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INVESTIGATING THE DOSE RESPONSE OF UAS NOISE: DESIGNING A LISTENING EXPERIMENT

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ABSTRACT

In collaboration with the UK Civil Aviation Authority, the Acoustic Research Centre (ARC) at the University of Salford is conducting research to better understand the human perception and dose response of Unmanned Aerial System (UAS) flyover noise. A listening experiment has been conducted to investigate the perception, both in terms of perceived annoyance and loudness, of a number of UAS flyovers in comparison with more familiar sources of transportation noise such as civil aircraft, helicopters and road vehicles. This paper discusses the decision making that went into the preparation of the listening experiment and provide an overview of state-of-the-art subjective experiments on UAS noise used to inform the development of this experiment. The findings of this experiment are expected aid the derivation of dose response relationships and penalties or relaxations (compared to other transportation noise sources) which could be applied to UAS noise to inform appropriate environmental noise impact assessment metrics.

Keywords: *UAS Noise, Listening Experiment, Experiment Design*

1. INTRODUCTION

The use of Unmanned Aerial Systems (UAS, also known as 'drones') has increased dramatically over the past couple of years and this trend is expected to continue particularly as Beyond Visual Line of Sight (BVLoS) and autonomation technology improves. Drones are a technology that could revolutionise sectors such as parcel delivery and the emergency services but the issue of noise pollution and potential impacts on communities are not yet fully understood.

A recent study found that 53% of people consider noise to be a concern for the introduction of civil drones [1]. Whilst the percentage of people who recorded noise as a cause for concern was lower than other issues such as; risk of damages and injuries, violation and privacy intrusion or crime and misuse, it is still significant for a number of reasons. Firstly, within this same study noise concerns were noted to have the strongest impact on acceptance amongst all the concerns about the use of civil drones. Secondly, those participants who were reported as already having personal experience with civil drones demonstrated a significantly higher percentage of noise concern. A similar finding was also reported in a different study [2] which polled members of the public in 2019 and 2022 about the challenges associated with the introduction of UASs. Between the two polling years noise nuisance was the only category that exhibited an increase, with all others showing a decrease. The findings of these surveys may suggest that noise nuisance is not yet considered to be as significant a problem in the eyes of the public owing to a lack of exposure.

Regardless, there are now several examples of UAS being used for parcel delivery direct to consumers in countries such as Australia, the United States of America and the Republic of Ireland. However, these commercial operations are still fairly rare and relatively small scale. In the UK, there are currently a number of trails taking place that demonstrate the positive impact UAS can have. For example, making use of drones to deliver medical supplies [3] to the Isle of Wight, reducing transport time from 4 hours to 30 minutes and delivering post to remote islands

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where transport is infrequent and can be severely disrupted by adverse weather conditions [4].

Whatever the purpose of the commercial use of UAS, in order to aid the planning and Environmental Impact Assessment (EIA) process, further research into the human response to the noise emissions from such vehicles is essential to aid the determination of suitable assessment metrics. Hence, this paper outlines how a listening experiment has been designed to investigate how participants respond to the noise from UAS and how this differs from other more well-known sources of noise such as road traffic, helicopters or conventional aircraft.

2. BACKGROUND

As UAS noise and its potential impacts on communities is still a relatively new consideration there is not the range of studies as what exists for other significant transportation or commercial noise sources. Nevertheless, there are a number of pioneering studies that have investigated a range of varied factors that might be significant in shaping our perception of UAS noise. All of these studies have concluded that perception may be significantly affected by factors other than broadband Sound Pressure Level (L_P).

When considering the characteristics of UAS noise, Figure 1, obtained from Torija & Clarke [5], presents the sound spectra of two conventional aircraft (737 Max 8 and Airbus A320), measured during departure from Heathrow Airport, approximately 900m from the end of the runway (approximate flight altitude of 435.2 +/- 57.4m), and two multi-copter drones (DJI Matric 200 and Yuneec Typhoon) measured during a flyover at 150ft (45.7m above ground). For comparison, the broadband level of all the sources have been normalized to 65 dB(A). What is clear is that the two drones have significantly more energy above 2 kHz than the conventional aircraft with energy continuing beyond 10 kHz. In contrast, the aircraft sound declines quickly above 2 kHz and is almost non-existent above 6 kHz. This observed reduction in high frequency content for conventional aircraft will in large part be a result of the atmospheric absorption and the larger separation distances between source and receiver. Gwak et al. [6] corroborates this observation by noting that one of the significant differences between the sound generated by conventional aircraft and drones is the amount of high frequency energy within the sound signature. This is also true when compared against noise from road traffic which peaks around the 1 kHz third octave band and quickly reduces above 1.6 kHz [7]. Another study by Torija & Nicholls [8] identified Sharpness, the Sound Quality Metric used to determine the ratio of high frequency content within a sound, as being significant to Perceived Annoyance.

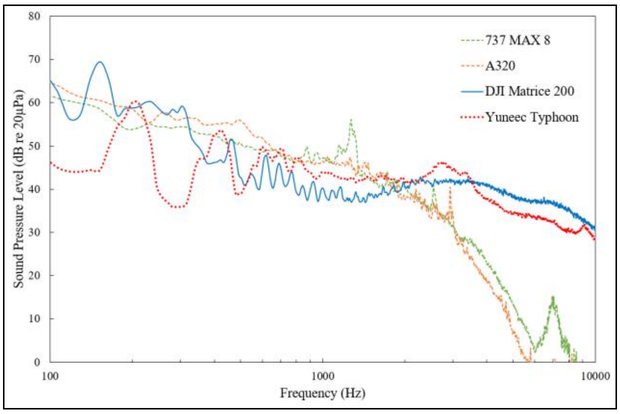

Figure 1. Frequency Spectra of two conventional aircraft (Airbus A320 and Boeing 737-8MAX) and two multi-copter drones (DJI M200 and Yuneec Typhoon). Frequency spectra normalized to 65 dB(A). Modified from [5].

Note. Figure 1 modified from "A Psychoacoustic Approach to Building Knowledge about Human Response to Noise of Unmanned Aerial Vehicles". Torija, A.J. and C. Clark. Int J Environ Res Public Health, 2021. 18(2). Copyright permission was granted by the author.

In terms of temporal characteristics, Christian & Cabell [9] found that when the sounds of UAS flyovers were presented at four different altitudes between 20 and 100m with all operational factors remaining constant, the Perceived Annoyance (*PAN*) only changed marginally even though there was a difference of 8 dB to the Sound Exposure Level (L_{AE}) between the playback levels. This lack of change to the perceived annoyance was attributed to the perception of the UAS loitering which resulted in the sound being judged more harshly.

All of the above highlight the significance of both the spectral and temporal characteristic of UAS noise to its perception. When designing the experiment it was considered important that these features were accurately presented to the participants.

In the initial design of the experiment the intention was to playback the UAS noise at noise levels at 5 dB intervals alongside a variety of different transportation sound sources. However, concerns we raised whether reproducing the UAS flyover audio in this way was representative of what receivers on the ground would actually be exposed to. Instead, it was thought that any changes to the UAS stimuli noise level should be representative of a change to the flightpath i.e. an increase in flyover altitude. Consequently, any change to noise level should consider changes to the temporal duration of the event, spectral balance of the sound that could be attributed to spherical spreading and atmospheric absorption and changes to the tonality associated with doppler shift. By processing the audio files in this way it was thought that more accurate data relating to *Perceived Annoyance* (*PAN*) and *Perceived Loudness* (*PL* might be collected.

The Acoustic Research Centre (ARC) completed two field measurement campaigns in August 2022 [10] and June 2023. In August 2022, measurements of four different UAS all flying at an altitude of 10 metres were collected using a 9-channel array that was set out perpendicular to the flight path on either side with microphones at 15° intervals (up to 60°). It was decided to use the measurements from two of these drones (DJI Matrice 300 and Yuneec 520e) as both of these UAS were capable of carrying a payload and could be representative of UAS which might be used for commercial applications. In June 2023, measurements of a larger commercial UAS with and without payload (mass 61.2 kg + 40 kg payload) were collected using the same microphone configuration. Additional audio recordings of UAS were also supplied by colleagues at the Civil Aviation Authority [11] and by the Volpe National Transportation Systems Centre [12] in the United States.

The experiment described within this paper was designed to assess the differences in human response between UAS flyover noise and other more familiar sources of noise such as conventional aircraft, helicopter and road traffic. This topic was selected to investigate the dose response of drone flyover noise compared to other more established sources of noise. This will in turn help to derive suitable criteria and metrics for the environmental noise assessment of commercial drone operations.

3. DESIGNING THE LISTENING EXPERIMENT

The objectives of the listening experiment were to investigate the following questions:

1. Develop an understanding of how *PAN* and *PL* vary between noise from familiar transportation noise source pass-bys or flyovers and UAS flyovers; and
2. By investigating the differences in annoyance between UAS and other vehicles with established dose response curves, can an indicative dose response curve for UAS flyover noise be proposed.

3.1 UAS Listening Experimental Methodology

During the design of the experiment, several approaches were researched and considered but two methodologies were eventually agreed upon. Part 1 of the experiment was designed to present each of the audio files, inclusive of the different noise sources, separately so that the questions *PAN* and *PL* could be answered individually. Part 2 presented the audio files in pairs, one test and one reference sound, in this case the test sound was the sound of a UAS flyover and the reference sound being another type of vehicle i.e. road traffic, aircraft or helicopter. The noise level of the test sound was then reproduced at various levels in order to collect participant response data relating to the probability that the test or reference stimuli was considered to be more annoying.

The method specified for Part 1 of the experiment, asking participants to rate sounds one by one without other ambient sound is the simplest method of conducting a listening experiment. However, there are several examples of this method being used to significant effect. Christian & Cabell [13] made use of this method in order to compare the *PAN* of UAS and road traffic vehicles. Through the use of regression analysis they were able to determine that an offset of -5.6 dB was required to the Sound Exposure Level (L_{AE}) for the UAS stimuli to be equally annoying as the road vehicles. This process of deriving a dB offset value or delta (Δ) is illustrated in Figure 2.

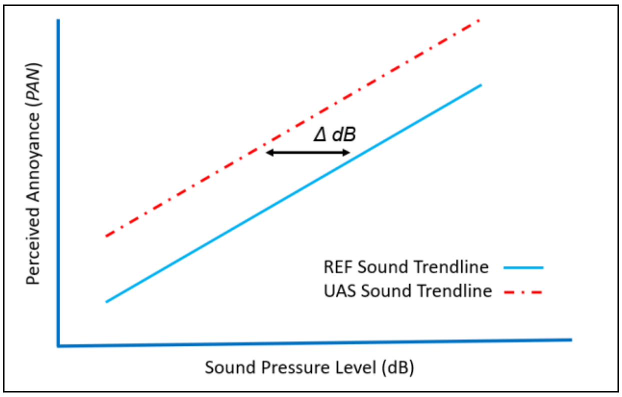

Figure 2. Illustration showing how the Δ dB value is derived from two trendlines summarising participant responses to two different sound sources.

Other studies including [8, 10] have followed a similar methodology but have varied the questions that are asked for each stimulus. For example, Torija & Nicholls [8] asked the participant to rate the *PAN*, *PL* and pitch relating to each of the stimuli. The interface for Part 1 of the experiment has been used previously by the Acoustics Research Centre [10]. This interface is designed to present the participant with a single audio file randomly selected from a bank sounds. The interface has a 'Play Sound' button, two 11-point sliders (0 to 10) one to rate the *PAN* and *PL*. The 11-point scale is commonly used for assessing annoyance with the typical focus being to quantify the % of participants who consider themselves to be 'highly annoyed', i.e. scoring 8 or higher. Figure 3 below shows the MATLAB interface used for the experiment.

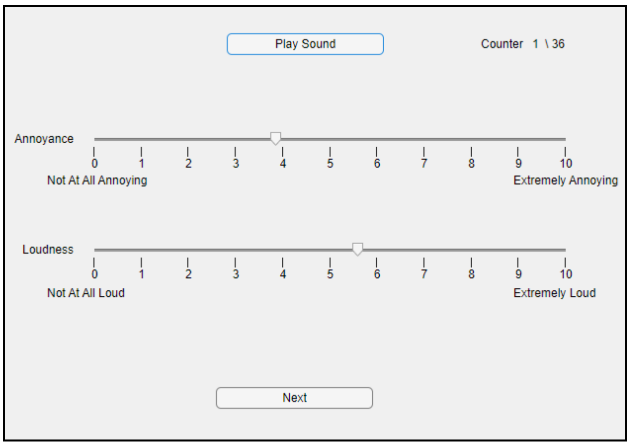

Figure 3. MATLAB Listening Experiment Interface: Part 1.

Whilst the limits of the 11-point scale are described subjectively in the interface above, the definition of the scale between the extents is less defined and could be subject to different interpretations depending on the participant. This could be addressed by including additional subjective descriptions along the scale such as those recommended by Fields et al. [14] who suggests an easy to understand scale which can be converted to a numerical scale for statical analysis. An example of this scale is presented within **Figure 4**.

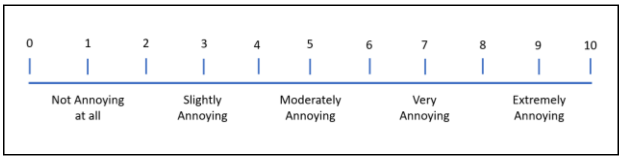

Figure 4. Example of Subjective Descriptions to supplement/replace the 11-point scale. Modified from similar scale used in [15].

For Part 2, the selected methodology has previously been applied in research into the perception of Urban Air Mobility (UAM) [16] and helicopter noise [17]. In the aforementioned experiment investigating UAM noise both the test and reference sounds were auralisations created using the NASA Auralisation Framework (NAF). The test sound was created to be representative of noise from a potential UAM vehicle whereas the reference sound had many of the temporal features removed by excluding the thickness, loading and modulation of the broadband self-noise from the auralised sounds. Thus, creating what was considered to be a bland noise with fewer noteworthy features. By varying the Loudness (N_5) of the test sound it was possible to derive the probability of either the test or reference sound being considered more annoying.

For this experiment it was possible to identify a number of significant relationships between the stimuli. For example, at equal Loudness the test sound was found to be more annoying than the reference sound by 73% of participants. The equal annoyance point, where 50% of participants found either the test or reference sound more annoying, was achieved with a reference stimuli Loudness of 9.3 sones and a test stimulus of 6 sones. This equated to a difference of approximately 6.3 dB in the Sound Pressure Level between the two sounds and is a strong indication that the temporal characteristics were a significant influence on participant response within this scenario. **Figure 5** presents an example set of results for a probability of annoyance experiment. The green circle denotes the probability of annoyance when both sounds are played at the same Sound Exposure Level (L_{AE}), the red cross denotes the L_{AE} of the test sound required so the % of participants found both the test and reference sounds equally annoying.

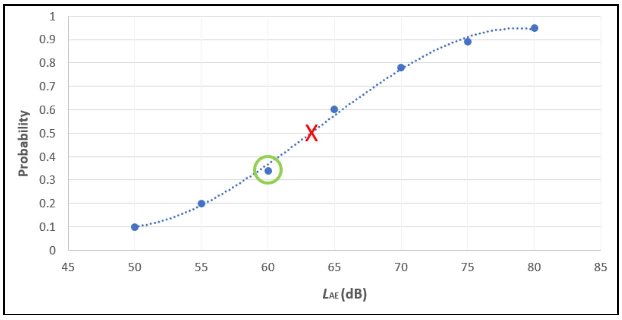

Figure 5. Example Illustration of Probability that the reference sound is more annoying than test sound. X-axis denoting the varying Loudness of the Test Sound, Y-axis denoting the probability of the Test sound being considered more annoying than the Reference sound.

By employing this approach to the design of this listening experiment, it is possible to compare several test sounds i.e. UAS against multiple reference sounds i.e. road, aircraft or helicopter sounds, reproduced at varying loudness in order to investigate the relationships in response between the different types of sound source. However, instead of using Loudness measured in sones as the metric for varying the level of the test sound, the L_{AE} has instead been used to be more easily relatable to typical environmental noise impact assessment metrics and compare the overall sound energy of the flyover or pass by event.

3.2 Audio Reproduction Apparatus

Previous listening experiments into the perception of UAS noise at the Acoustics Research Centre have chosen to use headphones as the audio reproduction apparatus. However, this experiment was conducted within the 'audio booth' at the Acoustic Research Centre. The audio booth consists of a 3-dimensional loudspeaker array with the setup consisting of 16 Genelec 8030A loudspeakers; 8 loudspeakers are located in the horizontal plane (positioned at azimuths ; ±45° ; ±90° ; ±135° ; +180°), 4 loudspeakers at ±39° elevation (positioned at azimuths ±45° ; ±135°), and 4 loudspeakers at -39° elevation (positioned at azimuths ±45° ; ±135°). The loudspeakers in the horizontal plane are at a distance of 1.26 m from the centre of the array, whereas the loudspeakers at ±30° elevation are at a distance of 1.54 m from the centre of the array. By making use of the 3-Dimensional loudspeaker array it will be possible to accurately spatialize the UAS and other airborne noise sources relative to the listener position. Figure 6 shows the audio booth at the ARC.

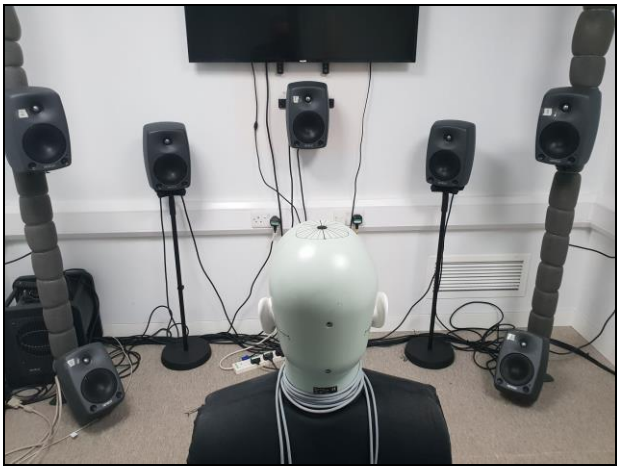

Figure 6. Picture of the ARC Audio Booth.

4. CONCLUSIONS

This paper set out to highlight some recent and significant listening experiments exploring the response to UAS noise and how these experiments influenced the design of this current experiment. As the focus for this experiment was to further investigate the dose response relationships between UAS flyovers and other sources of noise, two methodologies were identified for use within the experiment.

Part 1 of the experiment presented each of the sounds individually to the participant and provided them within an opportunity to give a perceived annoyance and loudness rating for each of the sounds. This approach was selected as: it is an established method for designing listening experiments, its simplicity in experimental design and ease of user interface for the participant. The experimental results are being used to determine the dose response relationships between the different sound sources including the % of participants who are 'highly annoyed' and the differences in loudness (Δ dB) that are required to result in the same annoyance rating.

Part 2 will give the participant an opportunity to directly compare two sounds, one reference and one test, multiple times with the loudness of the test sound being varied. The purpose of this experiment is to understand the specific relationship between annoyance and loudness of two sources and enables another method of exploring the Δ dB required to achieve equal annoyance. By structuring the experiment in this way it is possible to derive specific relationships between two sources of noise which may help determine penalties / allowances that need to be applied to UAS noise assessment metrics when compared against other more familiar sources of noise.

It is hoped that this paper highlights need for careful planning of the experimental design as this is pivotal to investigating the specific research question and obtaining the desired participant response information.

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6. REFERENCES

1. Eißfeldt, H. and M. Biella, *The public acceptance of drones–Challenges for advanced aerial mobility (AAM).* Transportation Research Procedia, 2022. **66**: p. 80-88.
2. VUL, *Was denken die Deutschen über unbemannte Luftfahrt*, V.U. Luftfahrt, Editor. 2022.
3. Trust, I.o.W.N. *World's First Chemo Drone Delivery Announced on NHS Birthday*. 2022; Available from: https://www.iow.nhs.uk/news/Worlds-First-Chemo-Drone-Delivery-Announced-on-NHS-Birthday.htm#:~:text=Drones%20will%20cut%20the%20usual,for%20treatment%20at%20the%20moment.
4. BBC. *Drones used to deliver post to remote Orkney island*. 2021; Available from: https://www.bbc.co.uk/news/uk-scotland-north-east-orkney-shetland-58792064.
5. Torija, A.J. and C. Clark, *A Psychoacoustic Approach to Building Knowledge about Human Response to Noise of Unmanned Aerial Vehicles.* Int J Environ Res Public Health, 2021. **18**(2).
6. Gwak, D.Y., D. Han, and S. Lee, *Sound quality factors influencing annoyance from hovering UAV.* Journal of Sound and Vibration, 2020. **489**.
7. Gjestland, T., *Background noise levels in Europe.* 2008.
8. Torija, A.J. and R.K. Nicholls, *Investigation of Metrics for Assessing Human Response to Drone Noise.* Int J Environ Res Public Health, 2022. **19**(6).
9. Christian, A.W. and R. Cabell, *Initial Investigation into the Psychoacoustic Properties of Small Unmanned Aerial System Noise*, in *23rd AIAA/CEAS Aeroacoustics Conference*. 2017.
10. Green, N., C. Ramos-Romero, and A.T. Martinez, *Advances in the Measurement and Human Response to Noise of Unmanned Aircraft Systems*. 2023, SAE Technical Paper.
11. CAA, *Noise measurements from eVTOL aircraft (CAP 2506)*. 2023.
12. Read, D.R., et al., *Noise Measurement Report: Unconventional Aircraft-Choctaw Nation of Oklahoma: July 2019*. 2020, John A. Volpe National Transportation Systems Center (US).
13. Christian, A.W. and R. Cabell. *Initial investigation into the psychoacoustic properties of small unmanned aerial system noise*. in *23rd AIAA/CEAS aeroacoustics conference*. 2017.
14. Fields, J.M., et al., *Standardized general-purpose noise reaction questions for community noise surveys: Research and a recommendation.* Journal of sound and vibration, 2001. **242**(4): p. 641-679.
15. Krishnamurthy, S. *Remote Psychoacoustic Test to Gauge Feasibility of Remote Urban Air Mobility Noise Testing*. in *Spring 2023 NASA Acoustics Technical Working Group and UAM Noise Working Group Meetings*. 2023.
16. Boucher, M., et al., *A Psychoacoustic Test for Urban Air Mobility Vehicle Sound Quality*. 2023, SAE Technical Paper.
17. Boucher, M.A., et al. *A perceptual evaluation of the efficacy of Sound Exposure Level in the*

rating of annoyance to helicopter noise. in *Vertical Flight Society Forum 76*. 2020.