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A DEEPER UNDERSTANDING IN THE PSYCHOACOUSTIC CHARACTERIZATION OF DRONE NOISE

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ABSTRACT

Emerging new technologies for sustainable transport will also come with new challenges. The implementation of drones for numerous applications may elicit negative noise impact, an important aspect of public acceptability. Prior research shows that drones are considered more annoying than helicopters for the same loudness level, but not more annoying than lawnmowers that also produce strong tonal sounds. Continuing on this finding, this study seeks to understand the subjective psychoacoustic characterization of these vehicles, that may explain some of the differences in annoyance scores. A laboratory study was set up to measure the subjective ratings of annoyance, loudness, threatening, squeakiness and tonality scores to drones, helicopters and lawnmowers that resemble drones. Participants of the study evaluated scripted events of these vehicles using a Virtual Reality headset with a sound simulation system. Results show that for all vehicles, loudness is a strong predictor of annoyance scores. For helicopters and drones, threatening was also a significant contributor to annoyance, while tonality contributed significantly to lawnmower annoyance scores. The visualisation contributes to the understanding of perceived safety of different drone models, as larger hovering drones were perceived as more threatening than smaller hovering drones, but only when the visual model was presented.

Keywords: *drone noise, annoyance, psychoacoustics.*

1. INTRODUCTION

Urban Air Mobility (UAM) is a relatively new emerging form of air transport, that could help battling the current climate battle as it, electrically propelled, may provide an alternative to current transportation networks and reduce the emission of greenhouse gasses, such as CO_2 [1][2]. Aside from the positive benefits of UAM on the climate, these vehicles could be useful for parcel delivery, person transport, surveillance or even as organ transport. Considering these applications, both small and larger drones, as well as (person carrying) electrical Vertical Take-off and Landing (eVTOL) vehicles are considered as part of the concept of UAM. Despite the positive aspects of implanting drones in an urban environment, public acceptability [3] is still the main concern for successful introduction of these applications. Negative impacts [4] are related to privacy and safety concerns, and, not surprisingly, noise concerns as well [5]. Existing studies show that drones elicit more annoyance than aircrafts [6], road traffic [7] and helicopters [8].

1.1 Psychoacoustics

There seems to be variability in the experienced annoyance to drones. In the study of Gwak et al. (2020) [6] the researchers found a significantly higher level of annoyance towards medium and large drones when compared to aircraft. An explanation for the high level of annoyance for drones could be due to the sharp characteristic of the produced sound [6]. Another study from Torija and Lawrence (2019) [9] provides evidence of the importance of the tonality of the

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sound when assessing the annoyance. In their study they found that recorded quadcopter noise has a significantly higher high frequency content than aircraft or road vehicles. They also found that due to the higher loudness, sharpness and tonality of the quadcopter, the calculated psychoacoustic annoyance was higher than for the tested aircraft and road vehicles. However, atmospheric disturbances of drones could create an unsteady acoustic signature [9], and therefore an emission model should account for the correlation between operating conditions and rotor speeds [10]. Furthermore, subjective evaluation of psychoacoustic properties of drone noise could provide further insight in the experienced annoyance in a similar way as the objective psycho-acoustic metrics of tonality, loudness and sharpness have a (negative) impact on annoyance.

1.2 Perceived safety

Aside from noise pollution, another aspect that could negatively impact public acceptance is the perceived safety of drones. A survey in Amsterdam [11] on the public acceptability of drones show that 79% of their respondents are concerned about the invasion on their privacy by drones and 77% agree that drones can cause unsafe situations. Furthermore, the study from Wojciechowska et al. (2019) [12] shows that the physical features of a drone could influence the perception of drones. They provided evidence that safety features of a drone, such as propeller guards, could have a negative impact on the perception, including trust, indicating that ensuring physical safety does not ensure perceived safety. Another study by Waveren et al. (2023) [13] indicates that drone's speed and distance from the observer are important for perceived safety. Also, it is not known in what way drones are perceived more or less threatening (or harmless) compared to other aerial vehicles, but considering the safety concerns, it is expected that drones are perceived as more threatening.

1.3 Research questions

In this paper the following research questions are addressed:

1. What is the influence of perceived threat and self-reported psychoacoustic measures on experienced annoyance?
2. What is the difference in perceived threat and psychoacoustic scoring between sounds generated by drones, helicopters and lawnmowers?

2. METHOD

In this study a dataset obtained from a previous study by Aalmoes and Sieben (2021) [8] was used where 30 participants rated the annoyance, loudness, tonality, squeakiness and perceived threat of the flyover of a drone and a helicopter, as well as the hovering of a drone and a lawnmower in a Virtual Reality (VR) setting. Here, drones were found to be more annoying than helicopters, but less than lawn mower sounds. Visual perception and urban background sound levels seem to have a smaller influence when evaluating drone annoyance than previously expected. In this study only annoyance scores were assessed, but not yet tonality, squeakiness, threatening and loudness. Tonality is defined as the perceived tonality of a single or narrow-band spectral component in the sound. Squeakiness is the perceived high frequency (pitched) portions of the sound.

2.1 Study set up and stimuli

The NLR Virtual Community Noise Simulator (VCNS) [14] was used in the experiment to provide the participants with a simulated environment. These simulated environments consisted of either a busier urban area, or a quieter urban area. Here, two types of drones, a larger Gryphon GD-40X (140cm motor to motor) drone and a smaller MK Quadro XL (56cm motor to motor) drone, a helicopter, and a lawnmower were presented. The helicopter and both drones were presented as an overhead flyover. Both drones and the lawn mower were also presented as hovering stimuli in about 45° angle overhead from the observer. The hovering and flyover sound stimuli were normalized to a similar Sound Exposure Level (SEL) value of 75 dB(A) to prevent bias of annoyance due to varying noise levels. More information on the specifics of these vehicles are described in the study by Aalmoes and Sieben (2021) [8]. Two distinct urban environments were used in the test. Also, participants were presented one time where the visual model was visible, and one time, where the visual model was not made visible, resulting in a combination of 26 different conditions.

2.2 Questionnaires

Questions that were asked during the VR experiment consisted of annoyance, feeling threatened, loudness, squeakiness, and distinguishable tones of the sound and were asked after each condition. Apart from annoyance and perceived threat, only the experience of loudness, squeakiness and tonality were assessed as psychoacoustic properties of the sound. Research shows that the psychoacoustic annoyance model is a function of the sound quality metrics for loudness, sharpness, roughness, fluctuation strength, and tonality [15]. In this experiment, only the experience of loudness and tonality were assessed as psychoacoustic properties of the sound, since these characteristics of sound distinguish drone noise from aircraft noise.

2.3 Procedure

After reading and signing the informed consent, participants viewed a PowerPoint presentation with additional information about the procedure and questions asked during the experiment. In these slides, examples of sounds were provided for the five questions asked after each condition, as well as an explanation of the questions asked. For example, for perceived threat the following description was presented: "*This question refers to your personal feeling of safety: how threating do you experience this vehicle? To answer this, these questions may help you: How threatening do you experience this sound/view of the vehicle? Do you feel uncomfortable when hearing / seeing this vehicle?*" , as well as a slider ranging from -5 (innocent) to 5 (threatening). After reading the descriptions the VR experiment started, where all participants answered the questions on annoyance, perceived threat, squeakiness and tonality, which popped up on the screen after each of the 26 conditions using a joystick. After the VR experiment, the participants filled in questionnaires regarding general attitudes towards drones and sound sensitivity. Results of these questionnaires are presented in the paper by Aalmoes and Sieben (2021) [8].

3. RESULTS

3.1 Annoyance contributors

3.1.1 Drones

A multiple regression was run to predict overall drone annoyance scores from overall drone threatening, loudness, tonality and squeakiness scores. These variables statistically significantly predicted annoyance, $F(4, 25) = 57.11$, $p < .001$, $R^2 = .901$. However, only threatening and loudness scores added statistically significantly to the prediction, $p < .05$. Here, loudness is the strongest contributor, $\beta = .573$, followed by how threating drones are perceived, $\beta = .456$.

3.1.2 Helicopter

Similar results were found for helicopter scores. Also here, a multiple regression was run to predict overall helicopter annoyance scores from overall helicopter threatening, loudness, tonality and squeakiness scores. These variables statistically significantly predicted annoyance, $F(4, 25) = 25.25$, $p < .001$, $R^2 = .802$. However, only threatening and loudness scores added statistically significantly to the prediction, $p < .05$. Here, loudness is the strongest contributor $\beta = .468$, followed by how threating drones are perceived $\beta = .448$ with a small difference.

3.1.3 Lawnmower

Another multiple regression was run to predict overall lawnmower annoyance scores from overall lawnmower threatening, loudness, tonality and squeakiness scores. These variables statistically significantly predicted annoyance, $F(4, 25) = 32.82$, $p < .001$, $R^2 = .840$. Only loudness ($p < .001$) and tonality ($p = .026$) added statistically significantly to the prediction. Loudness showed to be the strongest contributor ($\beta = .565$), followed by tonality ($\beta = .242$).

3.2 Psychoacoustic differences between vehicles

3.2.1 Perceived tonality

An overall effect was found of vehicle type on the subjective ratings of noticeable tones (tonality) measured with a three way repeated measures ANOVA, $F(3, 78) = 5.32$, $p = .003$, $\eta^2 = .155$, with the Huynd-Feldt correction method applied, $\varepsilon = 0.82$, $X^2 = 13.69$, $p = .018$. LSD post hoc analysis shows a difference in tonality between the helicopter, flyover of drones and the lawnmower. Here, the lawnmower ($M = 5.99$, $SE = .31$) was perceived as having more noticeable tones than the helicopter ($M = 4.86$, $SE = .42$, $p = .010$) and both the larger flyover drone ($M = 4.64$, $SE = .37$, $p = .002$) and smaller flyover drone ($M = 4.83$, $SE = .35$, $p = .005$). This distinct difference was not found between drones and the helicopter, $p < .05$.

A similar result was found for hovering drones ($F(3, 76) = 5.00$, $p = .005$, $\eta^2 = .147$, with a Huynd-Feldt correction method: $\varepsilon = 0.88$, $X^2 = 13.58$, $p = .019$ applied), where lawnmowers were perceived as containing more noticeable tones than the helicopter and both the larger and smaller hovering drones, $p > .05$.

3.2.2 Threatening

Three way repeated measures ANOVA shows that flyover of drones ($M = 5.58$, $SE = .29$, $p = .015$) and the lawnmower ($M = 4.85$, $SE = .35$, $p = .007$) were considered significantly more threatening than a helicopter ($M = 3.71$, $SE = .32$), $F(3, 87) = 4.59$, $p = .005$,

η^2= .137. No differences were found between the larger drone, smaller drone and lawnmower, $p > .05$.

Just like the flyovers of drones, an overall effect of vehicle type was found on how threatening these were experienced when compared to a hovering drone ($F(2, 71) = 12.76$, $p < .001$, $\eta^2 = .306$, with the Huynd-Feldt correction method applied: ε = 0.82, $X^2 = 15.21$, $p = .010$). Interestingly, we found that a larger hovering drone ($M = 5.78$, $SE = .30$) was considered as more threatening than a smaller hovering drone ($M = 4.75$, $SE = .35$, $p < .001$)

Furthermore, an interaction was found between visual presence of the 3D model and the drone type ($F(1, 29) = 25.88$, $p < .001$, $\eta^2 = .472$), meaning that the larger drone was considered to be more threatening when both audible and visually present ($M = 6.48$, $SE = 0.33$) than when it was only audible ($M = 5.07$, $SE = 0.33$). This difference was not found for the smaller drone when both audible and visual ($M = 4.77$, $SE = 0.37$) or only audible ($M = 4.73$, $SE = 0.37$). As seen in Figure 1, the difference between the perceived threat becomes larger between the smaller drone and the larger drone with the visual model present.

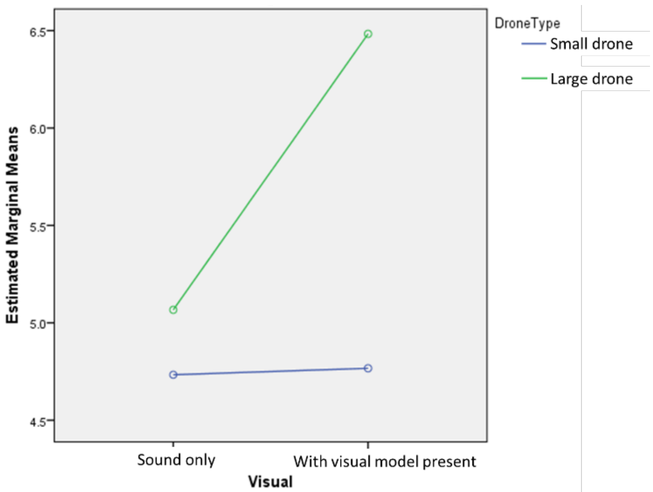

Figure 1. Difference in perceived threat for the different vehicles with and without the 3D visual model present

3.2.3 Squeakiness

A significant effect was found of vehicle type on the perceived squeakiness of the sound measured with a three way repeated measures ANOVA. ($F(2, 51) = 40.73$, $p < .001$, $\eta^2 = .584$, with the Greenhouse-Geisser correction method applied: ε = 0.58, $X^2 = 30.81$, $p < .001$). Post hoc LSD analysis shows a significant difference in squeakiness for the lawnmower, helicopter and flyover of the drones, where the lawnmower ($M = 6.68$, $SE = 0.42$) was considered most squeaky, followed by the smaller ($M = 4.15$, $SE = 0.35$) and larger drone ($M = 3.80$, $SE = 0.35$) and lastly by the helicopter ($M = 2.74$, $SE = 0.33$), $p < .05$. No significant difference was found between the smaller and larger drone, $p = .113$.

A similar result was found for the vehicle type with the hover of a drone included instead of the flyover ($F(2, 56) = 38.91$, $p < .001$, η^2= .573 with the Greenhouse-Geisser correction method: ε = 0.64, $X^2 = 22.19$, $p < .001$).

3.2.4 Loudness

A significant effect was found of vehicle type on the perceived loudness of the sound measured with a three way repeated measures ANOVA when comparing the flyovers ($F(3, 87) = 17.59$, $p < .001$, $\eta^2 = .378$) and the hovering of the drones ($F(2, 58) = 18.74$, $p < .001$, $\eta^2 = .393$ with the Greenhouse-Geisser correction method applied: ε = 0.67, X^2= 22.18, $p < .001$) with the lawnmower and helicopter.

When comparing the flyovers of the drones with the lawnmower and the helicopter, a significant difference was found between these vehicles. Here, the lawnmower ($M = 6.79$, $SE = 0.28$) was considered the loudest, followed by the drones ($p < .001$) and lastly by the helicopter ($M = 4.84$, $SE = 0.30$, $p < .001$). No significant difference was found between the larger ($M = 5.58$, $SE = 0.34$) and smaller drone ($M = 5.73$, $SE = 0.28$, $p = .463$).

A slightly different result was obtained when comparing the hovering drones with the lawnmower and helicopter. Here, the lawnmower ($M = 6.79$, $SE = 0.28$) was still considered to be loudest, followed by the drones ($p < .001$) and helicopter ($M = 4.84$, $SE = 0.30$, $p < .001$). However, no significant difference was found between the helicopter and the small hovering drone ($M = 5.43$, $SE = 0.31$), $p = .05$, while a significant difference was found between the larger ($M = 6.11$, $SE = 0.28$) and smaller hovering drone, where the larger drone was considered to be louder $p = .003$.

3.2.1 Frequency spectra of the sounds

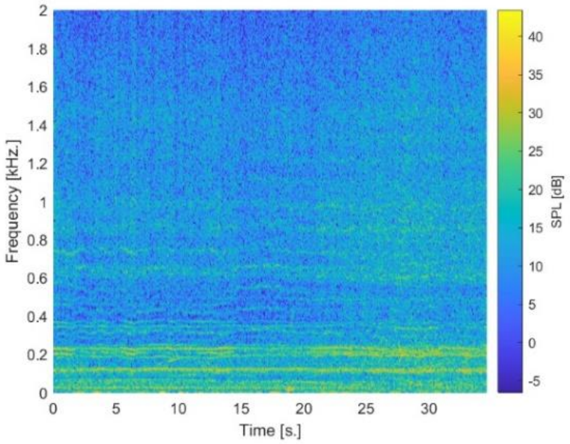

Figure 2. Spectrogram of the smaller hovering drone sound.

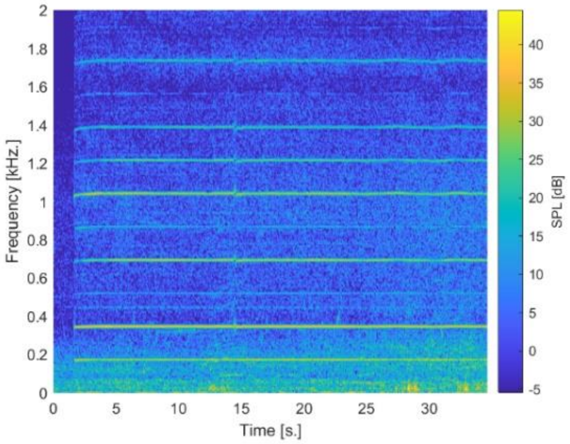

Figure 3. Spectrogram of the lawnmower sound.

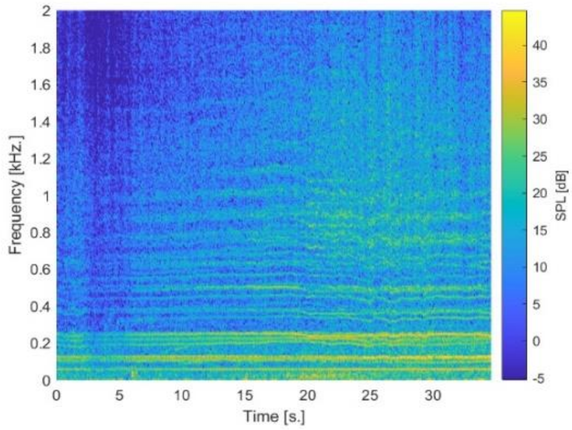

Figure 4. Spectrogram of the larger flyover drone sound.

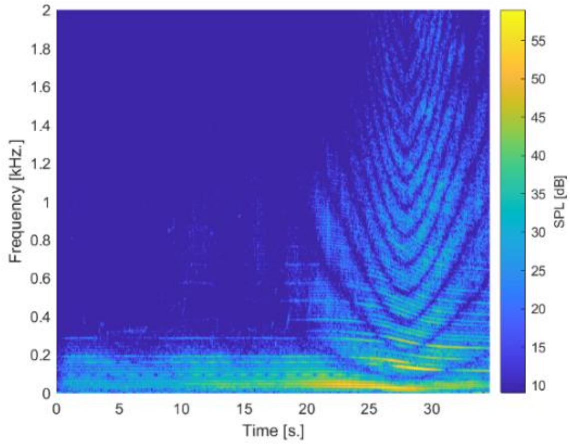

Figure 5. Spectrogram of the helicopter flyover sound

In Figures 2 through 5, the frequency spectra of the smaller and larger drones, lawnmower and the helicopter are presented. Despite normalized SEL values for the sound samples, the character of the sounds differs between the presented stimuli. Both in the spectrograms of the hovering of the smaller drone (Figure 2) and the lawn mower (Figure 3) a limited number of dominating frequencies can be recognized, that contribute to a high tonality in the sound sample.

The flyover spectrogram of the larger drone (Figure 4) differentiates from the flyover of the helicopter. The helicopter has a higher speed that can be recognized by the more prominent doppler effect and also a recognizable ground reflection pattern visible in the spectrogram on Figure 5.

4. CONCLUSION AND DISCUSSION

In this study the subjectively rated psychoacoustic properties of drone, lawnmower and helicopter noise were assessed. Data for this study was obtained from the study by Aalmoes and Sieben (2021) [8] where a Virtual Reality experiment was executed to assess drone perception compared to familiar vehicles with similar acoustic properties as drones. In this experiment the annoyance, loudness, perceived threat, squeakiness and tonality were rated on a 11 point Likert scale in the virtual environment. The sound of a large drone, small quadcopter drone, helicopter and lawnmower were presented either with or without the 3D visual model present. The previous study by Aalmoes and Sieben (2021) [8] shows that drones were perceived a more annoying than a helicopter, but less annoying than a lawnmower.

Results of this study show that for all vehicles, (perceived) loudness is a strong predictor of annoyance scores. For helicopters and drones, perceived threat was also a significant contributor to annoyance, while tonality contributed significantly to lawnmower annoyance scores. Furthermore, lawnmowers were perceived as having more noticeable tones compared to the helicopter and drones, while no difference was found between the helicopter and drones. This result may explain the contributed tonality in the annoyance scores for lawnmowers and confirm the finding from Torija and Lawrence (2019) [9] on the contribution of tonality on annoyance. Interestingly, the perceived squeakiness showed a similar pattern as the annoyance towards the vehicles, where the lawnmower was considered to be most squeaky, followed by the drones and lastly by the helicopter, while squeakiness was not a significant predictor of annoyance scores. This finding was unexpected, as squeakiness was described to the participants as: "*a high pitch/toned sound*" and tonality as: "*noticeable tones means if you hear any distinct tones, either lower or higher in the sound sample*". It would be expected that tonality and squeakiness would yield similar results and both contribute to annoyance. A possible explanation could be due to the monotonous sound of the lawnmower where the distinct tones are more audible than the other vehicles. This is also presented in the spectrograms of the sound (Figure 3), as the lawnmower only contained one single rotor, a dominating tonal frequency of 350Hz was found. This may explain the contribution of the subjectively rated tonality to the annoyance of lawnmowers and the higher squeakiness scores.

As expected, loudness scores showed similar scores as the annoyance scores and were also the strongest predictor of annoyance. However, a difference in perceived loudness was found for the smaller and larger hovering drone, with the larger drone being considered as louder. This result is unexpected since this difference was not found in annoyance scores, but similar results were found for the perceived threat of these two different drones, which may account for the difference found in perceived loudness. This study found that larger hovering drones were perceived as more threatening than the smaller hovering drones, but only with the 3D visual model present, meaning that the visualisation contributes to the understanding of perceived safety of different drone models. The difference found in perceived threat towards the drones and helicopter confirms earlier findings on the impact of perceived safety of drones on public acceptability [10][11][12][13]. A lawnmower was also considered more threatening than a helicopter. As the lawnmower was visualized as a hovering drone, similar results are found as expected.

as well., where we assume this contributes to perceived safety (threat) towards drones, as the lawnmower was visualized as a hovering drone.

Assumptions in this study were made with some limitations. Firstly, data collection took place during the COVID-19 pandemic and to prevent further spread of the COVID-19 virus, the participants were found within the personal circles of the researcher. Even though all of the participants were informed that the experiment was anonymous, this could have created some socially desirable answers. Some participants also knew beforehand that the topic of the experiment was about drone noise annoyance, which could have altered their perception of drones. For this reason it is better for future studies to have a more diverse pool of participants. Secondly, explaining the meaning of psychoacoustic characterizations, such as tonality to the participants proved to be difficult. Even though the participants were provided with example sounds, this could be interpreted in different ways and results in future studies should be validated by objectively measuring the psychoacoustics characteristics of the sounds, or by using a pool of expert or pre-trained sound listeners who better understand how to rate the requested sound characteristics.

This study contributes to a deeper understanding into annoyance towards new emerging aircrafts. Results in this study prove that noise annoyance research should not only evaluate sounds themselves, but also visual aspects that may subjectively change people's perceived safety. Furthermore, this study suggests psychoacoustic characteristics, such as perceived tonality of the sound and safety concerns play an important role in the acceptability of these new emerging vehicles. Additionally, this study provided novel insights in the impact of different operating conditions on psychoacoustic evaluation of the sound, as some differences were found in the flyover and the hovering of the drone. Future research could elaborate on this finding, taking into account rotor speeds and measuring the impact of objectively measured psychoacoustics on the experienced annoyance towards drones.

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