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Advances in the Measurement and Human Response to Noise of Unmanned Aircraft Systems

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Abstract

The sound produced by Unmanned Aerial Systems (known as UAS or Drones) is often considered to be one of the main barriers (alongside privacy and safety concerns) preventing the widespread use of these vehicles in environments where they may be in close proximity to the general public. To better understand the potential environmental noise impact of commercial UAS operations, work undertaken by the University of Salford has focused on two key areas. Firstly, how to characterise and measure the sound produced by UAS during outdoor flight conditions and secondly, better understanding of the dose response of UAS noise when the listener is in either an indoor or outdoor environment. The paper describes a field measurement campaign undertaken to measure several UAS performing flyovers at different speeds and take-off weights. The methodology of the measurement campaign was strongly influenced by emerging guidance and has been used to calculate the directivity of sound propagation which may be of significant benefit when modelling environmental noise impacts. This paper also presents details of a listening experiment designed to investigate the subjective response to a number of UAS operations when the listener is simulated to be either in an indoor or outdoor position. The results of the listening experiment have been analysed using linear regression analysis to understand which 'loudness' metric either conventional (L_{Aeq}, L_{ASmax} or L_{AE}) or more specialised loudness metrics such as Loudness (N_5), Perceived Noise Level (PNL) or Effective Perceived Noise Level (EPNL) are most appropriate for estimating perceived 'loudness' and 'annoyance'. The results of this experiment indicate that both L_{Aeq}, L_{ASmax} were equally good at predicting the perceived loudness and annoyance with an Adjusted R Squared value of 0.90 and 0.93 for loudness and annoyance respectively. Loudness metric performed marginally better with adjusted R Squared values of 0.96 and 0.90 for annoyance and loudness respectively.

Introduction

The use of Unmanned Aerial Systems (UAS or Drones) has increased dramatically of the past couple of years with numerous commercial industries making greater use of the technology. The benefits of using UAS within some industrial sectors such as offshore oil and gas, emergency response and infrastructure inspections are evident. The use of an UAS in these situations replace the need for a person to carry out a dangerous task, to provide a swift response to an emergency situation and/or operate away from human populations resulting in a lesser risk of adverse impacts. However, the justification for UAS for other tasks such as parcel delivery are more difficult in part as a result of potential adverse noise effects on individuals and communities.

There are now a few 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 order to aid the commercial planning and Environmental Impact Assessment (EIA) process, further research into noise emission, propagation and directivity which could be included within environmental noise propagation models and suitable assessment metrics to determine significance of effect on sensitive receptors is essential. Research into measurement, outdoor noise propagation and suitable assessment metrics has been undertaken through a field measurement campaign, which made use of a 9-channel microphone array to measure noise simultaneously at multiple angles along the lateral plane during flyover operations. A listening experiment has been designed to investigate perceived annoyance and loudness of different UAS and operations when the listener position is either outside or indoors. This paper presents an overview of the methodology for both the field measurement campaign, the listening experiment and preliminary results and analysis from both pieces of research.

Field Measurements

Site Information and Weather Conditions

A field measurement campaign was undertaken in August 2022 near to the village of Edzell, Angus, Scotland. The site was identified with the help of colleagues at *DTL Drone Technologies* and the *Dalhousie Estate* who own and maintain the land. The field used for the measurements was agricultural land that had been recently harvested but no new crop had yet been planted making the ground soft.

Figure 1. Satellite imagery showing measurement location. Blue dots indicate microphone array (centre point and outer limits), yellow dots the UAV flight path, green dot the meteorological station and orange where background measurements were taken

Apart from infrequent road traffic vehicles and a single aircraft flyover, specific sources of ambient noise were few and nondescript. Ambient noise levels were measured prior to the measurements and at regular intervals throughout the day and were measured to be approximately 35 dB L_{Aeq} throughout the measurement period. These ambient levels were considered to be sufficiently low to obtain a good signal-to-noise ratio between the background and flyover noise levels.

All measurements were carried out within a single day with meteorological conditions being favourable for acoustic measurements. Meteorological conditions were monitored using a weather station mounted on a 10m mast which allowed the monitoring of conditions at the UAS flight altitude. Throughout the measurement period, air temperature ranged from 13 – 16 °C (55 – 61 °F) with average wind speeds generally between 0 – 6 m/s and a prevailing wind direction from the southeast. A second weather station was set up at a height of 6m, the purpose of this weather station was to measure the difference in wind speed between the two heights to enable a wind shear coefficient (wind shear is the difference in wind speed at different altitudes, typically wind speed decreases closer to the ground) to be calculated. Unfortunately, the second weather station did not record owing to a battery failure so a wind shear coefficient could not be calculated.

Vehicle and Operational Information

All of the UAS measured were supplied and operated by a qualified drone pilot from the Edinburgh Drone Company. All of these UAS were flown manually by the pilot, fluorescent cones were laid out along the flight path to help the pilot maintain a straight line and cross the microphone array over the central microphone position. Unfortunately, it was not possible to obtain GPS or other positioning data from the UAS that could be synchronised with the acoustic measurement data. Instead, the UAS position along the flight path was calculated using the known flight speed and assuming the position where the UAS is directly above the microphone array. The lack of positioning data may have reduced accuracy of the UAS position and will in turn add uncertainty to the directivity plots. However, this is something that is being addressed for future measurement campaigns.

A total of four UAS were measured, these UAS ranged from small recreational ‘hobbyist’ camera vehicle to professional camera vehicles that were able to carry a payload. All of the measured UAS were of the ‘multi-copter’ design and had between four and six downward facing propellers as opposed to a fixed wing aircraft style. Details of the four UAS that were measured are presented in Table 1.

Table 1. Details of the UAS and Operating Speeds

Models	**Number of rotors**	**UAS Weight (g)**	**Payload weight (g)**	**Speed (m/s)**	
				Fast	**Slow**
DJI Matrice 300 (M3)	4	6300	930	15.0	5.0
Yuneec H520E (Yn)	6	1633	350	13.5	5.0
DJI First Person View (Fp)	4	795	-	27.0	15.0
DJI Mini Pro 3 (3p)	4	249	-	15.0	5.0

For the flyover measurements, a flyover altitude of 10 m was selected to ensure a good signal-to-noise ratio for the smaller UAS that were being measured and so meteorological conditions could be monitored at the flight altitude. Flyover operations were repeated a minimum of 6 times per vehicle flight speed and whether the UAS departed from the east or west so the influence of wind direction on both noise emissions and propagation could be considered. By having a large number of repeated measurements, exclusions could be made owing to the influence of other sources of noise that were not identified during the measurements whilst maintaining a reasonable number of samples to analyse and average across.

Microphone Array

To aid with the measurement of sound propagation directivity from the UAS, a microphone array consisting of 9 microphones was arranged on ground plates perpendicular to the flight path in an inverted tripod position (as described in Section 4.4.1 of ICAO Annex 16 – Volume 1: Aircraft Noise [1]). A small windshield was attached to each of the microphones to reduce the risk of wind interfering with the microphone diaphragm. The microphones were positioned with a central microphone underneath the flightpath and four microphones either side at 15-degree intervals up to a lateral angle of 60-degrees. With a flight altitude of 10m above ground, Table 2 presents the lateral distances between the central microphone (0°) underneath the flight path and the other microphones in the array.

Table 2. Lateral distances required for each microphone position from the centre microphone

Height above Ground (m)	**Lateral Distance (m) required for each Microphone Angle (Θ °)**				
	0°	15°	30°	45°	60°
10	0.00	2.68	5.77	10.00	17.32

Figure 2. Inverted microphone tripod, mounted onto ground plate with wind shield

This microphone configuration was selected to conform with emerging guidance presented within the Standard 'ISO/CD 5305 – Noise Measurements for UAS' [2] and the '*Urban Air Mobility Noise Working Group (UNWG) Subgroup 2 – Test Measurement Protocol*' [3] documents. By setting up the microphone array in this configuration it is possible to reconstruct both the 2D and 3D hemispherical directionality of the UAS flyover using data from the microphone array recorded on the approach and departure of the UAS then correcting the recorded sound pressures to a standardised distance and factoring in corrections for atmospheric and meteorological conditions. Figures 3 and 4 illustrate the microphone spacing and ground plate configuration used within the measurement campaign.

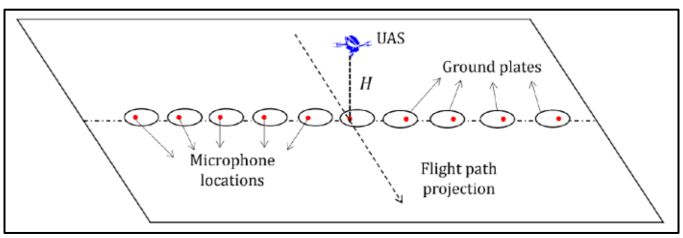

Figure 3. Schematic showing the microphone orientation and positions relative to the UAS flight path [2]

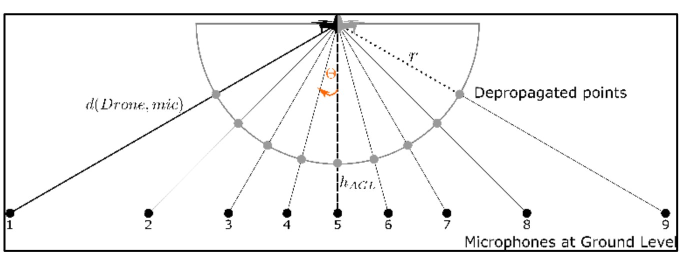

Figure 4. Ground microphone positions for lateral directivity resolution and depropagated points, illustrating how de-propagated drone noise distances will be defined

A tenth microphone was positioned underneath the flight path (above the central ground plate microphone) but mounted on a tripod at a height of 1.2m above ground level. The audio data from the 10-channels were all measured using a Dewesoft SIRIUS Modular Data Acquisition System (DAQ) with the data stored directly onto a laptop hard drive. An additional ambisonic microphone was set up underneath the flight path, approximately 5m from the 10-channel microphone array at a height of 1.2m above ground. A Brüel & Kjær Type 2250 Sound Level Meter was also set up at this position to measure acoustic energy. The purpose of the two tripod mounted audio recorders was to record audio suitable for use within future listening experiments and the data will not be used to determine directivity of the UAS noise.

A second 9-channel microphone array was organised by Hayes Mckenzie, an Acoustic Consultancy in the UK who were partners on the measurement campaign. Whilst the positioning of this second array along the lateral plane was the same as the first array, instead of mounting the microphones onto the ground plate using the inverted tripod position, these microphones were set up in the 'lying on plate' position where the microphone is laid flat against the ground plate with the diaphragm at a 90°-degree angle to the ground plate. Whilst this microphone configuration is not recommended within the ISO or UNWG documents, it is generally considered to be relatively flat and exhibit good agreement with either inverted tripod or flush mounting up to around 4 kHz [4]. The data collected from this microphone array has not been analysed by the University of Salford but there is the possibility in the future to compare the results of the two microphone arrays. Figures 5 and 6 show the measurement equipment and set up used for the measurements.

Figure 5. Photograph of the measurement set up. Left: 10m Meteorological mast, Centre right: Ambisonic microphone position Right: ground plate microphone array

Figure 6. Photograph of the measurement set up recording measurements of the DJI Matrice 300 (M3)

Results

For the initial analysis of the data, the two metrics that the study has focused upon are the L_{Amax} to quantify the maximum instantaneous sound associated with a flyover event. Sound Exposure Level (L_{AE}), used to quantify the portion of the flyover event between the peak noise level and 10 dB down on either side, used to better understand the total sound energy associated with a flyover event. These two metrics are both considered useful as there is not yet a consensus on how UAS noise will be assessed from an environmental impact perspective. Should an event-based criteria be assumed it will likely be based upon a number of exceedances over an L_{Amax} criterion during a time-period (for example, 23:00 – 07:00 hours during the night to avoid sleep disturbance). Should criteria that requires noise to be averaged over a time period be adopted such as $L_{Aeq,8hr}$ then the L_{AE} associated with each event will be of more value. For conciseness, the figures published within this paper present the L_{Amax} results from the measurements.

Figure 7 presents the L_{Amax} data collected from the centre microphone within the array for each of the UAS at different flight speeds. For the box and whisker plots shown in Figures 7 and 8, the 'box' illustrates the range of data between the lower and upper quartiles (25 – 75%) and the 'whiskers' denote the upper and lower limits (0 – 100%).

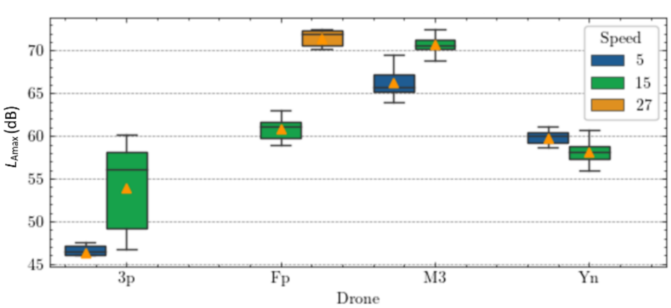

Figure 7. L_{Amax} measured at centre microphone for each of the four UAS and flight speeds (m/s)

It can be seen that three of the four UAS, the DJI Mini Pro 3 (3p), DJI FPV (Fp) and the DJI Matrice 300 (M3) all exhibit an increase to the measured L_{Amax} as flight speed increases. However, the Yuneec H520e appeared to show the opposite with L_{Amax} noise levels decreasing by approximately 2 dB between 5 and 15 m/s.Whilst the reduction in noise as the flight speed increases is fairly small it is unusual as the data does not show the same trend observed in the other UAS. The exact reason for this is unknown but it is thought that perhaps the increase in RPM is being offset by some secondary factor such as rotor-rotor interaction which is potentially more significant in the Yuneec H520e with it being the only UAS that was measured with more than four propellers. The spectral data around the blade passing frequencies will be analysed to determine the change in RPM between the two flight speeds to understand how this is contributing to the overall measured noise levels.

The M3 was generally measured to be the loudest UAS with an L_{Amax} median value of 66 dB at 5 m/s and 71 dB at 15 m/s when measured directly under the flightpath at a distance of 10 metres. This was expected as the M3 was the largest and heaviest UAS that was measured within the campaign. However, the Fp when flying at its top speed of 27 m/s was the single loudest UAS / flight speed scenario with a median L_{Amax} of 72 dB, this is likely a result of the very high RPM of the propellers required to operate at this speed. For the calculated L_{AE} values, M3 was found to be the highest at 71.0 dB at 5 m/s, 71.2 dB at 15 m/s. The Fp at 27 m/s was slightly below these values at 68.8 dB. It should be noted that none of the other UAS were able to be measured at 27 m/s to compare with the Fp as they could not achieve this flight speed.

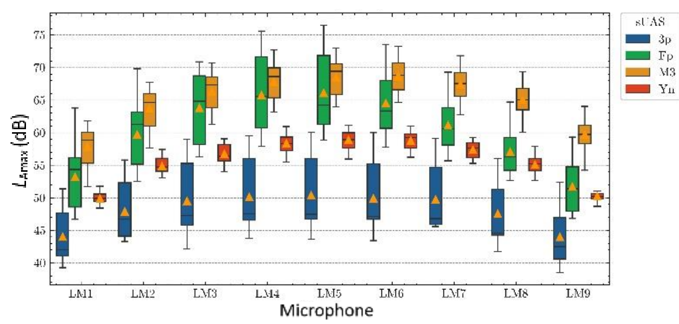

Figure 8. L_{Amax} data measured at each of the microphone positions for each of the four UAS

Figure 8 shows L_{Amax} data collected at each of the microphone positions when the UAS was directly above the microphone array. As can be seen, the median L_{Amax} noise levels measured along the microphone array tend to vary between 5 and 15 dB, with the 3p showing the least variation and the Fp exhibiting the most variation along the array.

The box and whisker plots show that greater variation in the noise levels were recorded for the Fp and the 3p, illustrated by the wider boxes (lower and upper quartiles) and whiskers (lower and upper extremes). This is likely a result of these being the two smallest and lightest UAS measured making them more difficult to pilot and susceptible to relatively minor gusts of wind which could move them away from the centreline position and require a greater degree of stabilisation. The M3 exhibited the most consistent noise level along the microphone array, with the range between the lower and upper quartile of data collected at each of the microphone positions showing to generally be within 2 dB.

Considering the data for the M3 as presented within Figure 8 in more detail, the data from each microphone position can be backpropagated to a distance of 1m from the drone by taking into consideration spherical spreading and atmospheric absorption effects.

The results of the 2D directivity along the lateral angle of the measurement array when corrected to a distance of 1m are presented in Figure 8.

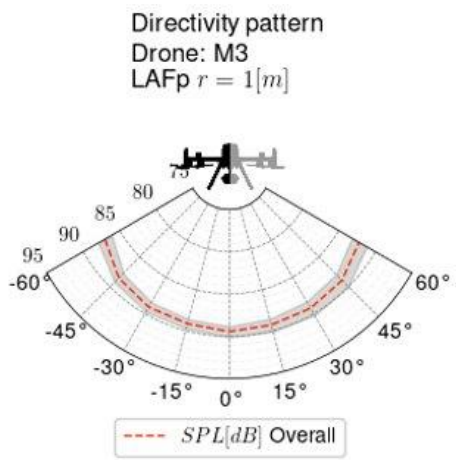

Figure 9. 2D directivity data of the broadband sound pressure level from the Matrice 300 (M3) backpropagated to 1m distance from the UAS

As Figure 9 shows, noise levels directly underneath the drone are highest with broadband A-weighted sound pressure levels approximately 2 dB higher than levels at the 60° angle. Work is continuing into the analysis of the collected data to investigate whether significant characteristics of the sound such as the tonal elements associated with the blade passing frequencies exhibit a similar directivity pattern. It is also intended to expand the directivity modelling from 2D to 3D by analysing the measured sound pressure levels on the approach to and departure from the microphone array.

Gathered data during this measurement campaign will allow psychoacoustic assessment of UAS noise under different operating conditions. Current efforts are focused on the post-processing of acoustic data measured for input into auralisation tools (e.g., NASA Auralization Framework and in-house auralisation framework for VR environments) to simulate and assess noise from UAS operations. Gathered sounds will also be used for listening experiments, where sample sounds of different UAS and operating conditions are assessed by a series of human participants.

Listening Experiment

Experiment Design (Preparation)

This listening experiment was designed to assess the perceived annoyance (*PA*) and loudness (*PL*) of drones performing different operations when the listener position is either outside or indoors with a window partially open or closed. The intention of this research was to determine whether particular operations are considered to be more annoying than others and the extent to which the listener position effects the perceived annoyance and response. The listening experiment was delivered via headphones using audio data provided by the Volpe National Transportation Systems Centre [5] .

The listening experiment methodology and data collection procedures were presented to and granted approval by the University of Salford's ethics committee. The grounds of this approval were granted based on the participants being treated correctly in terms of transparency of the experiment, that participant safety will be of upmost importance (e.g. will not be exposed to excessively loud sounds) and consent of the participant is explicitly obtained but could be revoked by the participant at any time without reason. Subject privacy was also of critical important with any sensitive information being collected and stored in line with General Data Protection Regulation (GDPR).

UAS Noise Audio Database

The database includes recordings of three types of small rotorcraft performing different flying operations, four operations were included within this experiment (hovering, fast flyover [15 m/s], take-off and landing). Table 3 presents the specifications of the UAS within the database that were used in this experiment.

Table 3. Specifications of the UAS used within the Listening Experiment

Multirotor Aircraft Models	Number of rotors	UAS Weight (kg)	MTOW* (kg)
Gryphon Dynamics GD28X	8 (4 contra-rotating pairs)	24.9	31.7
DJI M200	4	4.0	6.1
Yuneec Typhoon	6	1.9	2.4

For these field measurements, the microphone was mounted on a tripod at 1.2m above ground. For flyover operations, the microphone was positioned directly underneath the flightpath with the UAS operating at an altitude of 150 feet above the ground (~47.5m). For take-off measurements, the UAS flew to an altitude of 150 feet with a vertical ascent, then proceeded to move away from the measurement position until barely audible, the landing measurements followed the same process but in reverse. For hover measurements, the drone hovered at an altitude of 4 feet (1.2m) above the ground, held the position for 30 seconds and then rotated 90 degrees. For the take-off, landing and hover measurements the distance between the microphone and take-off/landing point was 30 feet (9.1m) from the microphone position.

Sound Reduction through Building Façade

To simulate the sound reduction through an external building façade, with either a partially open or closed window, test data was obtained from the document titled '*NANR116: Sound Insulation Through Ventilated Domestic Windows*' [6] and applied to the audio files. This document contains measured data of multiple different window configurations tested with multiple opening arrangements (free areas). The measurements presented within NANR116 are laboratory measurements but the receive room was designed to approximate a typical residential living room in terms of room dimensions and reverberation time. Therefore, the sound reduction values are presented within the document are the *Apparent Sound Reduction* (*R'*) values meaning the sound reduction performance is inclusive of reverberation time within the receive room. For this reason, no additional reverberation was applied to the audio files during the processing phase.

The sound reduction data used was collected by testing a typical double glazing window configuration. The partially-open scenario had a free area of 0.05 m^2, this free area was selected as the weighted apparent sound reduction value (R'_w) of 12 dB is consistent with guidance in documents such as *British Standard 8233:2014* [7] or '*Professional Practice Guidance on Planning & Noise*' (ProPG) [8] which state that transmission loss through a residential open window is typically between 10 – 15 dB.

When testing the sound reduction performance it is typical to only present data in third octave bands between 50 Hz and 5 kHz. For third-octave bands below 50Hz, the same values as the 50 Hz third octave band were applied as analysis of the UAS frequency content indicates they were not producing any significant levels of sound within this frequency range. For frequencies above 5 kHz, for the partially open window the average of the previous three third octave bands (3.15, 4 and 5 kHz) were calculated and applied to all third octave bands up to 20 kHz. For the closed window, it was assumed that the mass law would dictate the sound reduction performance over 5 kHz which assumes a 6dB increase in performance per octave. Therefore, a 2 dB increase to performance was assumed per third-octave above 5 kHz. Figures 10 and 11 present the third-octave sound reduction performance for both the window closed and partially open scenarios.

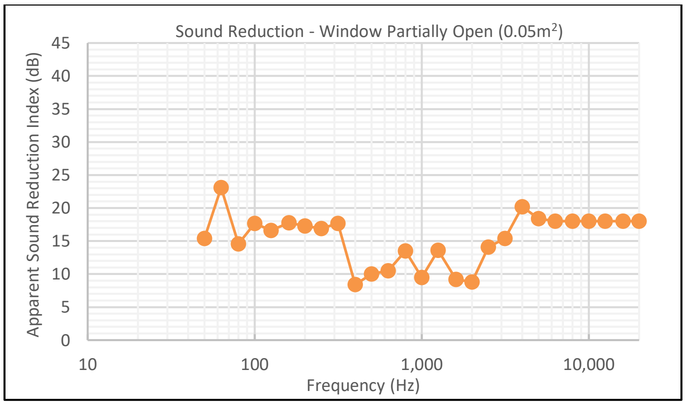

Figure 10. Third Octave Sound Reduction Values – Partially Open Window

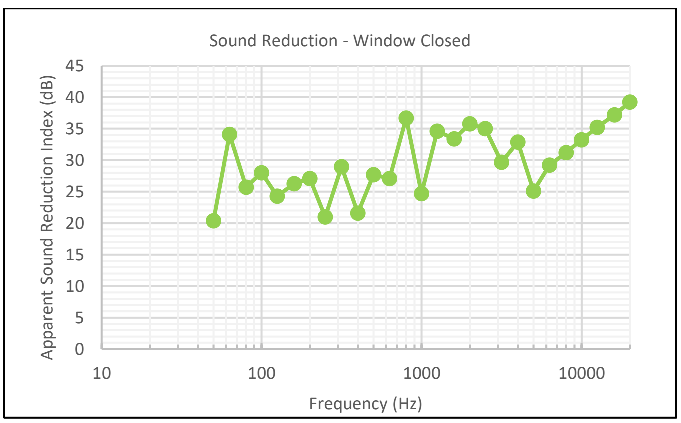

Figure 11. Third Octave Sound Reduction Values – Closed Window

Audio Reproduction System, Listening Room and Calibration

The experiment and calibration were both conducted within the 'Listening Room' at the University of Salford. This room is acoustically treated to reduce both reverberation and ambient sound levels with the L_{Aeq} value being measured as being between 20 – 22 dB.

The audio reproduction system used for the experiment was a laptop with Matlab software, external sound card (Motu 4Pre – Audio Interface), Headphone Amplifier (Little Labs 'Monotor') and headphones (Bayer Dynamic DT 1990 Pro). The equipment used for the calibration of the audio files and listening experiment set-up included a Brüel & Kjær 2250 Class 1 Sound Level Meter (SLM) and Brüel & Kjær Artificial Ear Type 4153.

Figure 12. Sound Level Meter and Artificial Ear Being Used for Calibration

The calibrated L_{Aeq} and L_{ASmax} noise levels of the 36 audio files (12 audio files for each simulated listener position) used within the listening experiment ranged between 26.0 – 76.3 dB and 24.3 – 75.4 dB for the L_{ASmax} and L_{Aeq} respectively. The wide range of sound levels were meant to simulate the actual level of noise that would be experienced by the listener in each of the indoor / outdoor listening positions.

Participants, Questionnaire and Interface

Initially, 31 participants took part within the experiment. However, due to an error with the data collection for one of the participants their results were excluded from the analysis. Therefore, the final number of participants was 30. Some basic demographical information was collected from the participants which showed that the participant pool was quite strongly weighted towards male participants (73%) and the majority of participants were either in the age range of 18 – 24 (37%) or 25 – 34 (30%) although participants from other age ranges up to 55 – 64 (3%) were also recorded. Three (10%) of the participants did self-identify as having a hearing impairment but all reported these were relatively minor and did not interfere with their daily lives. Therefore, they were allowed to participate within the experiment.

Prior to commencing the experiment, participants were provided with a brief overview of the task, interface and format of the experiment which did not specifically state the source of the sound or that filtering had been applied to estimate transmission through a window. Once the participants had been given time to read the instructions and ask questions they put on the headphones and were presented with 4 'familiarisation sounds', these sounds were not used within the main experiment but were selected as they highlighted the range of sounds the participant would be listening to throughout the experiment. Participants were able to replay the sounds if they wanted, once the participant had listened to each of these sounds, they were given one more opportunity to ask questions before the experiment began.

The listening experiment interface was created within Matlab (Version R2022a). The interface of the experiment presented the participant with a single audio file randomly selected from the 36 files. The interface had a 'Play Sound' button, two 11-point sliders (0 to 10) one to rate the 'Annoyance' and the other to rate the 'Loudness'. Figure 13 below shows the Matlab interface used for the experiment.

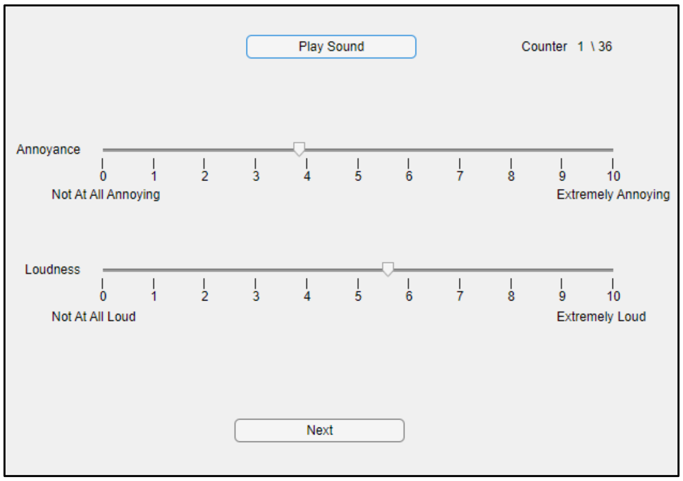

Figure 13. Listening Experiment Interface – Created in Matlab

Results

Participant Responses

Figures 14 and 15 present the participant response data for Perceived Annoyance (*PA*) and Perceived Loudness (*PL*) separated by the Listener Response position.

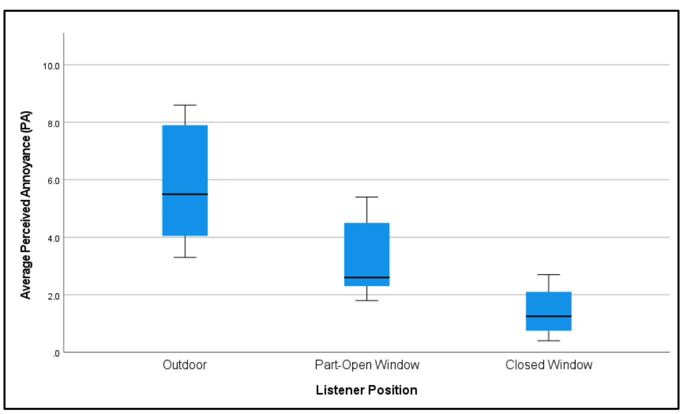

Figure 14. Participant Responses for Perceived Annoyance separated by listener position

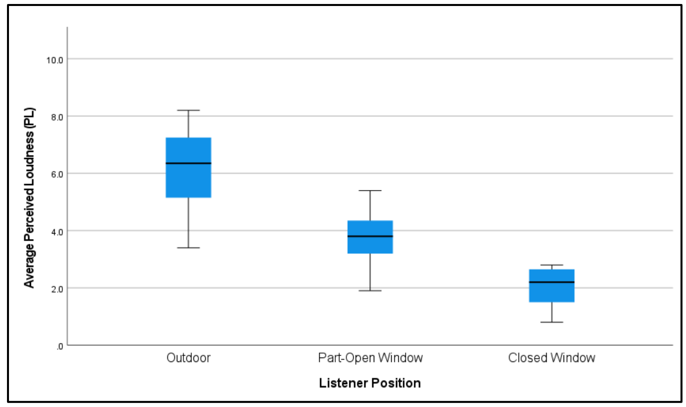

Figure 15. Participant Responses for Perceived Loudness separated by UAS type

The participant responses show a clear trend for both *PA* and *PL* with responses being the highest (i.e., most annoying and loudest) when in the outdoor position followed by indoors 'part-open' window then the 'closed window' scenario. This was expected as the filtering applied to simulate the indoor listening positions reduced the overall noise level of the stimuli, so the participant responses follow the same trend as the loudness of the audio files. One interesting trend to note is that the range of responses per listening position are wider for perceived annoyance than they are for loudness. This would suggest that the responses to the stimuli were not as consistent for annoyance as they were for loudness.

Whilst the data presented in Figures 14 and 15 show a clear trend based upon the Listener Position, the data is currently grouping all UAS and operations into the participant responses by listener position. Figures 16 and 17 show the same data set but separated by both listener position and UAS operation.

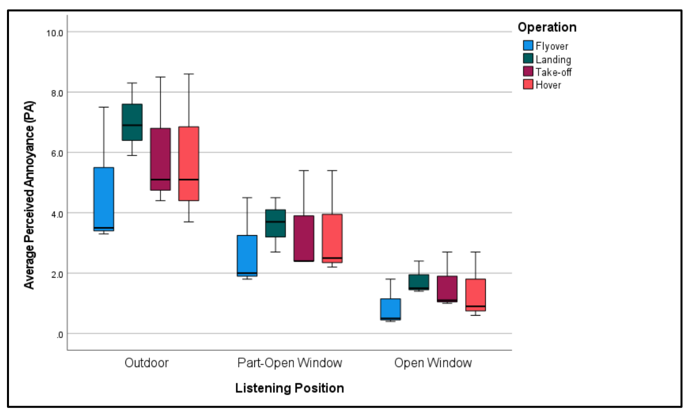

Figure 16. Participant Responses – Annoyance as a function of UAS operation

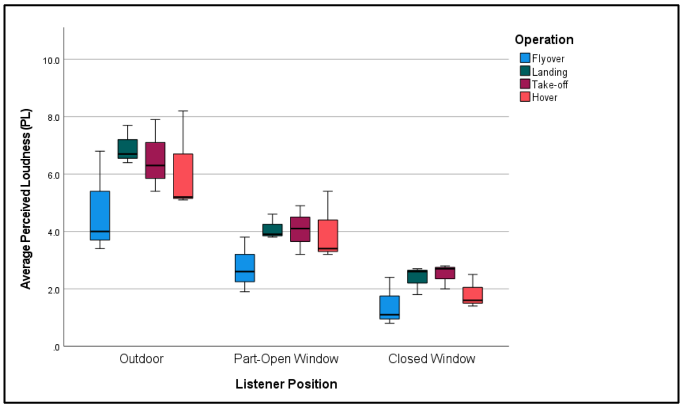

Figure 17. Participant Responses – Loudness as a function of UAS operation

Similar to the above, the same trend as Figures 14 and 15 in terms of the *PA* and *PL* are clear in Figures 16 and 17. However, when separating the data by operation other trends begins to appear. For *PA* the landing operation is consistently perceived to be the most annoying, followed by either take-off or hover with the 'flyover being the perceived to be the least annoying. For *PL,* similar trends are observed for the outdoor Listener Position but for the indoor (part-open window) and indoor (window closed) scenarios the responses to the landing and take-off stimuli are much closer with the median *PL* of the take-off operation being perceived as slightly louder.

The collected participant response data would indicate that overall, the operation which elicited the strongest responses in terms of *PA* is the landing operation, for *PL* the responses to take-off and landing are very close with landing perceived to be louder when outdoors but take-off perceived as louder when simulated in the two indoor positions. For both *PA* and *PL* the flyover operation was consistently scored the lower across all listener positions. However, as the sound levels of the audio files were not standardised between operations, some of these variations within the participant responses are likely a result of changes to noise levels. For example, the difference between the L_{ASmax} for the flyover and hover operations of the GD28X drone when the listener is in the 'Outdoor' position were +6.0 dB for the hover. Therefore, it is not entirely clear at this stage whether the increased *PA* and *PL* resulted from the characteristics of the operation or, whether the participants were responding to the difference in noise level. Work is currently being undertaken to account for these sound level variations between the different audio files and how they might be corrected for or 'offset' within the participant response data.

Analysis of Results

Previous research into the perception of UAS and other environmental noise sources has demonstrated that the 'loudness' of the sound is the most significant characteristic of the sound when assessing both perceived loudness and annoyance. To better understand which of the loudness metrics may be best at modelling the *PA* and *PL*, numerous metrics used to quantify the loudness of a sound have been used to model the participant response data. The conventional metrics of L_{Aeq}, L_{ASmax} and L_{AE} along with other metrics such as Perceived Noise Level (*PNL*), Effective Perceived Noise Level (*EPNL*) and the Sound Quality Metric (SQM) Loudness – ANSI model (N_5) have been modelled to see which metrics are best at predicting *PA* and *PL*.

Each of the metrics mentioned previously have been used to model the *PA* and *PL* response data using simple linear regression analysis. The Adjusted R^2 values for each of the loudness metrics (dependent variable) have been derived using regression modelling and are presented within Table 4. The Adjusted R^2 value indicates the accuracy of a dependent variable in predicting an independent variable, in this case either the *PA* or the *PL*.

Table 4. Results of the Linear Regression Analysis – Perceived Annoyance

Loudness Metric	Adjusted R^2	
	Annoyance (*PA*)	Loudness (*PL*)
L_{ASMax}	0.93	0.90
L_{Aeq}	0.93	0.90
L_{AE}	0.85	0.80
PNL	0.91	0.88
EPNL	0.90	0.89
Loudness (N_5)	0.96	0.90

Results of the regression analysis for *PA* show that the SQM Loudness was the best performing metric for predicting *PA* with an Adjusted R^2 value of 0.96. L_{Aeq} and L_{ASmax} scored marginally lower with Adjusted R^2 values of 0.93. PNL and EPNL (calculated by supplementing the PNL with a tonality correction) scored slightly lower with Adjusted R^2 values of 0.91 and 0.90 respectively. L_{AE} scored the lowest with an Adjusted R^2 value of 0.85. For modelling *PL*, L_{ASMax}, L_{Aeq} and Loudness all score an adjusted R^2 values of 0.90. *EPNL* scored slightly lower with 0.89, *PNL* with 0.88 and L_{AE} the lowest with 0.80. Work is currently being undertaken to determine why L_{AE} performed worse than other metrics in predicting both *PA* and *PL*. However, early analysis of the results would suggest that the reduced predictive performance of the L_{AE} metric is associated with the Hover operation which exhibited a significantly lower Adjusted R^2 value for both *PA* and *PL* than any of the other metrics. Work is continuing to investigate why this might be the case, but previous listening experiments have also found interesting results associated with *PA* and events that result in a sustained exposure. Christian and Cabell (2017) [9] found that the *PA* of drone flyovers at different altitudes were surprisingly similar even though the L_{AE} reduced with flight altitude. The reason was thought to be that even though the higher altitude flights were quieter overall they were longer in duration which resulted in increased annoyance. As such it was suggested that a 'loitering' penalty should be applied to UAS flying at higher altitudes and a similar correction could be applicable to hovering UAS.

The work required to better understand the subjective response and the selection of the metrics most suitable to model these responses is ongoing and will require significant further investigation. However, based on this listening experiment and analysis of results Loudness (N_5), L_{ASmax} and L_{Aeq} all appear to exhibit strong predictive capabilities for both *PA* and *PL*. Whilst Loudness was demonstrated to be the overall best predictor for *PA* and *PL* the difference between Loudness, L_{ASmax} and L_{Aeq} for *PA* was minor with an improvement to the Adjusted R^2 value of 0.03. For *PL* no difference in the adjusted R^2 value was observed between the three metrics. Based on these results, there appears to be a small benefit to using Loudness over L_{Aeq} or L_{Amax} but all of these three metrics performed well and could be considered good indicators of *PA* and *PL*. Further analysis work is to be carried out to investigate the inclusion of other SQMs such as

Sharpness and Fluctuation Strength, in addition to Loudness, to see whether the predictive models using SQMs can be improved. At this stage *PNL*, *EPNL* and L_{AE} do not appear to demonstrate as strong a predictive capability as the other three metrics although it is recommended that these metrics should still be analysed as part of future listening experiments to corroborate or oppose the findings of this research.

Further Work

A second measurement campaign is currently scheduled for early summer 2023 and is being designed in collaboration with the Civil Aviation Authority (CAA), UK. The organization of this measurement campaign is currently underway, it is the hope of the organizers that there will be access to larger drones, more similar to those that may be used for parcel delivery than those measured as part of this first measurement campaign. High quality Drone positioning data will also be collected using an Augmented GPS system which will increase the accuracy of the measurements and allow for a greater level of certainty within the directivity data.

A second listening experiment is also scheduled for Spring 2023; this experiment is being designed to further investigate the *PA* and *PL* of Drone noise. The experiment will in part make use of the audio recordings captured during the first measurement campaign. A different approach may be taken in this second listening experiment where the noise levels would be standardised to set L_{Aeq} or L_{Amax} values to allow for a more equitable comparison between results. This approach may help to investigate how other aspects of the sound, in addition to the loudness, can influence the *PA* and *PL*.

References

1. ICAO. "Aircraft Noise, Environmental Protection, Annex 16." International Civil Aviation Organization Montreal, Canada, 2008.
2. ISO. "ISO/CD 5305 - Noise Measurements for UAS." International Organization for Standardization, 2022.
3. Boyle, Devin, Juliet Page, and Kyle Pascioni. "UAM Noise Working Group Meeting Subgroup 2: Ground & Flight Testing." Paper presented at the 2022 NASA Acoustics Technical Working Group (ATWG) Meeting and UAM Noise Working Group (UNWG) Meeting.
4. Willshire Jr, William L, and Paul A Nystrom. "Investigation of Effects of Microphone Position and Orientation on near-Ground Noise Measurements." 1982.
5. Read, David R, David A Senzig, Christopher J Cutler, Eric Elmore, and Hua He. "Noise Measurement Report: Unconventional Aircraft-Choctaw Nation of Oklahoma: July 2019." John A. Volpe National Transportation Systems Center (US), 2020.
6. Waters-Fuller, Tim, Daniel Lurcock, Robin Mackenzie, and Richard MacKenzie. "Nanr116 Open-Closed Window Research Report." 2007.
7. Standard, British. "8233: 2014, ‘Sound Insulation and Noise Reduction in Buildings–Code of Practice’." British Standards Institution (2014).
8. Grimwood, C. et. al. "Propg: Planning & Noise - Professional Practice Guidance on Planning & Noise." 2017.
9. Christian, Andrew W. Cabell, Randolph. "Initial Investigation into the Psychoacoustic Properties of Small Unmanned Aerial System Noise", 2017.

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