park Kids Sunny). This indicates that no scene was perceived as highly annoying, with mean values over 7, overall.

However, for several scenes, the data shows spread opinions among participants. This is reflected in standard deviation values close to 2 and variance values reaching up to 5.54 (Echo Building). The relatively high variance across many scenes suggests a notable diversity in the participants' perceptions, with significant differences in how individuals rated the annoyance of specific scenes.

To test whether the issue appeared due to the sounds present in the scene, the signal to noise ratio was computed and plotted for all the scenes.

4.2.3. Signal-to-Noise Ratio

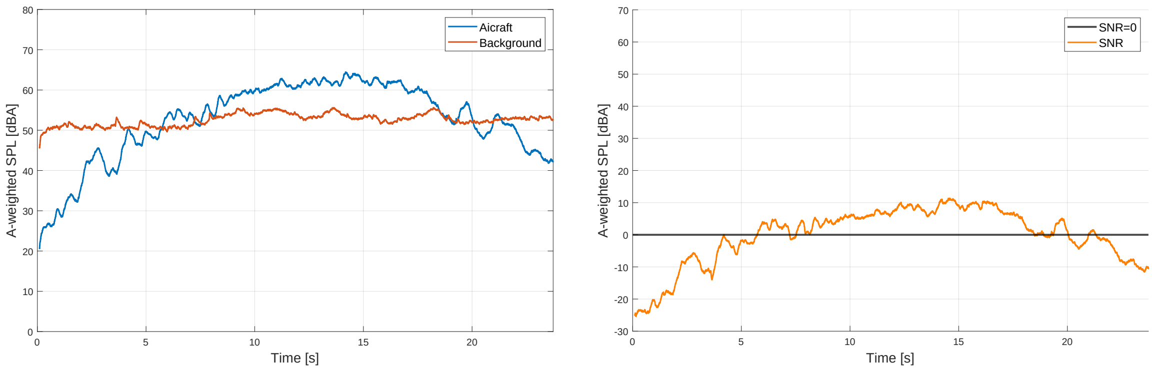
The signal-to-noise ratio (SNR) is an important metric in quantifying the relative level of a desired signal. In the scenario of this research, it is relevant to quantify how much the aircraft sound distinguishes itself from the background noise [50]. This gives a view towards understanding the correlation between the presence of the aircraft and the sound produced by it, and the perceived annoyance of the population.

The signal to noise ratio was calculated using a function built in the SQAT toolbox, called *Do_SLM*. This function computes the sound pressure levels in decibels. More options are present in this function, but for this analysis, the A-weighted sound pressure level with a fast weighting was used to calculate the SNR. Figure 4.11a was plotted using the aircraft and background sounds in the ”Bucuresti Unirii Sunny” scene. The rest of the SNR plots can be found in Appendix A.

Real-life background noise varies in level and the flight path of the aircraft gives an initial increase in the signal level, followed by a peak, and then a decrease. The SNR accounts for these variations and thus enables a more accurate analysis of the perceived aircraft noise in each scene.

A single numerical value for the SNR was calculated for each scene and they are tabulated in Table 4.3. As the A-weighted sound pressure level was already calculated in dBA, this was a matter of just subtracting the background noise from the aircraft sound and considering the maximum value as seen in Figure 4.11a. By doing this and calculating the correlation with the average annoyance ratings for the scenes, a correlation of 0.6 with a p-value of 0.013 was found. This hints to the fact that there is a higher correlation to the SNR of the scenes compared to the other psychoacoustic metrics and that aircraft noise seems to be perceived more annoying when it is more prominent with respect to the BGN (i.e higher SNR). Figure 4.11b shows the SNR values of this specific scene.

It has to be noted that two scenes in Table 4.3 (”Echo Building” and ”Hague City Cloudy”) present higher SNR values compared to the other scenes. At a first glance, this hints towards a very noisy aircraft flyover, but, as explained before, the aircraft sound is always the same in each scene. The high values are explained by the fact that the background noise was considered to be low, as these two scenes did not present elements that would generate a high background noise and were considered to be ”calm” scenes.



(a) **(b)**

Figure 4.11: A-weighted amplitude vs. time for the aircraft and background noise in the Bucuresti Unirii Fountains Sunny scene (figure (a)) and the signal-to-noise ratio of this scene (figure (b)).

In Figure 4.11a, it is seen that, as expected, the aircraft sound has a comparably higher amplitude compared to the background noise. In the initial part of the plot, the build-up of the aircraft sound is observed. This is due to the fact that in all the scenes, the aircraft flies from a distance, and as such, up to a point, the sound emitted by it is lower than the background. However, it is seen that for most of the scene, the aircraft sound represents the main sound emitter of the scene.

Figure 4.11b depicts, as stated before, the SNR of the ”Bucuresti Unirii Fountains Sunny” scene. In this plot, it can be observed that initially, the background noise is the main audio element of the scene, and as such the SNR presents negative values. As the aircraft approaches the participant's position, the SNR increases, reaching a positive value after approximately 6 seconds. This is expected, as the aircraft is slowly approaching. The SNR presents positive values for the majority of the duration, from 6 up to around 20 seconds, of the 24 seconds of the scene. As such, it is clear that the aircraft noise is the principal audio element in this scene, with an increase of up to almost 10 dBA in the SNR value from the scene with only the background noise present.

Table 4.3: Signal-to-noise ratio of each scene. The SNR value is considered to be the maximum difference between the aircraft and background noises.

Scene	SNR, [dBA]
Bowpub Sunny	13.79
Bucuresti Unirii Sunny	11.38
Colosseum Cloudy	22.12
Creepy Scottish House Cloudy	22.13
Delft Center Jumbo Sunny	14.76
Delft Markt sunny	9.980
Dutch Empty Street	16.17
Echo Building	45.69
Hague City Center Sunny	24.06
Hague City Center Sunny 2	22.12
Hague City Cloudy	51.53
Hague Park Kids Sunny	33.03
Scheveningen Day Grass Sun	29.07
Scheveningen Day Beach Cloudy	28.86
Timisoara Center Daylight	21.20
Timisoara Parcul Civic Daylight	15.21

Table 4.4 presents the mean SNR values for each scene attribute in order. Here, it is seen that some attributes, such as *rural*, *cloudy*, *natural* and *neutral city env* present high values, all close to 27. This, alongside the results seen in section 4.1 further enhances the results found, where the scenes from the later three attributes were perceived as more annoying. However, for the first attribute pair (urban-rural), it is seen that the rural scenes, although having a higher mean SNR value, were not perceived much more annoying compared to the urban scenes. This indicates that in this case, the visual elements of the rural environments led to a decrease in the perceived noise annoyance. As such, it may be the case that defining elements of rural environments, natural elements, in places outside of cities, can decrease the perceived noise annoyance in the case of aircraft flyovers.

Table 4.4: Mean SNR values for each scene attribute

Scene Attribute	Mean SNR, [dBA]
Urban	23.86
Rural	26.93
Sunny	22.96
Cloudy	27.04
Natural	26.87
Artificial	23.44
Neutral City Environment	27.20
City Center	21.33

Figure 4.12 shows the correlation between the mean annoyance ratings recorded in the experiments and the signal-to-noise ratio computed for each scene. Indeed a relatively strong correlation ($\rho = 0.6$, p-value = 0.013) is observed between these two variables. The variability proved by the error bars suggests that the correlation between the SNR and the mean annoyance ratings is not solely

influenced by the SNR. As such, it can be seen that the influence towards the mean annoyance rating is a complement of both acoustic and visual factors.

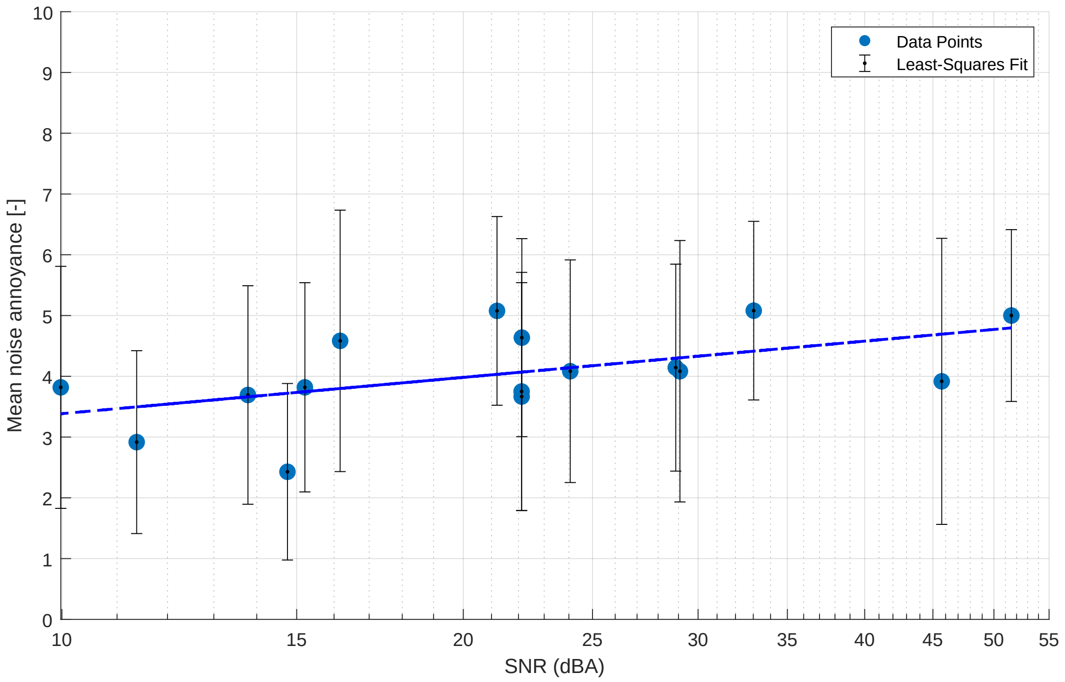


Figure 4.12: Mean noise annoyance ratings per scene with respect to the maximum signal-to-noise ratio. The error bars denote the standard deviations in the annoyance rating. The dashed blue line indicates the least-squares fit. It has to be noted that the x-axis presents a logarithmic scale

5
Conclusion & Recommendations

This research focused on developing an application to exemplify the use of virtual reality headsets in the field of psychoacoustics. Moreover, the results gathered from experiments give invaluable data towards understanding the influence that visual elements have on the psychoacoustic annoyance perceived by the population.

The development of the application was done using the Unity Game Engine, which proved its usefulness and ease in creating immersive scenarios that combine realistic 360° visuals with binaural audio. The application was used to gather relevant data through experiments on the perceived aircraft noise annoyance in several scenarios, defined based on 4 pairs of attributes: urban-rural, sunny-cloudy, natural-artificial, neutral city environment - city center.

The findings from the data analysis showed that there is an influence coming from the visual cues of the scenes, with attributes such as rural, natural, neutral city environment or cloudy showing a greater perceived annoyance from the participants in the experiment. Attention was further paid towards the sound quality and psychoacoustic metrics from the aircraft and background sounds, that were computed using an open-source MATLAB toolbox called SQAT. No concrete correlation was found between these metrics and the annoyance ratings. Related to the psychoacoustic field, the main finding of this research was the analysis of the signal-to-noise ratio, and the ratings, where a correlation coefficient of 0.6 was computed, which shows that this metric indeed influences the perception of the participants in the case of audio-visual experiments using virtual reality.

Based on these findings, it can be concluded that in the case of combining psychoacoustic and visual elements when testing the perceived annoyance created by the noise of an aircraft fly-over, both elements provide an influence. This signals the fact that the psychoacoustic analysis is indeed not enough to understand the full range of influence on the population when it comes to the annoyance created by aerospace application. Moreover, this research concludes the importance of creating and implementing novel technologies such as virtual reality in the analysis of psychoacoustic annoyance. This opens great new avenues for researchers to come closer to understanding the complex attributes that influence the annoyance perception created by the combination of acoustics and visuals.

The research presented several main limitations. First, the relatively small participant pool, which was further decreased by the filtering done as explained above, may have created a challenge for them to completely focus on the experiment. Secondly, the use of static 360° background images has also limited the realism and data accuracy in the scenes. Furthermore, the shared experiment environment, where the participants were first asked to rate the annoyance of 40 different aircraft fly-over recordings in a 20-minute long audio experiment, may have also influenced the final results of this research.

For further research it is recommended to implement more aerospace applications, such as drones, wind turbines, electric aircraft, or hybrid aircraft designs, as well as more locations and as such, scenes. Specific sound recording (aircraft and background), or even auralization tools that simulate the produced sound can also be implemented. Lastly, three-dimensional environment renders (such as cities including buildings and decorations) can be created to test aspects such as echoes, subject dynamism, or even different weather conditions, which can greatly help in the future. However, if the creation of three-dimensional environments is outside the scope, 360° videos of specific scenes may be used to increase the realism of the scenes.

References

[1] M. Basner et al. “Aviation Noise Impacts: State of the Science”. In: *Noise & Health* 19.87 (Mar. 2017), pp. 41–50. DOI: 10.4103/nah.NAH_104_16.

[2] M. Basner and S. McGuire. “WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Effects on Sleep”. en. In: *International Journal of Environmental Research and Public Health* 15.3 (Mar. 2018), p. 519. ISSN: 1660-4601. DOI: 10.3390/ijerph15030519. URL: http://www.mdpi.com/1660-4601/15/3/519.

[3] A. Kourieh et al. “Incident hypertension in relation to aircraft noise exposure: results of the DEBATS longitudinal study in France”. In: *Occupational and Environmental Medicine* 79.4 (2022), pp. 268–276. DOI: 10.1136/oemed-2021-107921. URL: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85126490255&doi=10.1136%2foemed-2021-107921&partnerID=40&md5=56d2732bbc36108e64ccbf504ec4e329.

[4] N. Itzkowitz et al. “Aircraft noise and cardiovascular morbidity and mortality near Heathrow Airport: A case-crossover study”. In: *Environment International* 177 (2023). DOI: 10.1016/j.envint.2023.108016. URL: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85162179412&doi=10.1016%2fj.envint.2023.108016&partnerID=40&md5=968dfdc4e5552f14c4af5270cdba7da0.

[5] A. A. Faiyetole and J. T. Sivowaku. “The effects of aircraft noise on psychosocial health”. In: *Journal of Transport & Health* 22 (2021), p. 101230. ISSN: 2214-1405. DOI: https://doi.org/10.1016/j.jth.2021.101230. URL: https://www.sciencedirect.com/science/article/pii/S2214140521002607.

[6] S. A. Stansfeld and M. P. Matheson. “Noise pollution: Non-auditory effects on health”. In: *British Medical Bulletin* 68 (2003). Cited by: 812; All Open Access, Bronze Open Access, pp. 243–257. DOI: 10.1093/bmb/ldg033. URL: https://www.scopus.com/inward/record.uri?eid=2-s2.0-1342325547&doi=10.1093%2fbmb%2fldg033&partnerID=40&md5=fa1f3080646a6cfe2fb8ea459b1f456d.

[7] B. Barbot, C. Lavandier, and P. Cheminée. “Perceptual representation of aircraft sounds”. In: *Applied Acoustics* 69.11 (2008), pp. 1003–1016. ISSN: 0003-682X. DOI: https://doi.org/10.1016/j.apacoust.2007.07.001. URL: https://www.sciencedirect.com/science/article/pii/S0003682X0700117X.

[8] L. J.J. Erkelens. *Development of Noise Abatement Procedures in the Netherlands*. Report. National Aerospace laboratory NLR, Nov. 1999.

[9] H. M. Miedema and C. G. Oudshoorn. “Annoyance from transportation noise: relationships with exposure metrics DNL and DENL and their confidence intervals.” en. In: *Environmental Health Perspectives* 109.4 (Apr. 2001), pp. 409–416. ISSN: 0091-6765, 1552-9924. DOI: 10.1289/ehp.01109409. URL: https://ehp.niehs.nih.gov/doi/10.1289/ehp.01109409.

[10] M. Lotinga et al. “Noise from Unconventional Aircraft: A Review of Current Measurement Techniques, Psychoacoustics, Metrics and Regulation”. In: *Current Pollution Reports* 9 (Dec. 2023), pp. 1–22. DOI: 10.1007/s40726-023-00285-4.

[11] L. Palumbo et al. “Annoyance to Noise Produced by a Distributed Electric Propulsion High-Lift System”. In: June 2017. DOI: 10.2514/6.2017-4050.

[12] R. Aalmoes and N. Sieben. “Visual and audio perception study on drone aircraft and similar sounds in an Urban Air Mobility setting”. In: 2021. DOI: 10.3397/IN-2021-2160. URL: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85117421126&doi=10.3397%2fIN-2021-2160&partnerID=40&md5=acc9d39b1cb93d6c12d03d064c3cc9c7.

[13] D. Thipphavong et al. “Urban Air Mobility Airspace Integration Concepts and Considerations”. In: June 2018. DOI: 10.2514/6.2018-3676.

[14] J. Woodcock et al. “Influence of operational and contextual factors on the human response to drone sound”. In: (Nov. 2024). DOI: 10.17866/rd.salford.27868722.v1. URL: https://salford.figshare.com/articles/conference_contribution/Influence_of_operational_and_contextual_factors_on_the_human_response_to_drone_sound/27868722.

[15] A. Thai et al. “Flyover Noise Computations of the Joby Aviation Aircraft”. In: 2023. URL: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85167734000&partnerID=40&md5=ef2727fffed1066af6833fd775fbd7a8.

[16] J. Benad. “The Flying V A new Aircraft Configuration for Commercial Passenger Transport”. en. In: (2015), 8 pages. DOI: 10.25967/370094. URL: https://publikationen.dglr.de/?tx_dglrpublications_pi1%5bdocument_id%5d=370094.

[17] L.A. Krakers et al. “A design & engineering engine to investigate acoustics in preliminary fuselage design”. In: 2003. DOI: 10.2514/6.2003-3162. URL: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85086490111&doi=10.2514%2f6.2003-3162&partnerID=40&md5=60fba2c77c837ad1ad17de0dbce0d2f5.

[18] S. Rizzi. “Toward reduced aircraft community noise impact via a perception-influenced design approach”. In: Aug. 2016.

[19] H. M. E. Miedema and H. Vos. “Demographic and attitudinal factors that modify annoyance from transportation noise”. In: *The Journal of the Acoustical Society of America* 105.6 (June 1999), pp. 3336–3344. ISSN: 0001-4966. DOI: 10.1121/1.424662. URL: https://doi.org/10.1121/1.424662.

[20] R. Aalmoes, B. De Bruijn, and N. Sieben. “The Influence of Contextual Non-Auditory Factors on Drone Sound Perception”. In: 2023. DOI: 10.4271/2023-01-1105. URL: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85160801922&doi=10.4271%2f2023-01-1105&partnerID=40&md5=ec904c0a6922c7e0be7a20ba3aedad39.

[21] C. Kawai et al. “Short-term noise annoyance towards drones and other transportation noise sources: A laboratory study”. In: *The Journal of the Acoustical Society of America* 156.4 (Oct. 2024), pp. 2578–2595. ISSN: 0001-4966. DOI: 10.1121/10.0032386. URL: https://doi.org/10.1121/10.0032386.

[22] A. J. Torija, Z. Li, and R. H. Self. “Effects of a hovering unmanned aerial vehicle on urban soundscapes perception”. In: *Transportation Research Part D: Transport and Environment* 78 (2020), p. 102195. ISSN: 1361-9209. DOI: https://doi.org/10.1016/j.trd.2019.11.024. URL: https://www.sciencedirect.com/science/article/pii/S1361920919309861.

[23] E. Pedersen and P. Larsman. “The impact of visual factors on noise annoyance among people living in the vicinity of wind turbines”. en. In: *Journal of Environmental Psychology* 28.4 (Dec. 2008), pp. 379–389. ISSN: 02724944. DOI: 10.1016/j.jenvp.2008.02.009. URL: https://linkinghub.elsevier.com/retrieve/pii/S0272494408000224.

[24] M. Szychowska et al. “The influence of audio-visual interactions on the annoyance ratings for wind turbines”. In: *Applied Acoustics* 129 (2018), pp. 190–203. ISSN: 0003-682X. DOI: https://doi.org/10.1016/j.apacoust.2017.08.003. URL: https://www.sciencedirect.com/science/article/pii/S0003682X17300336.

[25] A. Cranmer et al. “Worth a thousand words: Presenting wind turbines in virtual reality reveals new opportunities for social acceptance and visualization research”. In: *Energy Research & Social Science* 67 (2020), p. 101507. ISSN: 2214-6296. DOI: https://doi.org/10.1016/j.erss.2020.101507. URL: https://www.sciencedirect.com/science/article/pii/S2214629620300840.

[26] S. Viollon, C. Lavandier, and C. Drake. “Influence of visual setting on sound ratings in an urban environment”. en. In: *Applied Acoustics* 63.5 (May 2002), pp. 493–511. ISSN: 0003682X. DOI: 10.1016/S0003-682X(01)00053-6. URL: https://linkinghub.elsevier.com/retrieve/pii/S0003682X01000536.

[27] T. J. Cox. “The effect of visual stimuli on the horribleness of awful sounds”. en. In: *Applied Acoustics* 69.8 (Aug. 2008), pp. 691–703. ISSN: 0003682X. DOI: 10.1016/j.apacoust.2007.02.010. URL: https://linkinghub.elsevier.com/retrieve/pii/S0003682X07000436.

[28] A. Preis et al. “Audio-visual interactions in environment assessment”. In: *Science of The Total Environment* 523 (2015), pp. 191–200. ISSN: 0048-9697. DOI: https://doi.org/10.1016/j.scitotenv.2015.03.128. URL: https://www.sciencedirect.com/science/article/pii/S004896971500412X.

[29] A. Gidlöf-Gunnarsson and E. Öhrström. “Noise and well-being in urban residential environments: The potential role of perceived availability to nearby green areas”. en. In: *Landscape and Urban Planning* 83.2–3 (Nov. 2007), pp. 115–126. ISSN: 01692046. DOI: 10.1016/j.landurbplan.2007.03.003. URL: https://linkinghub.elsevier.com/retrieve/pii/S0169204607000722.

[30] R. Hoeger. “Aircraft noise and times of day: Possibilities of redistributing and influencing noise exposure”. In: *Noise and Health* 6.22 (2004). Cited by: 6, pp. 55–58. URL: https://www.scopus.com/inward/record.uri?eid=2-s2.0-1942531574&partnerID=40&md5=997c5ad9f49d2424cd12fc592e087ebf.

[31] J. Carles, F. Bernáldez, and J. Lucio. “Audio□visual interactions and soundscape preferences”. en. In: *Landscape Research* 17.2 (June 1992), pp. 52–56. ISSN: 0142-6397, 1469-9710. DOI: 10.1080/01426399208706361. URL: http://www.tandfonline.com/doi/abs/10.1080/01426399208706361.

[32] R. Aalmoes, B. Bruijn, and N. Sieben. “The Influence of Contextual Non-Auditory Factors on Drone Sound Perception”. In: May 2023. DOI: 10.4271/2023-01-1105.

[33] R. Merino-Martinez et al. “Psychoacoustic Analysis of the Noise Emissions from the Airbus A320 Aircraft Family and its Nose Landing Gear System”. In: *30th AIAA/CEAS Aeroacoustics Conference (2024)*. American Institute of Aeronautics and Astronautics, May 2024. DOI: 10.2514/6.2024-3398. URL: http://dx.doi.org/10.2514/6.2024-3398.

[34] B. von den Hoff R. Merino-Martínez and D. G. Simons. “DESIGN AND ACOUSTIC CHARACTERIZATION OF A PSYCHOACOUSTIC LISTENING FACILITY”. In: *The annual congress of the International Institute of Acoustics and Vibration*. July 2023.

[35] A. Heimes and M. Vorlaender. *A framework to conduct psychoacoustic experiments in virtual reality*. Aug. 2021. DOI: 10.13140/RG.2.2.18574.02883.

[36] A. Heimes; I. Muhammad; M. Vorländer. “A real-time virtual reality building acoustic auralization framework for psychoacoustic experiments with contextual and interactive features”. In: *PROCEEDINGS of the 23rd International Congress on Acoustics*. Institute of Technical Acoustics, RWTH Aachen University, Germany. Sept. 2019.

[37] R. Merino-Martinez, B. von den Hoff, and D. Simons. “Design and Acoustic Characterization of a Psychoacoustic Listening Facility”. In: July 2023.

[38] Bryce T. Lawrence et al. “Linking ecoacoustic indices to psychoacoustic perception of the urban acoustic environment”. In: *Ecological Indicators* 155 (2023), p. 111023. ISSN: 1470-160X. DOI: https://doi.org/10.1016/j.ecolind.2023.111023. URL: https://www.sciencedirect.com/science/article/pii/S1470160X23011652.

[39] M. Nwankwo et al. “Effects of Forest on Birdsong and Human Acoustic Perception in Urban Parks: A Case Study in Nigeria”. In: *Forests* 13.7 (2022). ISSN: 1999-4907. DOI: 10.3390/f13070994. URL: https://www.mdpi.com/1999-4907/13/7/994.

[40] S. Cao et al. “Cloudy or sunny? Effects of different environmental types of urban green spaces on public physiological and psychological health under two weather conditions”. In: *Frontiers in Public Health* 11 (Aug. 2023). DOI: 10.3389/fpubh.2023.1258848.

[41] Boyan Z. “Effect of soundscape on emotional response in an urban acoustical environment”. June 2021. URL: https://etheses.whiterose.ac.uk/31125/.

[42] H. Fastl Eberhard Zwicker. *Psychoacoustics - Facts and Models*. Springer, 2007.

[43] W. Aures. “Berechnungsverfahren fur den sensorischen Wohlklang beliebiger Schallsignale”. In: *Acta Acustica united with Acustica* (1958). URL: https://www.ingentaconnect.com/content/dav/aaua/1985/00000059/00000002/art00008.

[44] S. R. More. “Aircraft Noise Characteristics and Metrics”. PhD thesis. Purdue University, Dec. 2010. URL: https://web.mit.edu/aeroastro/partner/reports/proj24/noisethesis.pdf.

[45] G. Q. Di et al. “Improvement of Zwicker’s psychoacoustic annoyance model aiming at tonal noises”. In: *Applied Acoustics* 105 (2016), pp. 164–170. ISSN: 0003-682X. DOI: https://doi.org/10.1016/j.apacoust.2015.12.006. URL: https://www.sciencedirect.com/science/article/pii/S0003682X15003606.

[46] U. Widmann. “Aurally adequate evaluation of sounds”. In: Jan. 1998.

[47] P. Daniel and R. Weber. “Psychoacoustical Roughness: Implementation of an Optimized Model”. In: *Acta Acustica united with Acustica* (1997). URL: https://www.ingentaconnect.com/content/dav/aaua/1997/00000083/00000001/art00020.

[48] H. Fastl. “Fluctuation strength and temporal masking patterns of amplitude-modulated broadband noise”. In: *Hearing Research* 8.1 (1982), pp. 59–69. ISSN: 0378-5955. DOI: https://doi.org/10.1016/0378-5955(82)90034-X. URL: https://www.sciencedirect.com/science/article/pii/037859558290034X.

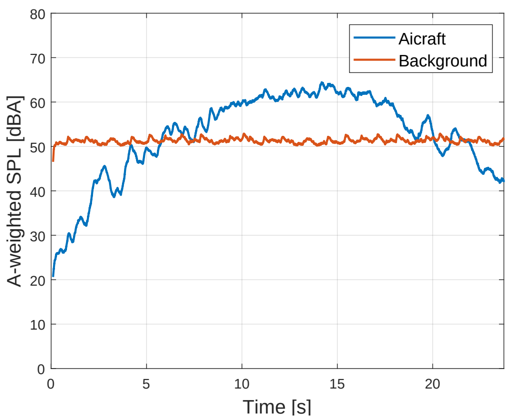
[49] G. Felix Greco et al. “SQAT: a MATLAB-based toolbox for quantitative sound quality analysis”. In: Aug. 2023. DOI: 10.3397/IN_2023_1075.

[50] D. R. Begault. *Psychoacoustic Measures for UAM noise in the Context of Ambient Sound*. Acoustical Society of America San Francisco Bay Area Regional Chapter Meeting. Oct. 2023. URL: https://ntrs.nasa.gov/citations/20230011330.

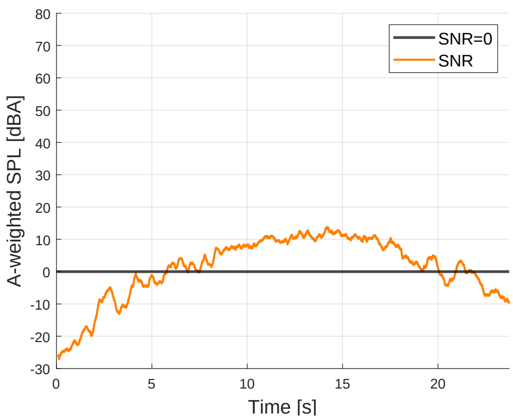
A

Signal-to-noise ratio plots for each scene

The figures shown in this appendix all represent the A-weighted sound pressure level of the aircraft and background sounds, as well as the signal-to-noise ratio for each scene.

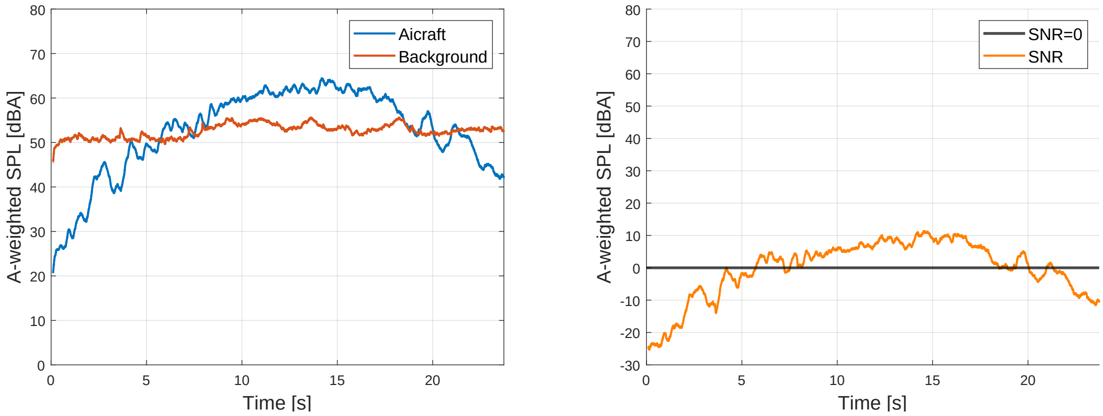


(a)



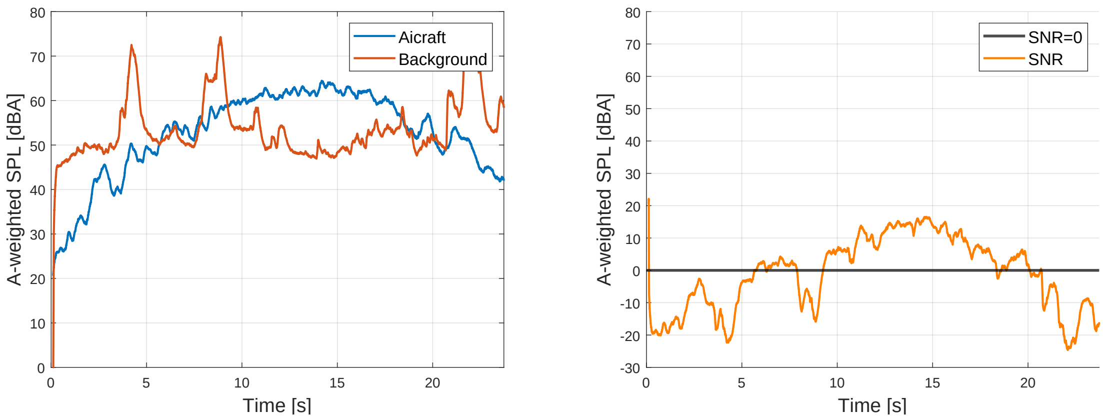
(b)

Figure A.1: A-weighted amplitude vs. time for the aircraft and background noise in the Bowpub Sunny scene (figure (a)) and the signal-to-noise ratio of this scene (figure (b)).



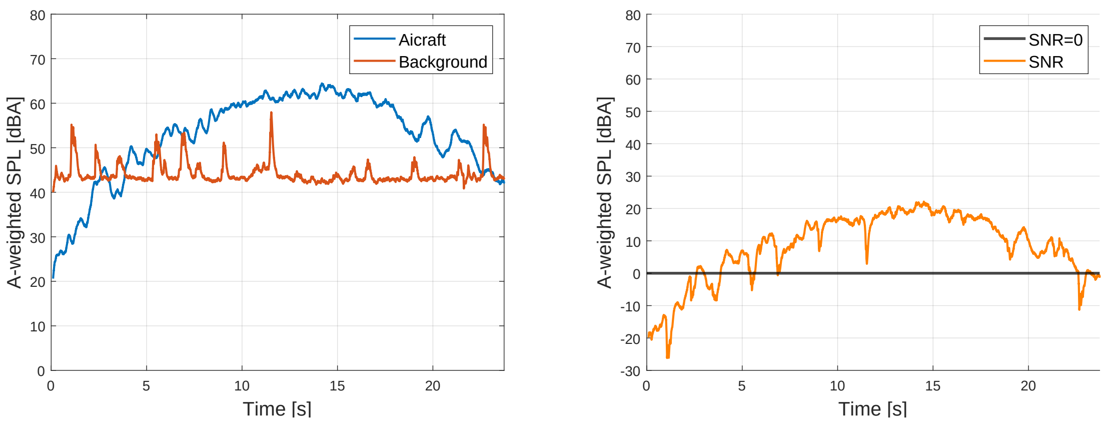
(a) (b)

Figure A.2: A-weighted amplitude vs. time for the aircraft and background noise in the Bucuresti Unirii Sunny scene (figure (a)) and the signal-to-noise ratio of this scene (figure (b)).



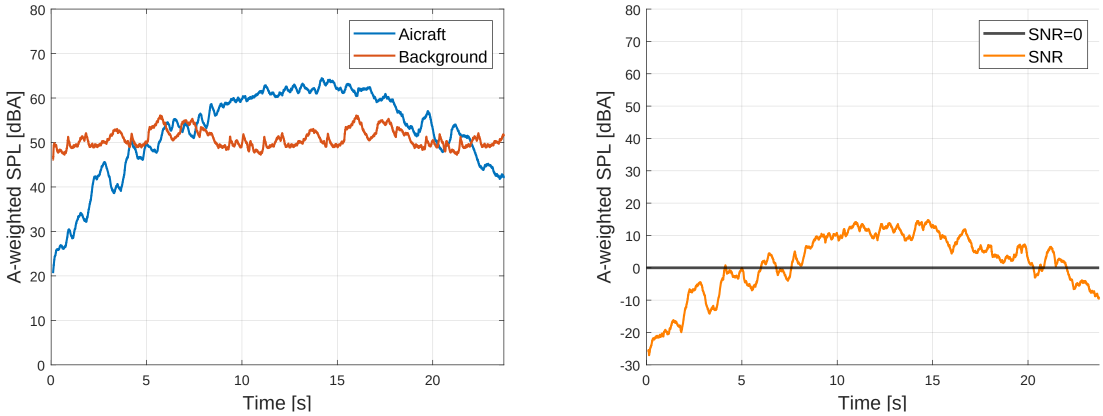
(a) (b)

Figure A.3: A-weighted amplitude vs. time for the aircraft and background noise in the Colosseum Cloudy scene (figure (a)) and the signal-to-noise ratio of this scene (figure (b)).



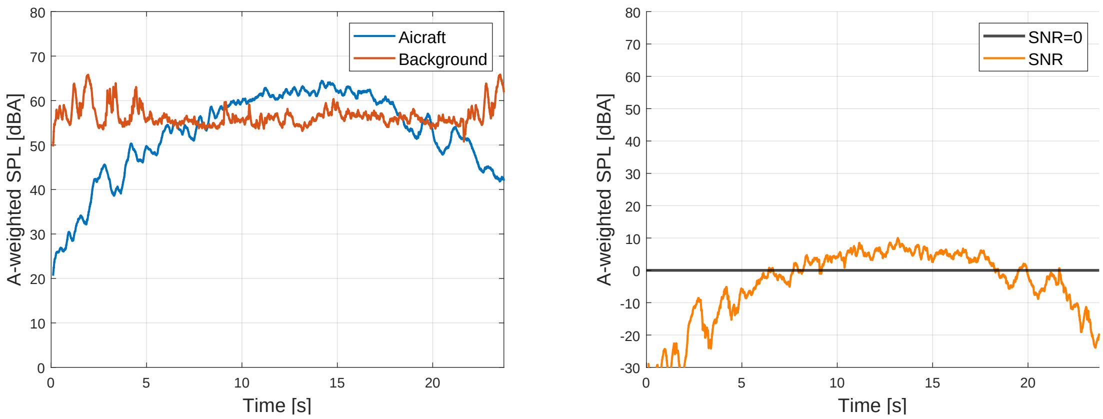
(a) (b)

Figure A.4: A-weighted amplitude vs. time for the aircraft and background noise in the Creepy Scottish House Cloudy scene (figure (a)) and the signal-to-noise ratio of this scene (figure (b)).



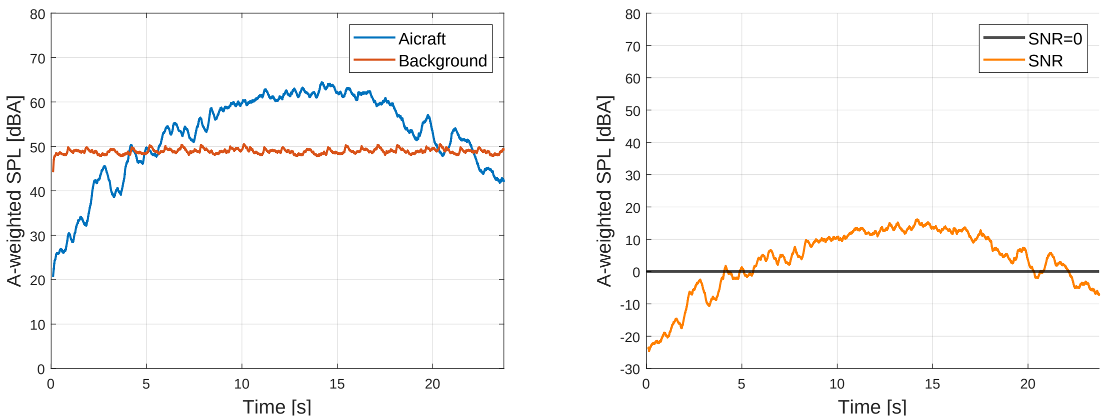
(a) (b)

Figure A.5: A-weighted amplitude vs. time for the aircraft and background noise in the Delft Center Jumbo Sunny scene (figure (a)) and the signal-to-noise ratio of this scene (figure (b)).



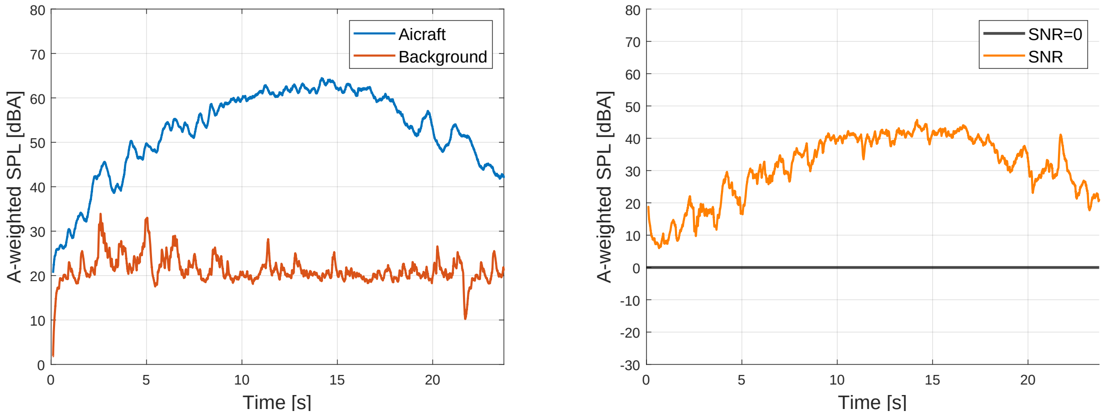
(a) (b)

Figure A.6: A-weighted amplitude vs. time for the aircraft and background noise in the Delft Markt Sunny scene (figure (a)) and the signal-to-noise ratio of this scene (figure (b)).



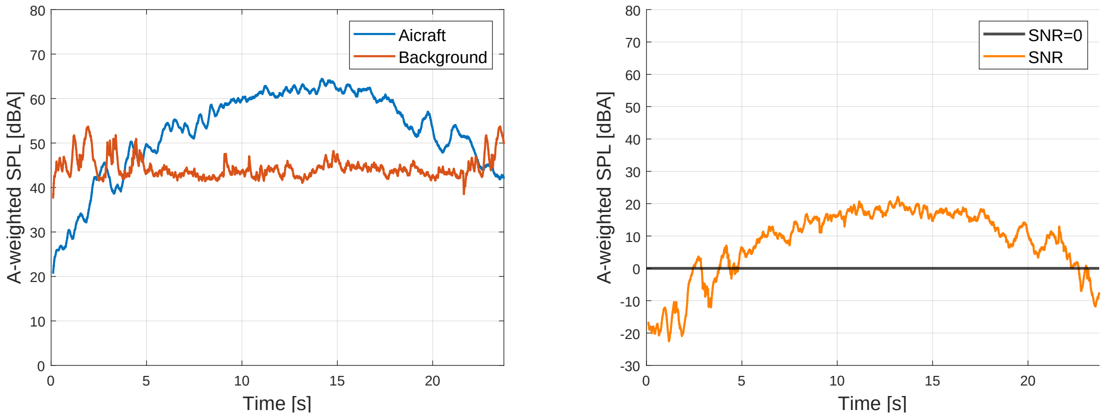
(a) (b)

Figure A.7: A-weighted amplitude vs. time for the aircraft and background noise in the Dutch Empty Street scene (figure (a)) and the signal-to-noise ratio of this scene (figure (b)).



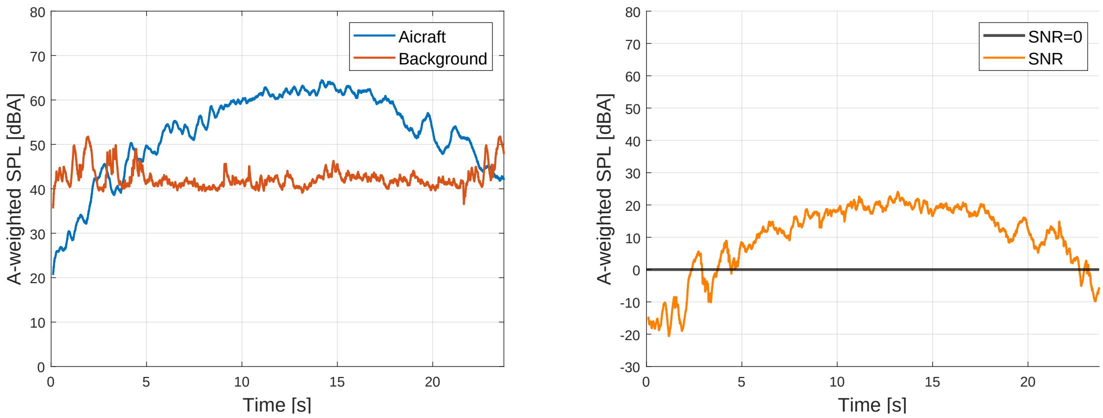
(a) (b)

Figure A.8: A-weighted amplitude vs. time for the aircraft and background noise in the Echo Building scene (figure (a)) and the signal-to-noise ratio of this scene (figure (b)).



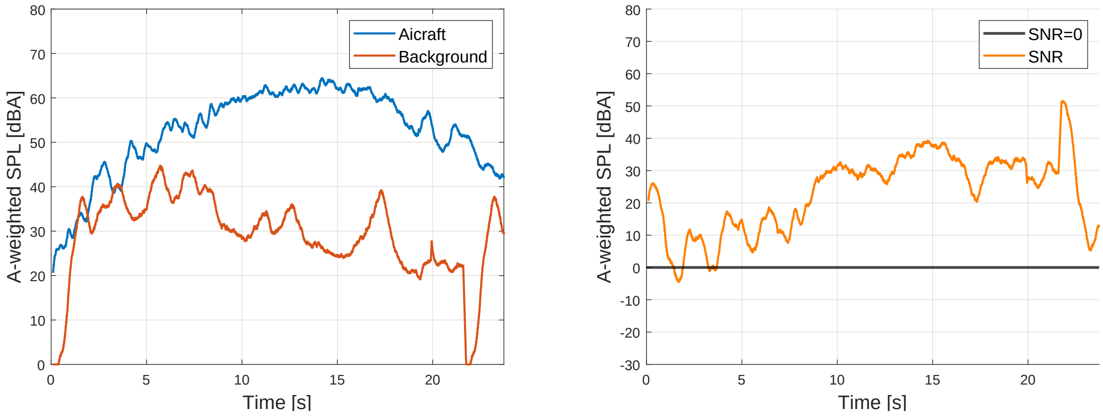
(a) (b)

Figure A.9: A-weighted amplitude vs. time for the aircraft and background noise in the Hague City Center Sunny scene (figure (a)) and the signal-to-noise ratio of this scene (figure (b)).



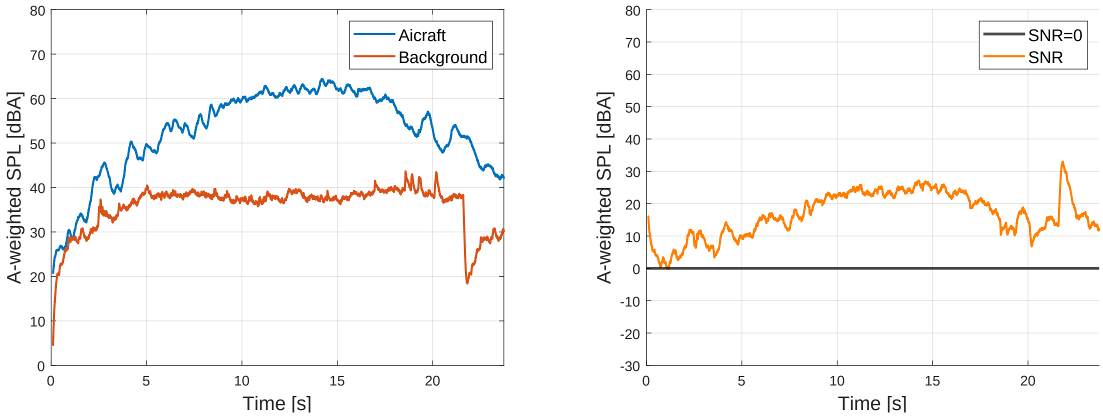
(a) (b)

Figure A.10: A-weighted amplitude vs. time for the aircraft and background noise in the Hague City Center Sunny 2 scene (figure (a)) and the signal-to-noise ratio of this scene (figure (b)).



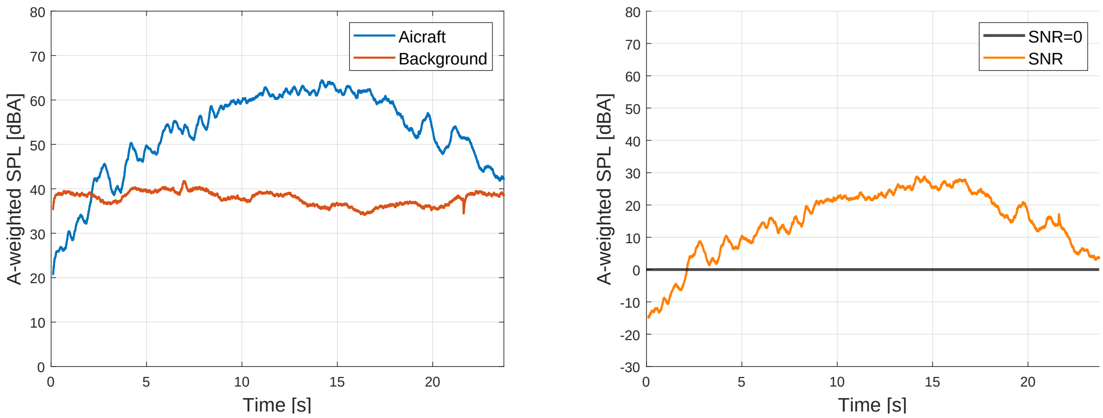
(a) (b)

Figure A.11: A-weighted amplitude vs. time for the aircraft and background noise in the Hague City Cloudy scene (figure (a)) and the signal-to-noise ratio of this scene (figure (b)).



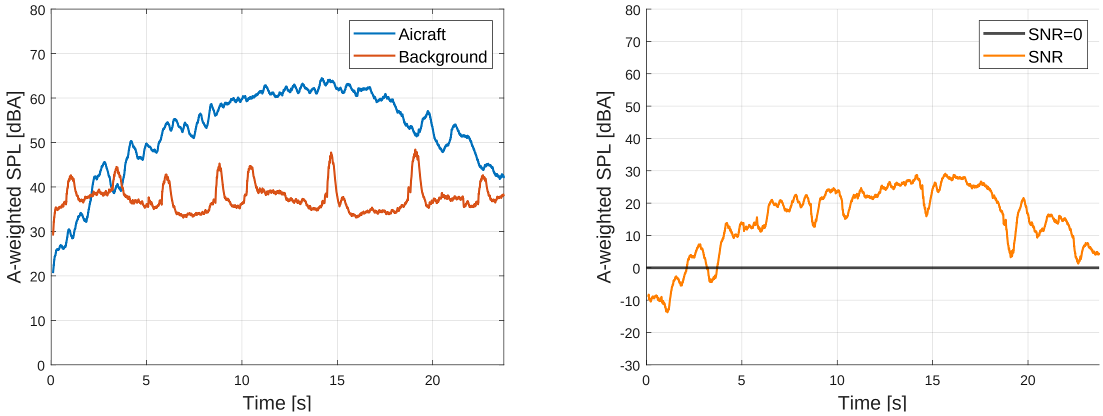
(a) (b)

Figure A.12: A-weighted amplitude vs. time for the aircraft and background noise in the Hague Park Kids Sunny scene (figure (a)) and the signal-to-noise ratio of this scene (figure (b)).



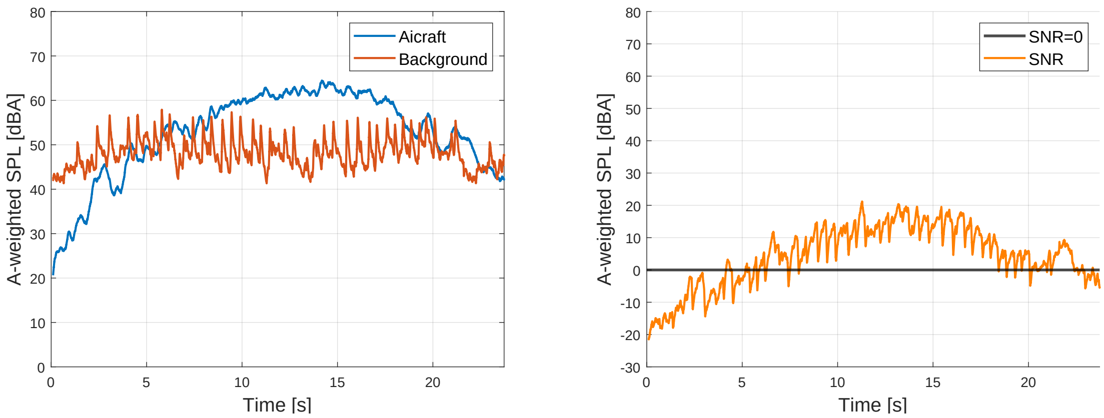
(a) (b)

Figure A.13: A-weighted amplitude vs. time for the aircraft and background noise in the Scheveningen Day Grass Sun scene (figure (a)) and the signal-to-noise ratio of this scene (figure (b)).



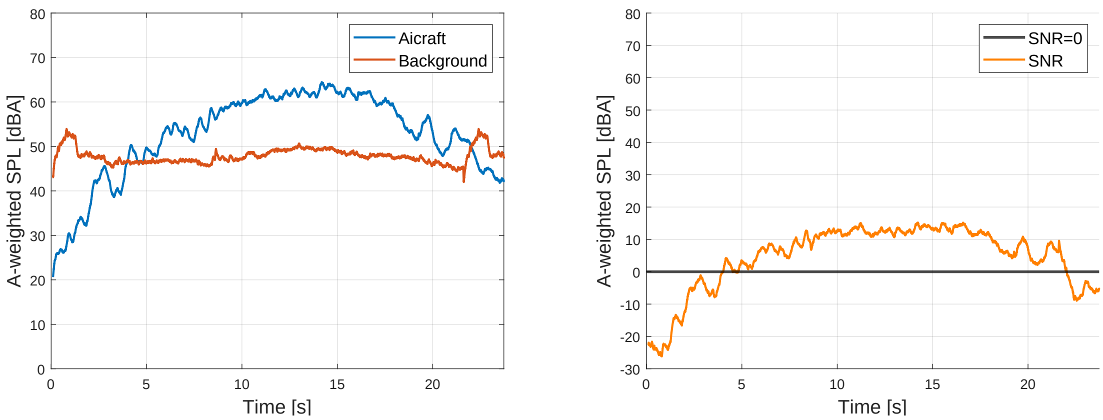
(a) (b)

Figure A.14: A-weighted amplitude vs. time for the aircraft and background noise in the Scheveningen Day Beach Cloudy scene (figure (a)) and the signal-to-noise ratio of this scene (figure (b)).



(a) (b)

Figure A.15: A-weighted amplitude vs. time for the aircraft and background noise in the Timisoara Center Daylight scene (figure (a)) and the signal-to-noise ratio of this scene (figure (b)).



(a) (b)

Figure A.16: A-weighted amplitude vs. time for the aircraft and background noise in the Timisoara Parcul Civic Daylight scene (figure (a)) and the signal-to-noise ratio of this scene (figure (b)).

B

References to background images and background sounds

Table B.1: The list of link references for the background images used in each scene

Scene Name	Link to Background Image
Bowpub Sunny	https://www.google.com/maps/@52.0063459,4.3716988,3a,75y,17.22h,71.63t/data=!3m7!1e1!3m5!1ssXyRZ5Pq4PbwAStU5AyPTg!2e0!6shttps:%2F%2Fstreetviewpixels-pa.googleapis.com%2Fv1%2Fthumbnail%3Fcb_client%3Dmaps_sv.tactile%26w%3D900%26h%3D600%26pitch%3D18.366753333221794%26panoid%3DsXyRZ5Pq4PbwAStU5AyPTg%26yaw%3D17.216434886507137!7i16384!8i8192?entry=ttu&g_ep=EgoyMDI1MDEwOC4wIKXMDSoASAFQAw%3D%3D
Bucuresti Unirii Sunny	https://www.google.com/maps/@44.4271225,26.1024896,3a,75y,223.6h,71.17t/data=!3m7!1e1!3m5!1sHn1sO9oU9FvtyanYWXFJNA!2e0!6shttps:%2F%2Fstreetviewpixels-pa.googleapis.com%2Fv1%2Fthumbnail%3Fcb_client%3Dmaps_sv.tactile%26w%3D900%26h%3D600%26pitch%3D18.83378429829918%26panoid%3DHn1sO9oU9FvtyanYWXFJNA%26yaw%3D223.59731942657038!7i16384!8i8192?entry=ttu&g_ep=EgoyMDI1MDEwOC4wIKXMDSoASAFQAw%3D%3D
Colosseum Cloudy	https://www.google.com/maps/@41.8893726,12.4924378,3a,75y,277.92h,90t/data=!3m8!1e1!3m6!1sAF1QipOGCGAT1XuJFoHmRYsB5wm8oFYiGnXaFbH7czpy!2e10!3e11!6shttps:%2F%2Flh3.googleusercontent.com%2Fp%2FAF1QipOGCGAT1XuJFoHmRYsB5wm8oFYiGnXaFbH7czpy%3Dw900-h600-k-no-pi0-ya277.9189044305527-ro0-fo100!7i10000!8i5000?entry=ttu&g_ep=EgoyMDI1MDExMC4wIKXMDSoASAFQAw%3D%3D
Creepy Scottish House Cloudy	https://www.google.com/maps/@57.2655732,-4.473485,3a,75y,274.15h,90t/data=!3m8!1e1!3m6!1sAF1QipNrBACIAuztqb_z_cGgQdKXqy_j15NFZiZY_jWP!2e10!3e11!6shttps:%2F%2Flh5.googleusercontent.com%2Fp%2FAF1QipNrBACIAuztqb_z_cGgQdKXqy_j15NFZiZY_jWP%3Dw900-h600-k-no-pi0-ya274.1481025369912-ro0-fo100!7i7200!8i3600?entry=ttu&g_ep=EgoyMDI1MDEwOC4wIKXMDSoASAFQAw%3D%3D
Delft Center Jumbo Sunny	https://www.google.com/maps/@52.0089035,4.3643356,3a,75y,161.85h,97.25t/data=!3m7!1e1!3m5!1s06F6C2RtzW_Xi0vPb59V5w!2e0!6shttps:%2F%2Fstreetviewpixels-pa.googleapis.com%2Fv1%2Fthumbnail%3Fcb_client%3Dmaps_sv.tactile%26w%3D900%26h%3D600%26pitch%3D-7.251484450424556%26panoid%3D06F6C2RtzW_Xi0vPb59V5w%26yaw%3D161.8540001158366!7i16384!8i8192?entry=ttu&g_ep=EgoyMDI1MDExMC4wIKXMDSoASAFQAw%3D%3D
Delft Markt Sunny	https://www.google.com/maps/@52.0117398,4.359219,2a,75y,219.47h,105.35t/data=!3m7!1e1!3m5!1s3tcpHLVHEReOXvepnHg3RA!2e0!6shttps:%2F%2Fstreetviewpixels-pa.googleapis.com%2Fv1%2Fthumbnail%3Fcb_client%3Dmaps_sv.tactile%26w%3D900%26h%3D600%26pitch%3D-15.346675980551936%26panoid%3D3tcpHLVHEReOXvepnHg3RA%26yaw%3D219.47087949000138!7i13312!8i6656?entry=ttu&g_ep=EgoyMDI1MDExMC4wIKXMDSoASAFQAw%3D%3D
Dutch Empty Street	https://assetstore.unity.com/publishers/28486

Table B.2: The list of link references for the background images used in each scene

Scene Name	**Link to Background Image**
Echo Building	https://www.google.com/maps/place/Van+Mourik+Broekmanweg+5,+2628+XE+Delft,+Netherlands/@51.9996929,4.3781207,3a,75y,159.41h,89.96t/data=!3m7!1e1!3m5!1s_NbPGpHS9ohXaZp_AVv2EA!2e0!6shttps:%2F%2Fstreetviewpixels-pa.googleapis.com%2Fv1%2Fthumbnail%3Fcb_client%3Dmaps_sv.tactile%26w%3D900%26h%3D600%26pitch%3D0.04296309485516758%26panoid%3D_NbPGpHS9ohXaZp_AVv2EA%26yaw%3D159.40946282886227!7i16384!8i8192!4m15!1m8!3m7!1s0x47c5b58c3bf41401:0x37512ddf7d101b12!2sVan+Mourik+Broekmanweg+5,+2628+XE+Delft,+Netherlands!3b1!8m2!3d51.9995663!4d4.3776958!16s%2Fg%2F11lcrzv3y9!3m5!1s0x47c5b58c3bf41401:0x37512ddf7d101b12!8m2!3d51.9995663!4d4.3776958!16s%2Fg%2F11lcrzv3y9?entry=ttu&g_ep=EgoyMDI1MDExMC4wIKXMDSoASAFQAw%3D%3D
Hague City Center Sunny	https://www.google.com/maps/@52.0795563,4.3126804,3a,75y,246.68h,90t/data=!3m8!1e1!3m6!1sAF1QipPrOJXjdzJgU_-OtGYCxbSf0-8bvE-o7kOu5Cqw!2e10!3e11!6shttps:%2F%2Flh3.googleusercontent.com%2Fp%2FAF1QipPrOJXjdzJgU_-OtGYCxbSf0-8bvE-o7kOu5Cqw%3Dw900-h600-k-no-pi0-ya192.6752753239869-ro0-fo100!7i8704!8i4352?entry=ttu&g_ep=EgoyMDI1MDExMC4wIKXMDSoASAFQAw%3D%3D
Hague City Center Sunny 2	https://www.google.com/maps/place/Fontein+Graaf+Willem+II/@52.0794135,4.3121413,3a,75y,102.14h,104.07t/data=!3m8!1e1!3m6!1sAF1QipM1W0w_8OK0nqyg_vxVE6gJb1I2W0xTxkDykO_5!2e10!3e11!6shttps:%2F%2Flh3.googleusercontent.com%2Fp%2FAF1QipM1W0w_8OK0nqyg_vxVE6gJb1I2W0xTxkDykO_5%3Dw900-h600-k-no-pi-14.069999999999993-ya30.14-ro0-fo100!7i10240!8i5120!4m9!3m8!1s0x47c5b724ea874159:0x13fa73e4e2c096f4!8m2!3d52.0793056!4d4.3123752!10e5!14m1!1BCgIgARICCAI!16s%2Fg%2F11bwn4kfjk?entry=ttu&g_ep=EgoyMDI1MDExMC4wIKXMDSoASAFQAw%3D%3D
Hague City Cloudy	https://www.google.com/maps/place/Pasta+OR+Foods/@52.0696932,4.3061889,3a,75y,323.9h,83.65t/data=!3m8!1e1!3m6!1sAF1QipMc9Vd2mQdiLGfeRVGau32P4LK-scgAn2fCnivT!2e10!3e11!6shttps:%2F%2Flh3.googleusercontent.com%2Fp%2FAF1QipMc9Vd2mQdiLGfeRVGau32P4LK-scgAn2fCnivT%3Dw900-h600-k-no-pi6.3513757040785634-ya325.29593447623535-ro0-fo100!7i9000!8i4500!4m18!1m8!3m7!1s0x47c5b6d8487492f7:0xe410f3d1fb850e38!2sVan+Dijckstraat,+Den+Haag,+Netherlands!3b1!8m2!3d52.0682448!4d4.3077065!16s%2Fg%2F1w8w95yj!3m8!1s0x47c5b6d7f8d6d8fb:0xc0b1a92fb978526!8m2!3d52.0696465!4d4.3061561!10e5!14m1!1BCgIgARICCAI!16s%2Fg%2F1tfmbdzq?entry=ttu&g_ep=EgoyMDI1MDExMC4wIKXMDSoASAFQAw%3D%3D
Hague Park Kids Sunny	https://www.google.com/maps/@52.0821405,4.2950836,3a,75y,325.84h,90t/data=!3m7!1e1!3m5!1s02r-3udNJTRO7VtIwPw6CQ!2e0!6shttps:%2F%2Fstreetviewpixels-pa.googleapis.com%2Fv1%2Fthumbnail%3Fcb_client%3Dmaps_sv.tactile%26w%3D900%26h%3D600%26pitch%3D0%26panoid%3D02r-3udNJTRO7VtIwPw6CQ%26yaw%3D325.83862594609195!7i16384!8i8192?entry=ttu&g_ep=EgoyMDI1MDExMC4wIKXMDSoASAFQAw%3D%3D
Scheveningen Day Grass Sun	https://www.google.com/maps/@52.1181571,4.28652,3a,75y,132.48h,89.82t/data=!3m7!1e1!3m5!1spDoQ_fzdcIrK26UMuKD_9Q!2e0!6shttps:%2F%2Fstreetviewpixels-pa.googleapis.com%2Fv1%2Fthumbnail%3Fcb_client%3Dmaps_sv.tactile%26w%3D900%26h%3D600%26pitch%3D0.17788520275411202%26panoid%3DpDoQ_fzdcIrK26UMuKD_9Q%26yaw%3D132.48168864637074!7i16384!8i8192?entry=ttu&g_ep=EgoyMDI1MDExMC4wIKXMDSoASAFQAw%3D%3D
Scheveningen Day beach Cloudy	https://www.google.com/maps/@52.0908818,4.252799,3a,75y,123.58h,90t/data=!3m8!1e1!3m6!1sAF1QipP9LO595kB15mG5-KES2eRoMhlXPH5QgKe1rW8z!2e10!3e11!6shttps:%2F%2Flh3.googleusercontent.com%2Fp%2FAF1QipP9LO595kB15mG5-KES2eRoMhlXPH5QgKe1rW8z%3Dw900-h600-k-no-pi0-ya26.580287487616744-ro0-fo100!7i8704!8i4352?entry=ttu&g_ep=EgoyMDI1MDExMC4wIKXMDSoASAFQAw%3D%3D

Table B.3: The list of link references for the background images used in each scene

Scene Name	**Link to Background Image**
Timisoara Center Daylight	https://www.google.com/maps/@45.7580472,21.2288715,3a,75y,195.99h,75.54t/data=!3m8!1e1!3m6!1sAF1QipNAYTvVf_k6fIcOP4JxopjOQ9xzhcYC5Ue32JT5!2e10!3e11!6shttps:%2F%2Flh5.googleusercontent.com%2Fp%2FAF1QipNAYTvVf_k6fIcOP4JxopjOQ9xzhcYC5Ue32JT5%3Dw900-h600-k-no-pi14.463842287245868-ya322.7230239631771-ro0-fo100!7i5760!8i2880?entry=ttu&g_ep=EgoyMDI1MDEwOC4wIKXMDSoASAFQAw%3D%3D
Timisoara Parcul Civic Daylight	https://www.google.com/maps/@45.7537806,21.2296106,3a,75y,209.57h,87.98t/data=!3m8!1e1!3m6!1sAF1QipOVNvGrPotEHnTw355WetsKAMunq4N3tgHSHOY1!2e10!3e11!6shttps:%2F%2Flh5.googleusercontent.com%2Fp%2FAF1QipOVNvGrPotEHnTw355WetsKAMunq4N3tgHSHOY1%3Dw900-h600-k-no-pi2.019279159320689-ya274.57026935364536-ro0-fo100!7i10240!8i5120?entry=ttu&g_ep=EgoyMDI1MDEwMi4wIKXMDSoASAFQAw%3D%3D

The sounds presented in Table B.4 were used multiple times in the scenes of the application in order to increase the level of realism presented in each scene.

Table B.4: The list of link references for the background sounds used in each scene

Background Sound Name	**Link to background sound**
Colosseum 1	https://pixabay.com/sound-effects/01-rome-colosseum-labicana-birds-crowd-steps-traffic-wind-selection-25760/
Colosseum 2	https://pixabay.com/sound-effects/02-rome-colosseum-fori-birds-crowd-bikes-steps-wind-selection-19112/
Ambiance Mountain	https://pixabay.com/sound-effects/ambience-mountain-outdoor-mirador-montbau-1-53134/
Beach Waves	https://pixabay.com/sound-effects/windy-beach-waves-33527/
Fountain	https://pixabay.com/sound-effects/rain-fountain-splashes-close-59654/
Birds	https://pixabay.com/sound-effects/birdsongs-31931/
Busy Street	https://pixabay.com/sound-effects/busy-street-ambience-195884/
Central Square	https://pixabay.com/sound-effects/central-square-in-frankfurt-29128/
Park With Stream	https://pixabay.com/sound-effects/franklin-park-stream-mid-day-spring-sunny-19728/
Evening Road Sound	https://pixabay.com/sound-effects/the-sound-of-the-road-in-the-evening-heavy-traffic-the-sound-of-cars-highway-16595/
Windy Forest	https://pixabay.com/sound-effects/windy-forest-32853/
Birds on beach	https://pixabay.com/sound-effects/birds-sunrise-portete-beach-16934/
Mountain Pasture	https://pixabay.com/sound-effects/mountain-pasture-ambience-223052/
Park Ambiance	https://pixabay.com/sound-effects/park-ambience02-60066/
Young People Talking	https://pixabay.com/sound-effects/summer-atmosphere-young-people-talk-and-have-fun-atmo-6197/

C

Pictures from the scenes of the Unity application

This appendix provides screenshots taken from each beginning position of each scene from the application. This is what the participants see when they initialize each scene.

Figure C.1: Screenshot from the Bowpub Sunny scene

Figure C.2: Screenshot from the Bucuresti Unirii Sunny scene

Figure C.3: Screenshot from the Colosseum Cloudy scene

Figure C.4: Screenshot from the Creepy Scottish House scene

Figure C.5: Screenshot from the Delft Center Jumbo Sunny scene

Figure C.6: Screenshot from the Delft Markt Sunny scene

Figure C.7: Screenshot from the Dutch Empty Street scene

Figure C.8: Screenshot from the Echo Building scene

Figure C.9: Screenshot from the Hague City Center Sunny scene

Figure C.10: Screenshot from the Hague City Center Sunny 2 scene

Figure C.11: Screenshot from the Hague City Cloudy scene

Figure C.12: Screenshot from the Hague Park Kids Sunny scene

Figure C.13: Screenshot from the Scheveningen Day Grass Sun scene

Figure C.14: Screenshot from the Scheveningen Day Beach Cloudy scene

Figure C.15: Screenshot from the Timisoara Center Daylight scene

Figure C.16: Screenshot from the Timisoara Parcul CiviC Daylight scene