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EVALUATION OF AUDIO-VISUAL PARAMETERS IN THE PERCEIVED AIRCRAFT NOISE ANNOYANCE USING VIRTUAL REALITY EXPERIMENTS

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ABSTRACT

Most aircraft noise research is solely based on audio recordings. Nevertheless, the use of virtual reality (VR) environments provides a more immersive experience and, hence, a higher level of realism when conducting psychoacoustic listening experiments in laboratory conditions. Moreover, this approach enables the analysis of non-acoustical factors (e.g. visual cues). This study evaluates the influence of different (audio-)visual parameters in the perceived noise annoyance reported in VR experiments. For this purpose, an open-source application developed in Unity was employed to simulate 16 different VR scenarios based on real-life locations. These scenarios were characterized by different binary visual aspects (e.g. rural vs. urban, sunny vs. cloudy, or artificial vs. natural). In each scene, the same binaural aircraft flyover recording was employed to focus on the effect of the different environmental conditions. However, the background noise differed per soundscape, providing different signal-to-noise ratio (SNR) values. The influence of the aircraft visibility (not rendered in some cloudy scenarios) was also evaluated. The results show that, in general, cloudy, rural, and natural environments were perceived as slightly more annoying. Moreover, a significant and moderate correlation was observed between the annoyance ratings and the SNR, showing that background noise can partly mask the presence of aircraft.

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Keywords: *Aircraft noise, Audio-visual parameters, Virtual reality, Listening experiments*

1. INTRODUCTION

The rapid development of the aeronautical industry motivates the increasing research on the negative health and well-being effects that its related noise emissions have on the population [1, 2].

Despite most research focusing on solely the auditory factors, these are not the sole influence on the perceived aircraft noise annoyance [3], and recent research suggests that several other non-auditory factors should be considered in applications, such as drones [4, 5], wind turbines [6–8], and general urban environments [9]. These non-auditory factors may include the visual representation of the noise source [10], the surrounding environment [11, 12], time of day [13], or background noise [14].

Thus, the current study aims to assess the influence that different visual parameters have on perceived annoyance during listening experiments featuring aircraft noise. For this purpose, an open-access virtual reality (VR) application was developed to simulate various environments. Audiovisual VR experiments were performed, featuring 16 different VR scenarios based on real-life locations. Each scene was characterized by different binary visual aspects (e.g. *rural* vs. *urban*, *sunny* vs. *cloudy*, or *artificial* vs. *natural*). To focus on the effect of the different environmental conditions, the same binaural aircraft flyover recording was reproduced in every scene. However, the background noise differed per virtual soundscape, providing different signal-to-noise ratio (SNR) values. This paper is a summary of the MSc thesis of Sergiu A. Priboi [15].

2. METHODOLOGY

2.1 VR application structure

The VR application employed in the audiovisual listening experiments was developed using Unity [1], an open-access game engine that enables the creation of VR applications. Unity was chosen due to its ease of use with virtual reality devices. Moreover, this engine also provides great usability in the manipulation of both background sounds and visual environments.

The visual representation of the sound emitters (in this case, an aircraft flying over the observer), as well as the surrounding environment, were implemented in the experiments, as well as other visual cues, such as time of day, weather conditions, etc. The application consists of 16 different scenes, built to cover 4 pairs of attributes: *urban* vs. *rural*, *sunny* vs. *cloudy*, and *natural* vs. *artificial*. The *urban* scenes were further subdivided into *neutral city environment* and *city center*. Each scene of this application is built based on free-access 360° images downloaded from Google Maps. In the current research, the movement of the observer was limited to a static position within these 360° images, but the users could look around the environment and perceive the data from the scene almost as if they were actually standing in the real-world location. Figures 1 and 2 depict two examples of the VR scenes employed.

In all the scenes considered, the same aircraft render was employed, which is based on a free asset from the Unity Asset store [2]. It should be noted that in some of the scenes characterized as *cloudy*, the visual render of the aircraft was not shown in order to simulate the low visibility due to the clouds and assess the effect of the source visibility in the annoyance.

Figure 1. Example of a VR scene labeled as *urban*, *cloudy*, *artificial*, and *neutral city environment*.

Figure 2. Example of a VR scene labeled as *rural*, *sunny*, and *natural*.

2.2 Aircraft sound and background noise

The aircraft sound employed corresponded to a CRJ-701 aircraft flyover recorded in acoustic field experiments from previous research [16]. The aircraft was equipped with two GE CF34-8C1 engines. The total duration of the aircraft sound was 24 s. The audio file was scaled down to prevent excessive noise exposure during the experiments. After the scaling, the equivalent and maximum A-weighted sound pressure level ($L_{p,A,eq}$ and $L_{p,A,max}$) were 52 dBA and 64 dBA, respectively. This sound is directly linked with the virtual aircraft rendered flying over the participant, such that the sound can be emitted by it and propagated to the observer location, taking into consideration the aircraft movement during the scene and the head-related transfer function (HRTF) to obtain a binaural rendering [17]. The same aircraft sound was used in every scene, such that the investigation focused mainly on the influence that the visual attributes of the environment had on the perceived noise annoyance.

On the other hand, each virtual scene contained one or several background sounds corresponding to the elements surrounding the user. These sounds ranged from recordings of general noise in residential areas to people talking, water fountains, wind, or even quiet road traffic. They were added to provide an additional layer of realism to

[1] https://unity.com/solutions/vr

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

the scenes and to help the participants get more immersed in the scene.

3. EXPERIMENTAL SETUP

3.1 Psychoacoustic listening laboratory (PALILA)

The experiments were conducted inside the Psychoacoustic listening laboratory(PALILA) [18] 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) $\times$ 2.32 m (width) $\times$ 2.04 m (height). It is constructed out of acoustic-absorbing foam panels that dampen sound reflections, creating an acoustically dead space with a 0.07 s reverberation time and free-field sound propagation for frequencies higher or equal to 1600 Hz. Moreover, the facility is highlt isolated from any other external influence with a transmission loss of 45 dB and an A-weighted background noise level of only 13.4 dBA. The facility has no windows and no external light penetrating, as such, the participants can be fully immersed in the experiment.

PALILA is equipped with a pair of calibrated Sony WH-1000XM4 over-ear, closed-back headphones, and a Meta Quest 3 VR headset with two controllers, which were used for this experiment. Figure 3 depicts the setup where the experiment was performed, as well as an example of how one participant was using the hardware.

Figure 3. Example of a VR experiment in PALILA.

3.2 Test subjects

A total of 30 people participated in the experiment, out of which 21 were male and 9 female, with an average age of 23 years old (and a standard deviation of 3 years). 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. Out of the 30 participants, 9 of them were employed, while the rest were students.

29 participants were affiliated with Delft University of Technology by either being students - active, recent graduates, or employees. No participants communicated utilizing hearing aids, and their self-reported hearing rating ranged from "good" to "excellent", with only one participant declaring they had a "fair" hearing rating. Out of the 30 participants, three of them self-reported a mild cold, giving a score of either 1 or 2 on a 5-point scale. However, none of these parameters were found to have any significant statistical influence on the outcome of their responses.

3.3 Experimental protocol

The individual participants were welcomed and briefed about the characteristics of the VR 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). After that, they were introduced to the VR setup and provided explanations on how to use it properly since most participants had no previous experience using VR headsets. After an introductory scene to familiarize themselves with the VR environment and collect some demographic data, the actual audiovisual experiment commenced.

The 16 different scenes were divided into two sets of 8 scenes each, such the users did not experience fatigue, especially because using a VR headset for the first time can feel tiring. The participants sequentially experienced the different VR scenarios, where the background noise started playing the moment the visual scene started and, once the participants selected it using the controller, the aircraft flyover (both render and sound reproduction) would begin.

After each scene, an ICBEN 11-point scale was used so the participants could answer 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?*".

The experiment took, on average, between 20 and 25 minutes. 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-euro universal voucher to compensate for their time spent in the experiment.

4. RESULTS AND DISCUSSION

4.1 Influence of visual parameters

This section gathers the main results from the listening experiments as box plots of the annoyance ratings collected. The results are divided per pair of binary attributes used for classifying the scenes in the VR application. In the box plots, the box represents the interquartile range, the whiskers extending from the box show the data within ± 1.5 times the interquartile range (IQR), the horizontal black lines denote the median annoyance rating, and the black circle markers the mean values.

4.1.1 Rural vs. urban scenes

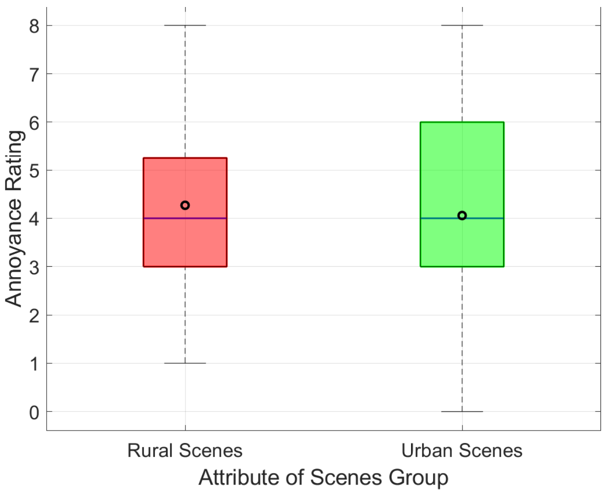

Figure 4. Box plot of the mean annoyance ratings for the urban and rural scenes.

Figure 4 shows that the *rural* and *urban* scenes present the same median values of the annoyance ratings (4/10). Their mean values are also approximately 4, but *urban* scenes have a trend towards slightly higher annoyance ratings, with the IQR spanning from 3 to 6 instead of 3 to 5 for the *rural* scenes.

4.1.2 Sunny vs. cloudy scenes

In Fig. 5, it can be seen that a slightly higher overall annoyance was perceived in the *cloudy* scenes, with their

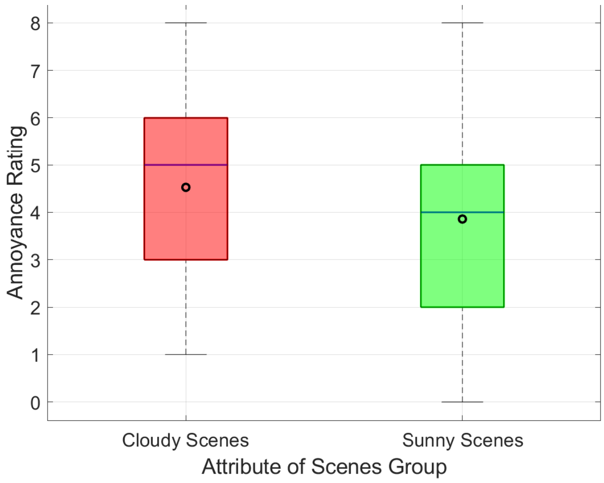

Figure 5. Box plot of the mean annoyance ratings for the sunny and cloudy scenes.

IQR ranging from 3 to 6, a median annoyance rating of 5, and the mean one around 4.5. On the other hand, their *sunny* counterparts present an IQR from 2 up to 5, a median of 4, and a mean value slightly of 3.9. It should be noted that, for some of the *cloudy* scenes, the flying aircraft was not rendered to simulate low visibility conditions, but this factor was found not to have a significant influence in the annoyance ratings [15].

4.1.3 Natural vs. artificial scenes

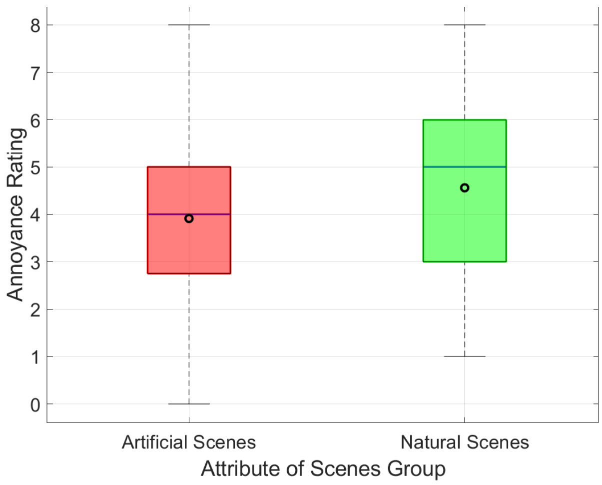

Figure 6. Box plot of the mean annoyance ratings for the natural and artificial scenes.

In general, the scenes considered as *natural* were perceived as more annoying with an IQR from 3 to 6, a median annoyance rating of 5, and a mean of 4.6, seeFig. 6. Meanwhile, the *artificial* scenes presented both median and mean ratings of approximately 4. The higher annoyance recorded in the *natural* scenes may be explained by the disturbance of the peace typically associated intrinsically with such environments by the presence of the aircraft flyover.

4.1.4 *Neutral city environment vs. city center scenes*

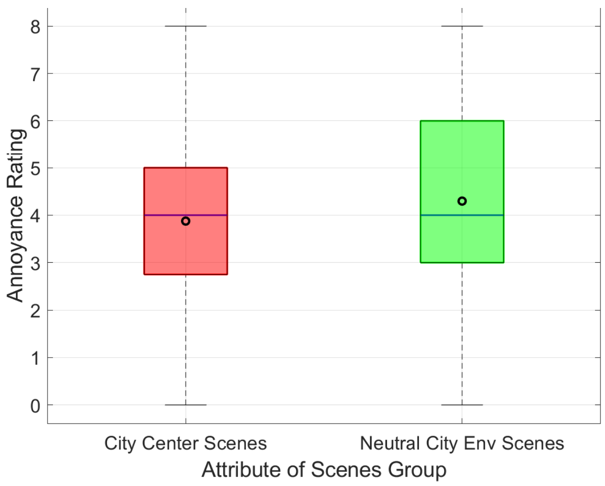

Figure 7. Box plot of the mean annoyance ratings for the *neutral city environment* and *city center* scenes.

The scenes labeled as *urban* were further subdivided into *neutral city environment* and *city center* scenes to evaluate whether the visual presence of some recognizable locations influenced the perception of the aircraft flyover. Looking at Fig. 7, it is observed that although having the same median value, the overall trend of the scenes with the *neutral city environment* attribute is towards slightly higher annoyance ratings, with the IQR of the data extending up to 6, instead of 5. This is further supported by their higher mean value of around 4.3, compared to 3.9 for the *city center* scenes.

4.1.5 *Numerical Values for All Attributes*

As a summary, Tab. 1 presents the mean and median annoyance ratings for each binary attribute. It is seen that, in general, scenes with *rural*, *cloudy*, and *natural* attributes are perceived as somewhat more annoying. Within the urban scenes, those with a more *neutral city environment*

Table 1. Mean and median annoyance ratings per scene binary attribute

Attribute	Mean	Median
Urban	4.06	4
Rural	4.27	4
Sunny	3.86	4
Cloudy	4.53	5
Natural	4.56	5
Artificial	3.91	4
Neutral City Environment	4.30	4
City Center	3.88	4

(i.e. lack of monuments or recognizable landmarks) were also experienced as slightly more annoying than those in the *city center*.

Nevertheless, all the annoyance ratings fall within close range of each other, most likely because the aircraft sound was the same in every scene. In fact, the differences found between attributes are not very large, and are (at most) of one point (out of ten), when considering the median ratings and of 0.7 points between the means.

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.

4.2 Influence of the signal-to-noise ratio (SNR)

In acoustic assessments, the SNR is an important metric to quantify the relative level of a sound signal with respect to the surrounding background noise. Since the same aircraft sound was reproduced in every scene, but with different background noise sources present, it is relevant to quantify how much the aircraft sound *protruded* from the surrounding background noise and how this parameter influenced the perception of the scenes [19].

In the example *urban* scene of Fig. 8, it is seen that, as expected, the aircraft sound has a comparably higher (A-weighted) sound pressure level compared to the (relatively high) background noise [3]. In the initial part of the plot, the increase of the aircraft sound level is observed, due to the fact that, at the beginning of the scene, the aircraft

[3] In fact, the example scene of Fig. 8 corresponds to the highest background noise level of all cases considered.

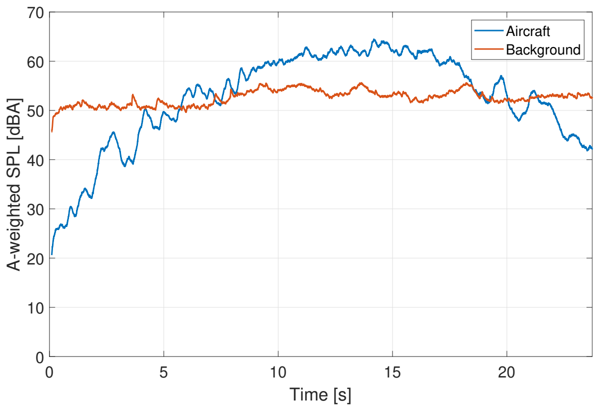

Figure 8. A-weighted sound pressure level (SPL) time histories for the aircraft and background noise in an example *urban* scene in the *city center*.

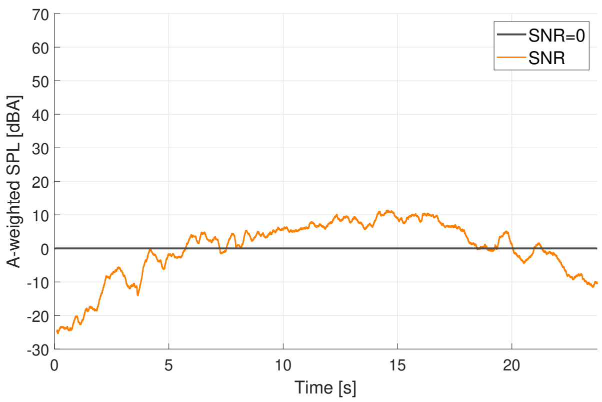

Figure 9. SNR (A-weighted) for an example *urban* scene in the *city center*.

flies from a distance towards the observer, and as such, up to a point, the sound emitted by it is lower than the background noise level. However, for most of the scene, the aircraft sound represents the main sound source of the scene.

To better observe this difference, Fig. 9 depicts the A-weighted SNR (SNR_A) of the same 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 observer's position, the SNR increases, reaching a positive value after approximately 6 s. The SNR presents positive values for the majority of the 24 s of the duration of the scene (from 6 s up to around 20 s). As such, it is confirmed the aircraft noise is the principal audio element in this scene, with maximum SNR_A values of roughly 10 dBA.

Table 2. Maximum A-weighted SNR ($SNR_{A,max}$) values averaged for each scene attribute

Scene Attribute	Mean $SNR_{A,max}$, [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

Table 2 gathers the $SNR_{A,max}$ values averaged for each scene attribute. The $SNR_{A,max}$ values in the scenes ranged from 10 dBA (relatively loud environment) to 52 dBA (very quiet environment). Here, it is seen that some attributes, such as *rural*, *cloudy*, *natural*, and *neutral city environment* present the highest values, all close to 27 dBA. These attributes coincide with those presenting higher annoyance ratings, as observed in Tab. 1.

To investigate the influence of the $SNR_{A,max}$ in the (mean) annoyance ratings from the audiovisual listening experiment, Fig. 10 presents the correlation analysis between the two parameters. A moderate, significant correlation ($\rho \approx 0.6$, p-value = 0.013) is observed between these two variables. Therefore, higher background noise levels might mask to some extent the presence of the aircraft and mitigate the annoyance perceived. Nevertheless, the $SNR_{A,max}$ only explains $\rho^2 \approx 36\%$ of the variability in the annoyance ratings, suggesting that the perceived annoyance is influenced by a complex combination of visual and acoustical factors. In fact, recent research has shown that psychoacoustic sound metrics are able to explain up to 90% of the variance in annoyance responses to aircraft noise in listening experiments (without VR) [20], whereas conventional sound metrics (e.g. sound exposure level) only reached values around 60%.

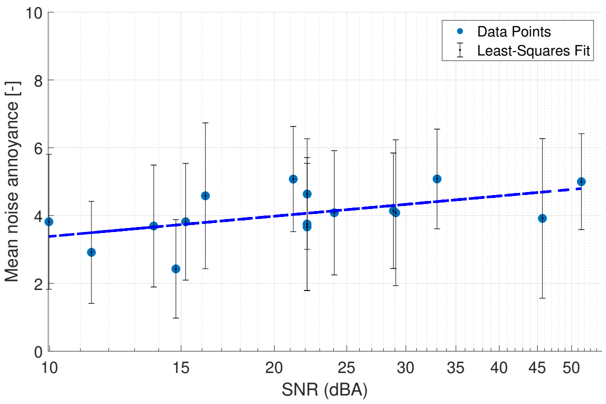

Figure 10. Mean noise annoyance ratings per scene vs. $SNR_{A,max}$. The error bars denote the standard deviations in the annoyance ratings. The dashed blue line indicates the least-squares fit. Note that the x-axis is depicted as a logarithmic scale.

5. CONCLUSIONS AND FUTURE OUTLOOK

This research focused on developing a VR application to conduct audiovisual psychoacoustic experiments on aircraft noise. The main research question of this study was to evaluate how the different visual cues (weather, type of surroundings) and the environment (background noise levels) influenced the perception of an aircraft flyover. A total of 16 different VR scenes were evaluated, each with different visual cues and background noise sources but with the same aircraft sound flying over the observer.

The results from an audiovisual experiment featuring 30 participants seem to indicate that there is a mild influence coming from the visual cues of the scenes, with attributes such as *rural*, *natural*, *cloudy* presenting slightly higher perceived annoyance. For some of the cloudy scenes, it should be noted that the aircraft render was not present to assess whether the visibility of the sound source influenced the perception, but this was found not to have a significant effect.

A moderate and significant correlation ($\rho \approx 0.6$) was found between the mean annoyance ratings reported in the experiments and the maximum A-weighted SNR of each scene. This shows that (for the same aircraft sound) higher levels of surrounding background noise might mask to some extent the presence of the aircraft and mitigate the annoyance perceived.

The findings of this study seem to indicate that the perceived annoyance of aircraft flyovers is influenced by both visual parameters as well as the SNR of the scene (i.e. the background noise level in this case). However, since the same aircraft sound was employed throughout the experiments, the variability in the (mean) annoyance ratings is quite limited (from 2.5 to roughly 5, in the ICBEN 11-point scale) compared to other studies that featured different noise sources [21].

Therefore, this research highlights the importance of creating and implementing novel technologies, such as VR, in the analysis of psychoacoustic annoyance that can represent both visual and acoustical features of a scene.

For further research it is recommended to investigate more aerospace applications, such as drones [21], wind turbines [22], or unconventional aircraft designs, as well as different visual parameters for the scenes. A higher variety of sound recordings (aircraft and background) and even real-time auralization tools [17] that simulate the produced sound and consider the location and head position of the observer can also be implemented. This study employed static 360° images as VR visual environments but more , three-dimensional environment renders where the participants can move around, should also be considered to evaluate aspects, such as sound reflections, subject dynamism, or different weather conditions.

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