The Effects of Emerging Technology Aviation Noise: an annual update

CAP 3086

Published by the Civil Aviation Authority, 2025

Civil Aviation Authority
Aviation House
Beehive Ring Road
Crawley
West Sussex
RH6 0YR

First published 2025

Enquiries regarding the content of this publication should be addressed to: noise@caa.co.uk

The latest version of this document is available in electronic format at: www.caa.co.uk

Contents

Chapter 1
Introduction

1.1 The presence of emerging aviation technologies is an expanding area of aviation and includes vehicles such as Unmanned Aviation Systems (UAS) which are also known as drones[1], and Urban Air Mobility (UAM) aircraft, including air taxis, sometimes referred to as Unmanned Aerial vehicles (UAVs) and electric Vertical Take-Off and Landing vehicles (eVTOLs). This modern technology has several potential uses, for example aerial mapping and photography, military surveillance, search and rescue, delivery, and air taxis amongst many others. This presents new challenges for noise legislation and understanding of how these types of noise sources may impact people on the ground. In 2023 the CAA published CAP report 2505, which provided an overview of the current knowledge on the impacts of such emerging technology noise on humans over the past few years to the start of 2023. CAP 2692 was then published in 2024 as update to CAP 2505.

1.2 This report aims to provide an update from the past year (March 2024 - March 2025) on the current knowledge around potential human impacts from noise generated by emerging flight technologies. The scope of this report does not cover the effects on humans from spaceflight vehicles, which is covered separately.

1.3 The report will provide an overview from the relevant findings presented at the Quiet Drones conference, held in September 2024, the Internoise 2024 conference, and any other published research findings from the past twelve months that relate to the human impacts of emerging technology noise. The CAA has not validated the research findings or conclusions included in this report, nor takes any view on their applicability to UK policy making.

[1] Although *UAS* is the regulatory term used by the CAA, there are various other terms in use within the sector for these types of aircraft. This is evident in the range of terminology used by the authors of the papers and studies which are summarised in this report.

Chapter 2
Quiet Drones 2024

2.1 The Quiet Drones conference was held in Manchester, UK, in September 2024 and this chapter describes some of the findings pertinent to emerging technology aviation noise impacts that were presented at this meeting.

2.2 As with aviation noise, drones have the potential to cause annoyance to those on the ground. Several studies have concluded that drone noise may be more annoying than aircraft noise and helicopters. **Kawai et al** presented findings from a laboratory listening study measuring annoyance in relation to size, type of manoeuvre, and flight speed of the drone.

2.3 The concept of a 'loitering effect' is explained by the authors. Previous listening experiments have indicated that even if drone noise decreased when drones operated at high altitudes, noise annoyance ratings did not reflect this change in noise level. The authors propose that because drone speed is also linked to exposure duration (and therefore sound exposure level, L_{AE}), it is possible that a 'loitering penalty' is increased when drones fly past slowly.

2.4 Thirty-six participants were included in the study. Two sizes of quadcopter were used (0.9kg and 6.3kg), and five different manoeuvres were flown: two, vertical manoeuvres (take-off, landing) and three horizontal flybys (altitude: high = 80 m, medium = 20 m, low = 6 m). All these were flown at low and high speed. Other types of transportation noise were also included, (total number per participant = 40 drone stimuli plus 28 other transportation vehicle stimuli, intermixed). The results from the other noise sources were not included by the authors in this paper.

2.5 The annoyance rating screen showed the following question (in German): 'If this were the noise situation outside your home, which number between 0 and 10 best describes how disturbed or annoyed you would be by it?' (adapted from ISO/TS 15666, see ISO, 2021). The question was answered with an 11-point horizontal rating scale numbered from 0 to 10, with 'not at all' and 'extremely' being at either end of the scale. Self-reported noise sensitivity was also measured.

2.6 The results indicated that annoyance was higher for the smaller drone compared to the larger one (Figure 1). At the same noise level (L_{AE}) vertical manoeuvres (take-off and landings) were more annoying than flybys.

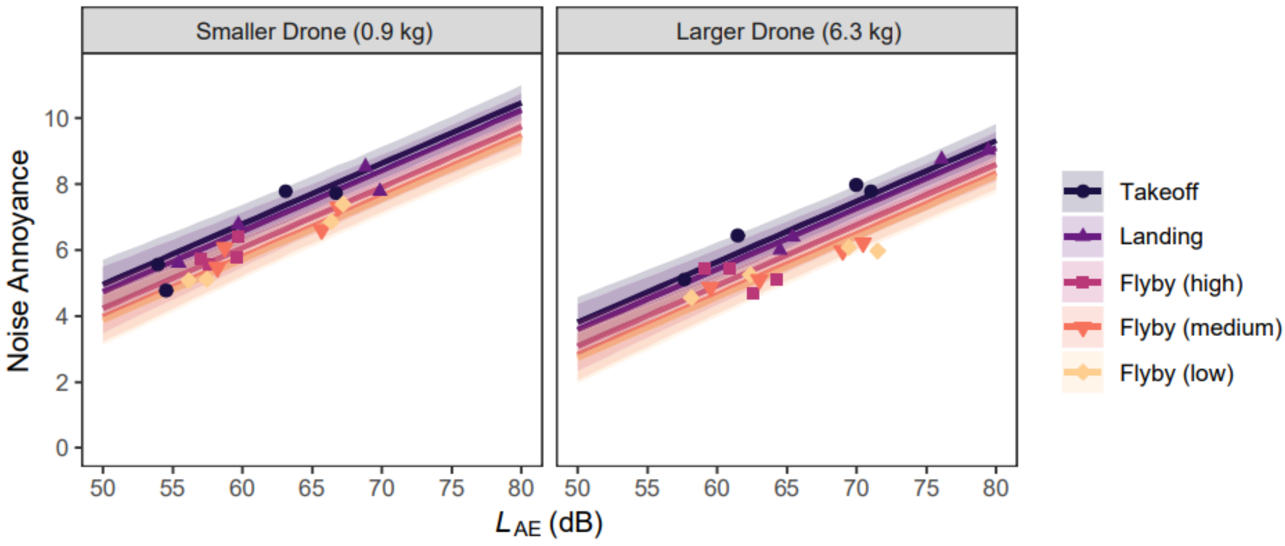

Figure 1: Mean noise annoyance as a function of the L_{AE} for all manoeuvres flown by the two drones. Symbols represent aggregated observed data per stimulus. Regression lines and 95% confidence intervals correspond to predictions from the linear mixed-effects model, averaged over speed.

2.7 The speed of the drone was a significant predictor of annoyance and interacted with the type of manoeuvre. At the same noise level (L_{AE}), fast take-offs were more annoying than slow take-offs ($p < .001$). There was no significant difference in annoyance between slow versus fast landings. In contrast to the vertical manoeuvres, slow (horizontal) flybys were associated with increased annoyance, compared to fast flybys. This effect was strongest for high flybys ($p < .001$) and decreased with reduced flight height ($p = .011$ for medium flyby; $p = .037$ for low flyby). These data indicate that speed is an additional factor modifying the loitering perception, apart from flight altitude. It is also explained that these two factors interact: the higher the altitude, the stronger the annoyance response when the flyby is slow. The authors concluded by stressing the importance of other factors than noise level when predicting annoyance caused by drone noise, adding to the unique challenges posed during assessment and regulation of this type of noise.

2.8 **Woodcock et al** from Arup, UK, presented findings on the influence of operational and contextual factors on the human response to drone sound. The context for the study is project CAELUS, which is trialling the UK's first medical delivery drone network. This study was designed to collect data on annoyance related to overflight and take-off operations of the drone proposed for use in the project CAELUS trials. In particular, the researchers were interested in factors such as distance from the drone, ambient soundscape, and how contextual information influences the annoyance response to these operations.

2.9 Participants rated their annoyance on a 7-point scale and answered the question: "*To what extent are you personally bothered, annoyed or disturbed by* *the sound of the drone?"* . Two separate experiments were conducted, focusing on drone overflights and take-off operations respectively. For overflight operations, variations in listener-drone distance were achieved by adjusting the altitude of the drone (120m, 90m, and 60m). For the take-off operations, differences in distance were achieved by changing the distance between listener and final approach and take-off area (30m, 60m and 120m). The drone operations were presented against three ambient soundscapes: remote rural, rural village, and urban environments. This design resulted in nine stimuli for each of the two experiments. To examine the effect of contextual factors, half of the participants were told about the purpose of the drones and their intended use for medical reasons, and half were not.

2.10 In addition to the sound recordings of the drone noise for each soundscape, a visual stimulus representing the three environments were also presented alongside the auralisations. After the participants (N = 703) had rated the nine stimuli, they were asked to answer a series of open text questions to collect data on what may be contributing to annoyance.

- What characteristics of the drone sound influenced your responses?
- Do you believe the purpose/application for which the drones are used would influence your response to the sound? Please explain your reasoning.

2.11 The results revealed significant main effects for altitude, soundscape and context on annoyance. In addition, there were significant interactions between context and altitude, between context and soundscape, and between soundscape and altitude. The authors explain that these effects indicate that the impact of drone altitude on annoyance varies depending on the contextual information provided and the type of soundscape.

2.12 The results also indicated significant differences in annoyance ratings between drone altitudes of 60m and 120m, and 90m and 120m. Annoyance ratings differed between rural and village, rural and urban, and village and urban soundscapes (Figure 2). There was also a significant difference between the context and no-context participants in terms of annoyance ratings, with those who were told about the purpose of the drones reporting significantly less annoyance than those people who were not given any information.

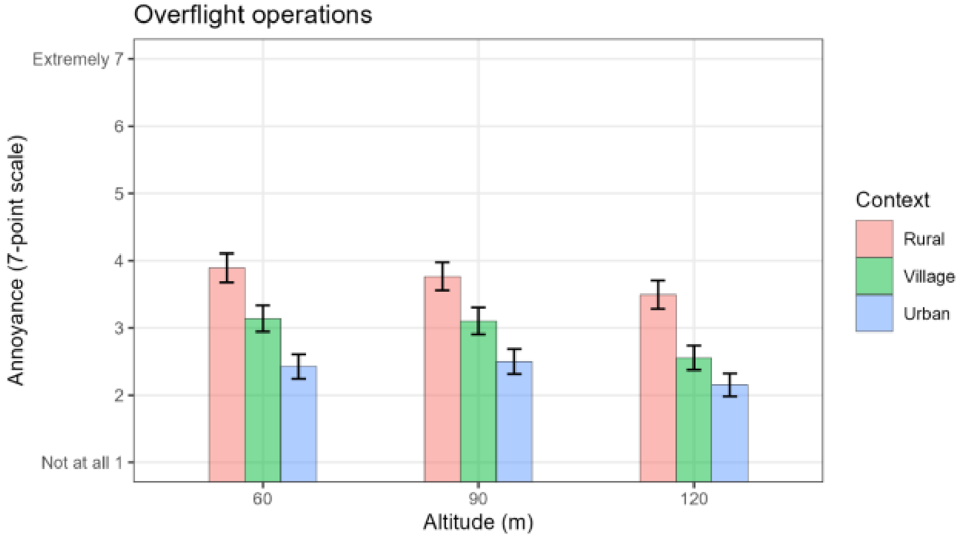

Figure 2: Mean annoyance ratings and 95% confidence intervals for overflight operations for different drone altitudes and soundscape types.

2.13 Figure 3 illustrates the significant differences that were also found in terms of distance from the drone, soundscape and context and annoyance ratings. Significant interactions were observed between context and distance, and between soundscape and distance. These results suggest that the impact of drone-listener distance on annoyance perception varies depending on the contextual information provided and the type of soundscape experienced.

2.14 Further analysis revealed significant interactions between 30m and 60m, 30m and 120m, and 60m and 120m. Annoyance ratings also differed between rural and village, rural and urban, and village and urban soundscapes in terms of annoyance. There were also significant differences between the context and no-context conditions.

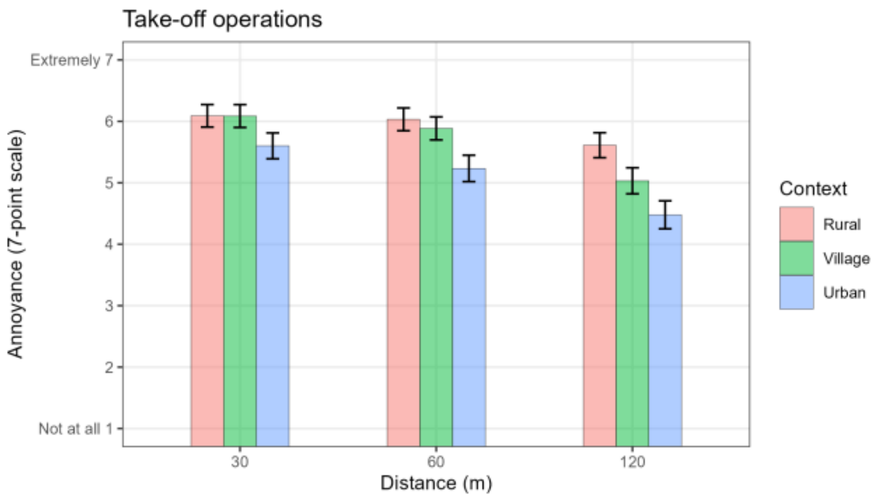

Figure 3: Mean annoyance ratings and 95% confidence intervals for take-off operations for different drone altitudes and soundscape types.

2.15 The answers to the open questions were analysed, revealing that the most common words for both take-off and overflights were *loud, harsh, buzz* and *annoying*. The authors explain that *loud* and *harsh* were used more frequently in the context of the take-off sounds compared to overflights. Participants cited the use cases *emergency* and *medical use* as being the top two most acceptable/tolerable reasons for drone usage, with *delivery* and *commercial use* being the least. The authors stress the importance of considering contextual factors in terms of drone assessment, and that more socially valuable use cases are more likely to be perceived as acceptable and less annoying if their purpose is well explained. They suggest that visual clues may aid this.

2.16 **Bauer et al** presented the methodology for an investigation into UAM community noise impact studies in the Bavarian State Ministry-funded project PAULA. The purpose of PAULA is to examine how two or four-seated UAM vehicles (or air taxis) would be perceived by the population in terms of noise and general acceptance. PAULA aims to use two sub-studies to examine in detail the effects of this new aircraft noise on:

- acoustic passenger comfort inside the aircraft and
- on the affected population residing near vertiports.

2.17 The project started in January 2024 and comprises five work packages:

1. definition and specification (e.g. audio parameters)
2. noise sources (two types of air taxis)
3. passenger cabin (comfort of passengers)
4. noise impact on population (noise effects research)
5. analysis and results (establishment of action plan and guidelines for minimising UAM noise near vertiports)

2.18 The design of the noise impact work package, and variables that will be studied included:

- Operation type: departure and approach (2 factors)
- Movements: Number of movements during the test period (4 factors).
- Distance to vertiport: observer points under the centre line and in lateral position parallel to the centre line (up to 9 factors).
- Background noise: No background noise versus urban ambient sounds (2 factors).

2.19 The noise scenarios differ regarding the number of movements. A session is limited to a duration of approximately 30 min, one to seven movements are presented. Examination will be repeated for nine different observer points. Departures and approaches are tested separately. In half of the scenarios, continuous background noises from distance urban road noise and nature sounds are added to the air-taxi sounds in order to evaluate the potential of masking air-taxis sounds by ambient noise and its effect on annoyance and disturbance. There will be 144 different scenarios in total.

2.20 The study will be conducted at the DLR Institute of Aerospace Medicine in Cologne. The air-taxi scenarios will be presented via headphones in a sound insulated laboratory furnished like a living room. Annoyance will be assessed by a question referring to the home environment. Participants will be instructed to imagine that they are sitting in a/their garden and are hearing the presented scenarios and will rate their annoyance on an 11-point numerical scale.

2.21 In addition, a further listening test is planned on a sub-set of the data, with the aim of producing exposure-response relationships between sound level and annoyance responses.

2.22 **Aalmoes and Sieben** presented findings from a study on the human response to drone noise. This study employed visual and auditory stimuli of drones and aircraft noise in rural or urban environments, to examine which sources elicit a higher annoyance response for a given sound level. The authors provide a background on the factors impacting the perception of drone noise, including whether the drone is hovering or flying over the observer, and propagation effects such as the doppler effect. In addition, they explained that the diffraction of sounds due to objects close to the observer and ground reflections and sound scattering may have an effect. The position of the person's head and the shape of the observer's ear also determine how sounds are perceived. The influence of non-acoustic factors is also stressed by the authors. Noise sensitivity, personal attitudes towards the noise source, and perception of the authorities responsible for the noise source are all important factors for consideration, as well as the perceived usefulness/importance of operation.

2.23 This sound perception study with 21 participants was developed to compare a drone flyover event with other aircraft in different environmental locations. The focus in this study was the sound characteristics comparison between the different types of aircraft. The simulator used in the study was able to simulate both a visual and audible flyover within two pre-recorded environments: a rural environment, with a highway in the distance at 500 metres, and an urban environment, with housing and a nearby local road with busy traffic. Participants wore headphones and virtual reality glasses. The recorded flyover sounds that were evaluated were a DJI Matrice 600 hexacopter (with six rotors) drone flyover with a take-off weight of 15.3 kg, a Boeing 737-800 aircraft flyover, a Pipistrel Velis Electro aircraft flyover, and a Eurocopter EC-135 helicopter flyover. Sound events were presented at sound levels of 60 and 65 dBA L_{Amax} for the Pipistrel, 50 and 65 dBA L_{Amax} for the Boeing 737, and 65 dBA for the helicopter and the drone. All events were played at the same 65 dBA peak sound level. The noise events were randomly presented, and the participants were asked to rate their annoyance level on an 11-point scale.

2.24 The results for reported annoyance and loudness for each of the presented flyover sounds in a rural environment were presented. The reported annoyance mean and standard deviation values in rural environment for L_{Amax} 65 dBA events were:

- Drone: mean 4.29 (SD=2.26)
- Pipistrel: mean 3.67 (SD=2.08)
- Helicopter: mean 4.71 (SD=2.37)
- Boeing: mean 5.52 (SD=2.14)

2.25 The reported loudness mean and standard deviation values in a rural environment for L_{Amax} 65 dBA events were:

- Drone: mean 4.62 (SD=2.56)
- Pipistrel: mean 3.48 (SD=2.16)
- Helicopter: mean 4.57 (SD=2.40)
- Boeing: mean 5.33 (SD=2.33)

2.26 The results indicated that the Boeing aircraft and the helicopter were rated as more annoying than the drone, and the Boeing aircraft was perceived more loudly than the drone. Further analysis revealed that the drone was significantly less annoying than the Boeing 737 at the same sound level (65 dBA) in the rural area. In the urban environment, the Boeing 737 was significantly more annoying than the drone, but was not significantly rated as being louder. Higher loudness scores were given in the rural environment for the drone and the Boeing 737 compared to the urban area. No significant differences in annoyance or loudness were observed between the drone and the helicopter in the rural setting.

2.27 These results are contradictory to previous findings by Gwak, who found that drone noise was perceived as more annoying than aircraft noise, although the authors explain that this study was conducted on hovering drones only, which may be considered more annoying in terms of noise than when a flyover occurs.

2.28 **Merino-Martínez** et al presented findings from a listening experiment on the response to flyover noise from different types of drones recorded in field measurements. The study (N = 57) was conducted at Delft University and included six quadcopters with single propellers, a quadcopter with counterrotating propellers, and two types of hybrid electric vertical take-off and landing (eVTOL) drones.

2.29 The study comprised two elements. The first part was conducted in October 2022 at a Dutch military base and included noise from five single-propellor quadcopters. The second part of the study was conducted in June 2023 in Valkenburg in the Netherlands. This included noise from a single-propeller quadcopter, a coaxial-propeller quadcopter, a quadplane eVTOL, and a tailsitter eVTOL. Both parts of the study were conducted in the field, with large open grassy areas to minimize background noise.

2.30 Participants gave their annoyance ratings via a graphical interface and their annoyance rating was given on an 11-point scale. They were asked to imagine the sound was present while they were in their garden and rate their annoyance accordingly. The Sound Quality metrics loudness, tonality, sharpness, roughness and fluctuation strength were calculated for each drone flyover and the 5% percentiles were calculated (representing the value of each SQM exceeded for 5% of the total recording time). These 5% percentile values were then combined into global psychoacoustic annoyance (PA) metrics following the models by Zwicker (Fastl & Zwicker, 2007) More (2010), and Di et al (2016). Impulsiveness (a metric that assesses the loudness N over time to quantify the degree of impulsive content within a sound) was also included in the study.

2.31 Figure 4 indicates the annoyance ratings grouped by drone type, with the first five group of drones in the first part of the experiment, with the second group of four being in the other part.

2.32 The authors described that the annoyance trend suggests that annoyance increases with the mass of the drone, except for two hybrid eVTOL vehicles which were perceived as less annoying despite having larger mass and volume, and the Dronevolt H20 quadcopter, which was rated the highest in terms of annoyance.

2.33 Further analysis was performed on the quadcopter data, and strong correlations were found between mass and volume and annoyance ratings. The authors also examined the metrics to assess which one was the best predictor of annoyance. Both conventional metrics and the PA metric were assessed, and in this study, the PA metric was found to have the strongest correlation with annoyance (ρ = 0.857, p-value = 0.003). The authors suggest that future work could include a wider range of drones and masses, and more operations such as take-off, landing etc in a variety of environments.

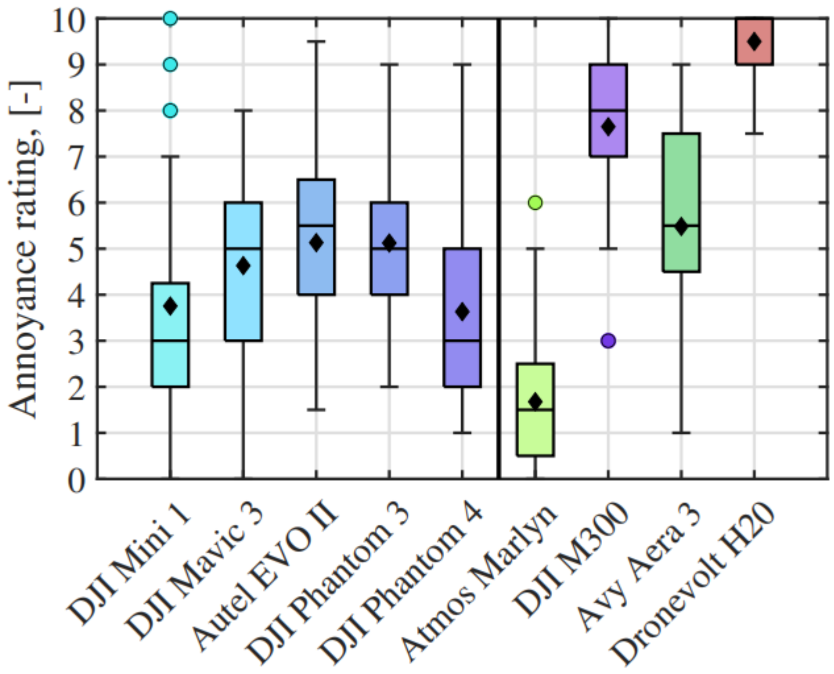

Figure 4: Boxplot showing the distribution of annoyance ratings per drone type (in ascending order of mass). Diamond markers denote mean values, the central horizontal line denotes the median values, the edges of the box are the 25th, and the 75th percentiles, and the whiskers extend to the most extreme data points. The outliers are plotted individually as circles. The vertical black line divides the drone types investigated in the two parts of the study.

2.34 **Masulo et al** described findings from an investigation on the effects of two types of drones (small and medium sized) noise in an urban setting during different flight operations and at different distances of drones from outdoor and indoor listeners. The noise measurements were taken in the area surrounding the University in Aversa, Italy in 2024. The drones included were the DJI Mavic 2 Enterprise Dual (DR1) (medium size) and DJI Mavic 2 Mini (small size). The recordings were also taken for flight at different trajectories and distance from the receivers' positions (outdoor and indoor).

2.35 As with the previous study, PA values were calculated for each of the conditions. Two models were used, the first was by Zwicker which includes sound quality metrics such as loudness, sharpness, fluctuation strength and roughness. In addition, a second model was used in the analysis which added in tonality. The results from both models are displayed in Figure 5. The results indicated that the smaller drone elicited a stronger annoyance response in all of the conditions, and this was further pronounced when the tonality element was added into the analysis.

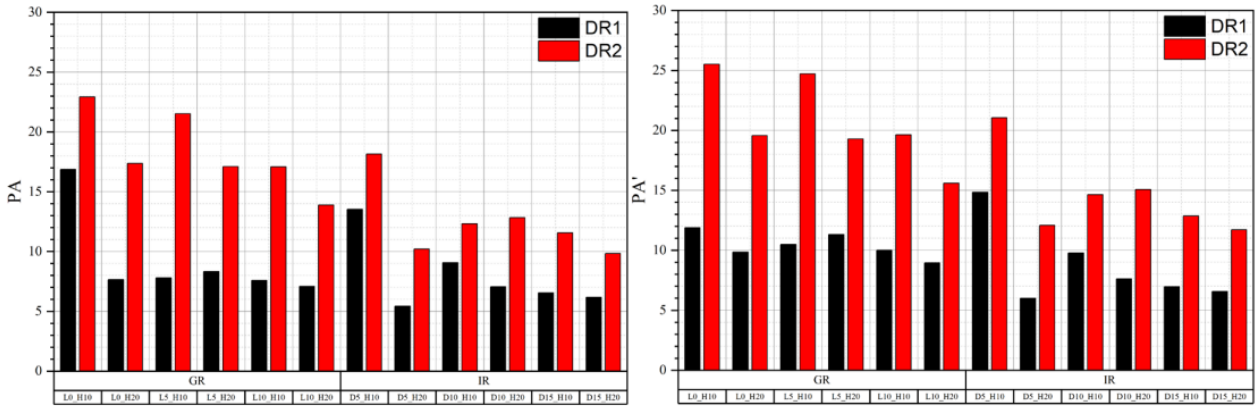

Figure 5: PA (left) and PA' (right) values on DJI Mavic 2 Enterp. Dual (DR1) (in black) and DJI Mavic mini 2 (DR2) (in red).

2.36 **Green and Torija** conducted a study into the perception of noise from six different types of UAS compared with road traffic, aircraft noise and helicopters. The aim of the study was to examine mean levels of perceived loudness and annoyance, along with the percentage of people highly annoyed (%HA) and the factors that may influence differences in these between the noise sources. The authors used a statistical method known as offset analysis to determine the difference in dB (ΔdB) required to achieve an equal level of annoyance or perceived loudness between the vehicle types. Differences in perceived loudness and annoyance between the six types of UAS were also investigated.

2.37 Forty participants were asked to rate their annoyance on an 11-point scale, with a score of 8 or more classed as HA, and were asked how loud they perceived the sound from each of the sources to be.

2.38 The results indicated that for mean annoyance, aircraft noise elicited the highest level with a median value of 6.1, followed by helicopters (Md = 5.9), UAS (Md = 5.1) and then road traffic (Md = 3.1). The authors describe that the range of responses was similar across aircraft, helicopters and UAS, with annoyance for road traffic noise being lower. When the annoyance data was examined with relation to sound exposure level L_{AE} the aircraft noise, UAS and helicopter all produce a mean level of annoyance at around the same L_{AE}. As before, the road traffic annoyance responses were lower at similar L_{AE} than the other noise sources. All types of vehicles indicated a clear positive correlation between increased sound level and annoyance. An exception to this trend was for the two UAS vehicles (DJI Mini 3 pro) that was the smallest and lightest in the study but produced a relatively high annoyance response.

2.39 The perceived loudness data followed a similar pattern to the annoyance data. However, the perceived loudness response data for the two DJI Mini 3 Pro stimuli did not exhibit the same increase in participant rating as annoyance did. The authors suggest that although these vehicles are perceived as not as loud as the other UAS, they still elicited a high annoyance response which means that non-acoustic factors must be contributing to the response.

2.40 The difference between perceived loudness and annoyance ratings ∆APL was also analysed by subtracting the loudness rating from the annoyance rating. If there was a positive difference, the stimuli scored a higher rating for annoyance than perceived loudness. For aircraft, helicopter and road traffic the ∆APL ratings were -0.7, -0.2 and -1.1 respectively. On average, the perceived loudness of the stimuli was typically higher than the annoyance response. For UAS, the ∆APL was +0.1, highlighting that the mean annoyance response was marginally higher than perceived loudness. For some of the lightest UAS, differences indicated that annoyance ratings could be over twice as high as their perceived loudness, again suggesting that participants found the noise from very small UAS to be particularly annoying relative to their perceived loudness.

2.41 The authors examined the HA data, which showed that the helicopter noise had the highest median value of %HA, followed by aircraft, UAS and road traffic. The authors stressed that this does not reflect the range of responses for UAS, where although the median for HA UAS was 13.4 %, some of the UAS had associated HA of up to 73 %.

2.42 The results of the offset analysis are shown in Table 1 for annoyance and Table 2 for loudness.

Table 1: Offset analysis: change in sound level required to achieve equal Annoyance (expressed in dB or Phon). Data reproduced from Green and Torija.

Vehicle Type	**Helicopter**	**Aircraft**	**Road**
L_{ASmaxS}	3.3	2.0	-17.3
L_{Aeq}	-0.1	-1.2	-15.1
L_{AE}	0.6	-0.5	-13.2
Loudness (N)	0.3	0.3	-11.2

A positive value means that an increase to the UAS sound level is required.

Table 2: Offset analysis: change in sound level required to achieve equal Perceived Loudness (expressed in dB or Phon). Data reproduced from Green and Torija.

Vehicle Type	Helicopter	Aircraft	Road
L_{ASmaxS}	5.7	5.3	-6.3
L_{Aeq}	2.1	1.8	-4.7
L_{AE}	2.8	2.5	-3.5
Loudness (N)	1.9	2.5	-1.6

2.43 These results indicate that for the metrics L_{AE}, L_{Aeq} and loudness, the helicopter, aircraft and UAS all elicited similar levels of annoyance and perceived loudness. They all required only small changes in sound level in order to predict equal annoyance or perceived loudness.

2.44 In terms of L_{ASmax}, there were slightly larger changes required to achieve equal annoyance, and with increases in UAS sound of 3.3 and 2.0 dB compared to helicopter and aircraft stimuli respectively. For road traffic the difference was greater and required reductions between 11.2 and 17.3 dB/Phon to achieve equal annoyance. When calculating the Δ dB values required to achieve an equal perceived loudness level the differences were lower.

2.45 The authors suggested that future work should aim to continue investigating the differences in response between vehicle types, and for further understanding of perceptions to a wider range of vehicles. A greater understanding of the differences in perceived loudness and annoyance adds to the knowledge of perception to new sound sources such as UAS.

2.46 **Lotinga et al** presented findings on a study into how flight operations and ambient acoustic environments influence noticeability and noise annoyance associated with UAS. The aim of the study was to investigate how changing UAS flight operations, vehicle types and event quantities could impact the noticeability and annoyance in relation to noise from these vehicles. The design of this listening study included 3D spatially rendered controlled acoustic environments. Participants were exposed to a range of UAS sounds embedded within recordings of real acoustic environments and asked to provide annoyance ratings accordingly.

2.47 The three UAS vehicles in the study were a ‘small’ 2kg hexacopter (Yuneec H520E), a ‘medium’ 6kg quadcopter (DJI Matrice 300), and a ‘large’ 60kg contra-rotating octocopter (in a 4-arm configuration, or ‘X8-copter’; Malloy T150). Each UAS was unladen, and operational modes included flyby, landing and take-off operations. The audio recordings were taken in two settings, namely a 'calm urban park' (CUP), normalised to 52 dB L_{Aeq}, and a 'busy city street' (BCS), normalised to 58 dB L_{Aeq}.

2.48 The experiment ran in two parts. The first part involved 25-second-long stimuli, which comprised single UAS events embedded within the two environment scenes. Each UAS event was normalised to one of four sound levels between 42–60 dB L_{Aeq} at 6 dB intervals. The experimental design was 3 × UAS types × 3 flight operations × 4 sound levels × 2 ambient environments. There was also a 'no UAS' stimulus for each of the two environments.

2.49 The second part of the experiment used 75-second-long stimuli, which included multiple UAS events sequenced with 1, 3, 5 or 9 events. UAS types and sound levels were reduced to two (the small hexacopter and the large X8-copter, each presented at 54 dB and 60 dB L_{Aeq}), for flyby operations only, within the CUP ambient environment (only). This led to 4 × 2 × 2 UAS stimuli, plus a 'no UAS' stimulus condition.

2.50 42 participants completed the study, in Part A they were asked to rate their annoyance on an 11-point scale, along with selecting which sound sources they had noticed during each recording. The intention with this design was to obtain, via an indirect method, an indication of 'noticeability' of each UAS sound. The noticeability of the UAS in each stimulus was then taken as the proportion of participant 'UAS noticed' classifications for that scene. In Part B participants were asked to rate annoyance, but not identify noticeable sounds given there were multiple fly-by events that were at noise levels expected to be clearly audible in the CUP setting.

2.51 The results indicated that UAS were more noticeable in a CUP environment than in a BCS scene, even when compensating for the differences in averaged sound levels between the environments. The degree of noticeability also had a stronger impact on annoyance levels in the park compared to the street setting.

2.52 Within subjects' results indicated that:

- the large T150 X8-copter in flyby mode tended to be rated the least annoying.
- flyby operations tended to be associated with lower annoyance ratings than landing or take-off, with the take-offs typically producing slightly higher ratings than landings.
- the small H520 hexacopter was generally rated as more annoying at equivalent operating modes than the other UAS types, and the H520 in take-off mode was typically rated as the most annoying UAS sound event.

2.53 When the sound quality metrics were investigated, the authors concluded that higher levels of tonality, fluctuation strength, roughness, sharpness and impulsiveness contributed to the differences in annoyance for the various types of operations.

2.54 Psychoacoustic Annoyance (PA) was modelled based on sound quality metrics, and was found to be a good predictor of aggravated annoyance ratings of UAS sounds. The authors explain that a novel finding from this study is that the individual UAS and ambient environment components constituting the sound scenes could be separately analysed for PA, and the resulting values combined to predict annoyance with negligible loss of accuracy (compared with analysing PA for the overall sound scene). They concluded that this result could be particularly useful in enabling efficient annoyance predictions for a wide range of UAS types and operations over varying environments.

2.55 **Green and Torija Martinez** presented findings from a study using a soundscape approach to drone noise assessment. The soundwalking methodology involves participants being taken on guided walks and recording their responses to the acoustic environment. Due to the lack of exact repeatability and control over the acoustic surroundings, there have not been many previous studies using in-situ responses.

2.56 The soundwalk took place in the Crescent Meadow, near the University of Salford's Peel Park campus in Manchester. It is explained that: "the basic structure of the soundwalk followed the specifications detailed in the ISO soundscape standard (ISO 12913-2, 2018). Three stops were defined along the footpath on the outer edge of the Meadow to allow separate locations to assess the impact of drone take-off, flyby, and landing operations." The route was repeated twice, once to assess the participants' responses to the existing soundscape, and once with the added drone events timed to take place within each allocated minute. L_{Aeq}, L_{A5}, and L_{A95} were measured at each stop. The drone used was a XAG P40, which is a large model weighing 20 kg with a diagonal wingspan of 2.1 metres. This type of drone is usually used to spray pesticides or other agricultural tasks.

2.57 In part one of the assessment, the sixteen participants were asked to identify each of the three main types of sound sources specified previously by Brown et al – human, natural, and mechanical. Part two assessed perceived affective quality using a set of five semantic differential scales:

- Unpleasant / Pleasant
- Uneventful / Eventful
- Inappropriate / Appropriate
- Uncomfortable / Comfortable
- Chaotic / Calm

2.58 The first two parts were assessed with a 7-point scale. The third part was the 11-point annoyance question. Participants were also asked a set of open-ended questions after completion of the soundwalk.

2.59 The perception results indicated that when the drone sounds were added to the soundscape, drone landing events had statistically significant effects on perception in terms of comfort and calmness, as well as the prevalence of natural and human sounds. At Stop B on the soundwalk which had no drone activity and was 80 metres away from the take-off and landing points, the perception of natural sounds was the highest.

2.60 When the results were analysed for significant differences between stops, there was no significant effect on human sound or eventfulness ratings, and no significant difference for annoyance ratings. Mechanical, natural, pleasantness, appropriateness, and calmness ratings are shown to be significantly different for the different locations.

2.61 The authors provide a detailed analysis of the responses for each of the locations, and correlations between the activity or inactivity of the drones. They propose that further investigation should examine whether the perception of drone landings is to do with the acoustics of the event or more linked to the interaction with the existing soundscape at that location. They suggest further soundwalks with larger numbers of participants would be useful, given some of the analysis in this study was close to reaching significance.

2.62 The authors also suggest that future soundwalks could vary the stops at which the drone events occur to avoid the question raised in this study in terms of separating the relative impact of the drone event itself as opposed to interaction with the existing soundscape. The soundwalk could be conducted in reverse order, and with drones flying in opposite directions. They also propose using different kinds of soundscapes and varying heights, speeds and weights of drones to gain more data using this methodology.

2.63 **Barrado et al** reported findings from a study on perception during three days of outdoors flight demonstration. The CORUS-XUAM project ran six drone flight demonstrations of urban air mobility in seven different European countries. Flights were demonstrated in Sweden, Germany, Belgium, Italy, France, and Spain. The Swedish demonstration was a long-range flight connecting two cities, mainly above rural areas. The German, French and Belgian demonstrations were in a segregated area, with no access to citizens. In the Spanish demonstration, drones were flying above the beach of Castelldefels, an urban area in which citizens often walk. The Italian demonstration was somewhere in between these scenarios.

2.64 The aim of the study was to obtain data on perceptions of the noise from the drone demonstrations across countries. The authors also compared the data with annoyance data from aircraft approaching and landing at the Barcelona-El Prat airport over highly populated areas. A total of 52 responses were collected: 36 from citizens, 10 from law enforcement agents and emergency responders, and 6 from local/regional authorities. Citizens were not specifically invited to the study like the other stakeholders, they just happened to be walking through the area.

2.65 The number of responses collected in Castelldefels were much higher than in the rest of the study areas. Together, the other five exercises collected only 30 citizens' responses, due to the selected flight areas being far from any populated areas. The results indicated that the most optimistic respondents were the law enforcement agents and medical/emergency personnel, for whom drone use may assist in their jobs. When the responses to the three questions to citizens were analysed, concerns about natural life yielded the most concern, followed by noise, and then the reduction of greenhouse emissions rated as the most positive.

2.66 The authors compared the data on drones to aircraft operations, taken on the same time of day and area at the same time of year, but with different participants. Most of the people listening to aircraft labelled their noise as neutral, while for drones the most frequent label was silent. When the neutral option is removed, aircraft noise was rated more annoying than drone noise. The authors offered the following explanations for this, including the lower sound pressure of drones in comparison with aircraft; the already noisy urban environment where flights are taking place; and the short-range propagation characteristics of high frequency waves.

2.67 **Straub et al** presented a novel approach to collecting large volumes of data on engine design and noise perception of UAM noise. The authors are developing an app to enable a high volume of people to be able to set engine parameters, listen to the corresponding sound and then rate that sound using a standardised questionnaire. The idea is that by obtaining large volumes of data the perceptions of different psychoacoustic properties can be fed back and used as part of the design process in the initial stages of propulsion system development. The authors aim to establish a database which can be used to examine links between the design of the propulsion system and the subjective sound perception (design-to-perceived-noise).

2.68 After setting their engine parameters and listening to the playback, the user rates a) how unpleasant the sound was using a numerical 0-10 scale b) how annoying the sound would have been in an outdoor home environment and c) how the sound could be described to another person. To account for non-acoustic factors, the app also includes an optional sociodemographic questionnaire which asks about age, gender, attitudes towards aviation, circumstances under which the app was used, and more. The authors explain it is the intention for the app to be publicly available and designed to be usable and attractive to a broad range of users. It will include layperson-level explanations about psychoacoustics and electric aviation with the aim to identify crucial acoustic factors that contribute to the acceptance of aircraft with distributed electric propulsion systems such as UAM vehicles.

Chapter 3

Internoise 2024

3.1 This chapter contains findings that were presented at the Internoise 2024 conference, which was held in Nantes, France. The first paper is by **Green et al** and compared the perception of noise from conventional aircraft with that from UAS.

3.2 In this listening study, the authors wanted to design the annoyance element in a way that would allow for comparison with aircraft noise, due to it being more familiar to the participants. The idea was this would enable analysis of the contrasting sound characteristics of the stimuli, to gain insight into why participants responded how they did. The authors aimed to answer the following questions:

- What % of people find UAS noise more annoying than conventional aircraft noise at equal Loudness.
- The difference in noise level (∆ dB) required to achieve equal annoyance between UAS and conventional aircraft stimuli.

3.3 Three UAS sounds and three conventional aircraft sounds were chosen and were presented in pairs (one test and one reference sound). Participants (N = 41) answered the question "Which sound do you judge to be more annoying, disturbing or bothersome?". Loudness was normalised to 6 sone for each of the six reference sounds, and then the UAS sound level was varied over 7 noise levels (in ± 3 dB increments) above and below the reference sound level. The types of aircraft and UAS were selected to represent a wide range of sounds, and included:

- UAS

  DJI Matrice 300 (flight altitude 10m, cruise speed 5 m/s)

  Yuneec H520e (flight altitude 10m, cruise speed 5 m/s)

  Malloy T150 (flight altitude 25m, cruise speed 5 m/s)

- Conventional aircraft

  Boeing 787-8 Max (flight altitude estimated to be 435.2 ±57.4 m, cruise speed unknown)

  Airbus A320

3.4 For the UAS, the vehicle altitude and speed were known, therefore it was possible to recreate the flight path. For the aircraft sounds, an approximation of the flyover was re-created using the data available from a previous study.

3.5 The sound quality metrics (SQMs) for each of the vehicles were assessed to include loudness, sharpness, fluctuation strength, roughness, impulsiveness, and tonality. Sharpness was consistently higher in the UAS vehicles than for aircraft, and for tonality the opposite was observed. Fluctuation strength and impulsivity for all stimuli were both consistent and generally low, with the authors suggesting that any differences in participant response would not be a result of either of these acoustic characteristics. In terms of roughness, the A320 and M300 exhibited a higher level than the other stimuli.

3.6 The results indicated that at equal loudness, the percentage of participants who found the UAS sound to be more annoying varied between 37 and 61% depending on the test/reference pair. For the M300 vs 787-9 Dreamliner comparison, when the stimuli were at equal Loudness 54% of the participants found the UAS sound to be more annoying. Regression analysis was used to determine the difference in sound level (Δ dB) required to achieve equal annoyance between the two sounds. For this pair, this analysis revealed that the M300 would need to be 1.5 dB quieter than the 787-9 Dreamliner to be considered as equally annoying. For the other sound pairs, these values ranged between ranged from -2.7 to 1.9 ΔdB.

3.7 The authors explained that the comparison in which the UAS had the highest % annoyance rating at equal Loudness was the ’H520e vs. 787-9 Dreamliner’ at 61%. This pair was analysed in more detail and time histories and spectral analyses were presented. The time histories showed that the 787-9 Dreamliner had a more gradual rise in noise level, but the H520e had a higher peak (approximately +1 dB higher). The H520e also exhibited a higher sharpness level, which the authors believe contributed to the higher annoyance ratings.

3.8 The comparison in which the UAS had the lowest % annoyance rating at equal Loudness was the ’T150 vs A320’ at 37%. The time histories indicated that the T150 noise level showed a steady rise and fall with only around ±5 dB noise level change. The A320 noise level was more erratic and changes throughout the stimuli. Both roughness and tonality were much higher for the A320, particularly around 3 seconds into the stimuli, which the authors believe is the main driver of the higher annoyance rating for this stimulus.

3.9 **Green and Torija** presented findings from their work into using neural networks to predict perceived annoyance. The aim for this was to assess whether this method of predicting annoyance was more successful than using conventional sound pressure levels, which do not account for the character of sounds. Although, as explained in this report the concept of psychoacoustic annoyance (PA) has been developed to help achieve this, with the inclusion of SQMs, the authors explain that there is still a weighting towards loudness as the most important factor.

3.10 It is explained that previous work (Wang et al) used Convolutional Neural Networks[2] to predict annoyance from road noise using frequency amplitude spectra (with no time dimension). The aim of this study was to present a new method of predicting perceived annoyance of conventional and UAV aircraft sound events using a CNN with mel-spectrogram features. A Mel spectrogram is an acoustic time-frequency representation of a sound, showing the power spectral density on a Mel frequency scale. It is an adjusted spectrogram that enhances the low-frequency components for better human understanding.

3.11 The authors explain in detail how the network is trained and tested using data collated from five separate listening tests. The results indicated that the network is shown to outperform conventional regression models based on psychoacoustic annoyance as a predictor of perceived annoyance. The authors suggest further study could include testing different network architectures, and the addition of further collated data from studies on aircraft and UAV noise perception.

3.12 **Evensen et al** examined whether the direction of sound from UAVs had an impact on perceived annoyance. The rationale for this study is that it has been suggested that annoyance is higher for UAVs rather than conventional aircraft, due to listeners being unable to locate the source of the sound. This was a laboratory study including seventeen participants, designed to assess whether listeners found the sound from UAVs more annoying if they were unable to locate the direction from which the sound was coming. The experiment also aimed to determine if any particular direction of sound (such as from the left, right, or above) was perceived as more annoying than others.

3.13 Ten loudspeakers were installed in a circle with the listener sat in the middle, each at a heigh of 1.2 metres. Only two of these speakers, positioned at the front right and back left, were actively used. These speakers emitted pink noise throughout the entire experiment, creating a diffuse background noise environment. The remaining eight speakers were just used to disguise the actual noise source. Above the seating area, five additional speakers were mounted at a height of 2.5 metres, arranged in a cross pattern with one speaker at each core point and one directly overhead. These upper speakers, oriented downwards, were used to play back drone noise. Eight directions spaced 45 degrees apart plus directly overhead were indicated as response options. Participants responded via touch screen.

[2] A Convoluted Neural Network (CNN) is a specialised type of deep learning neural network designed primarily for processing structured grid data, such as images.

3.14 The results indicated that when the sound was played from the back speaker, participants only correctly identified this direction 13% of the time. When the sound came from the left speaker it was correctly localised 79% of the time, and the signal from the right speaker was correctly identified 70% of the time. From the front speaker, the sound was correctly identified 63% of the time. In terms of annoyance, sound from the front speaker was perceived as the least annoying, with left and back indicating the highest levels of annoyance. The authors concluded that there does not appear to be a significant correlation between the annoyance level and the success rate for correct localisation for signals coming from left, front and back. They suggest that this is not an important non-acoustic factor in determining annoyance from UAV noise.

Chapter 4

Other Publications

4.1 There have been a number of other publications on the human impacts of emerging technology aircraft noise over the past twelve months. Many of these focus on the public acceptance of any proposed movements, and the arising considerations around this.

4.2 **Lingham et al** published a paper discussing the challenges and future directions of human-drone interaction (HDI) research. This aim of this study is to address the gap in identifying and addressing human factors challenges associated with the introduction of drones in public space. The authors address this by interviewing field experts to identify relevant use cases and major human factors challenges in HDI.

4.3 The main contributions of the study are to:

- Provide insights into the human factors that are relevant for the potential HDI use cases in public spaces.
- Distinguish between the roles of bystanders and recipients and their respective challenges.
- Identify and address critical human factors challenges for both trained and untrained individuals.

4.4 Eleven experts from academia, research institutes, and industry across the world were recruited for a semi-structured interview. The recruitment criteria were that the experts needed to have at least five years of experience in their field and at least a year of experience in HDI. Participants were from eight countries, primarily from Europe, including France, Germany, Poland, Spain, Slovenia, the Netherlands, and the United Kingdom, with one expert from Canada. Figure 6 indicates the structure of the interviews.

4.5 The authors explain that four themes with fourteen sub-themes were identified from the thematic analysis. The main themes consisted of 1) landscape of use cases, 2) human-roles and safety concerns, 3) human factors challenges, and 4) solution areas to human factors challenges.

4.6 For the first, *landscape of use cases* the participants talked about emergency response case uses e.g. search and rescue operations, locating victims in war zones, natural disasters and firefighting and use in directions evacuees in emergency situations.

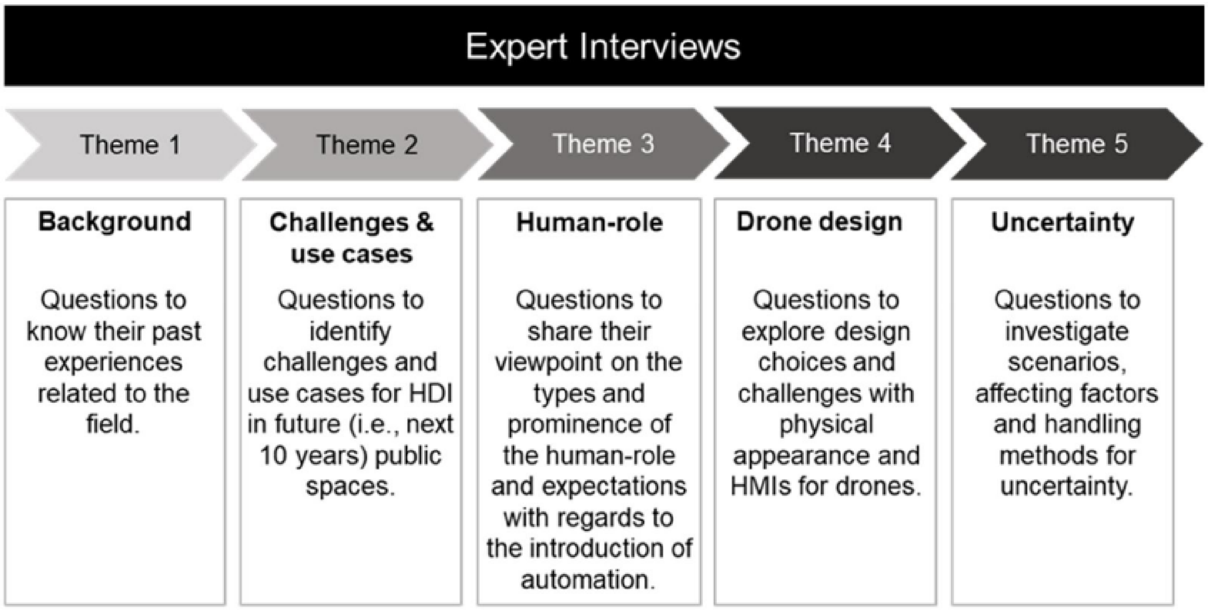

Figure 6: Description of the five themes for the semi-structured interviews with the experts.

4.7 Under this category, interviewees also discussed delivery drones (including for healthcare and commercial uses), in medical delivery use cases, and for delivery of goods and suggested that the recipient should not be allowed to handle the drone for safety purposes. Surveillance use cases were raised, such as monitoring traffic, crowd monitoring and assisting the police at events. Entertainment cases such as displays and filming were also discussed, and finally human assistance scenarios.

4.8 In terms of *human roles and safety concerns*, three areas were identified: operator, recipient and bystander. Interviewees reflected on the control and safety challenges that arise with the shift in operator role. It was discussed that recipients are likely to have very little to no experience or training on how to interact with drones. Safety emerged as a primary concern, with minimal interaction expected between a drone and a recipient. In terms of bystanders i.e. those people not directly involved with the operations, interviewees mentioned that bystanders are sensitive to the implications of drone capabilities towards privacy and security.

4.9 For the third theme of *human factors challenges*, responses included issues around uncertainty, awareness, and perceived risk. Uncertainty included operators and receivers, e.g. for an operator, uncertainty could arise due to the lack of situational awareness or the lack of clarity on the takeover procedures. Factors such as drone behaviour, identification, proximity, physical appearance, and sound were identified as possible causes for uncertainty in a recipient. Uncertainty arises when the recipients are not used to drones, and when the flying behaviour of drones is not natural to predict.

4.10 It is explained that interviewees emphasised the importance of both operators and recipients being aware of the drone’s purpose and position in the environment. Operators need situational awareness to safely operate the drone, while recipients require awareness to understand the drone’s intent and safely interact. Perception of safety was frequently recognised as a factor affecting the interaction experience and caused by uncertainty.

4.11 For the fourth theme, *solution areas to human factors challenges*, four sub-themes were identified: flying behaviour, propellor sound, physical appearance, and human-machine interaction. In terms of flying behaviour, interviewees expressed that drone flight paths and patterns influence recipient perception of drones. Interviewees mentioned the relationship between flying behaviour and human factors, such as trust, uncertainty and social acceptance and suggested exploring the effect of different flying behaviour. One of the participants suggested that conducting user research on sound design such as propellor sound, could assist the acceptance of drones in human environments.

4.12 In relation to physical appearance, interviewees all agreed that the appearance of the drone is an important factor in the experience of recipients. They expressed the need for drone design to reflect its intention and purpose based on a specific use case as this may positively influence the uncertainty factor and increase awareness of the intention.

4.13 Human-machine interface design was also discussed as a way to improve awareness and reduce uncertainty for both operator and recipient. The authors summarise the findings and conclude that to address the issues of uncertainty of recipients, it is suggested that designers should develop specific drone behaviour, physical appearance and drone interfaces that are easy to interpret and help predict the drone’s intention.

4.14 **Stolz et al** published their findings from an online survey into drone acceptance across six European countries. Nearly 3000 participants answered questions on their general attitudes towards drones, concerns, approval for different use-cases, acceptable flight areas and the impact of personal and demographic characteristics on drone acceptance. The survey was part of the USpace4UAM project, and included Germany, the UK, Poland, Spain, the Czech Republic, and Austria.

4.15 Respondents’ overall attitude, acceptance of use cases, and different concerns about drones were measured on a 7-point scale with extrema labelling (attitude: 1 = very negative, 7 = very positive; concerns: 1 = not concerned at all, 7 = very concerned; acceptance of use cases and flying area: 1 = strongly disagree, 7 = strongly agree). Participants were also offered a “Don’t know” option for the items mentioned. Concerns (10 items) and uses cases (11 items) were measured via matrix questions in which the participants were asked to rate each item from the matrix on the scale. Concerns were captured by asking participants to write their worries about drones in an open text form. The survey ran from April to May 2022.

4.16 The results indicated that for attitudes towards drones, the most positive attitudes were found in Poland, with the most negative in Austria. A question on attitudes was asked at the start of the survey and again at the end, with the results shown in Figure 7.

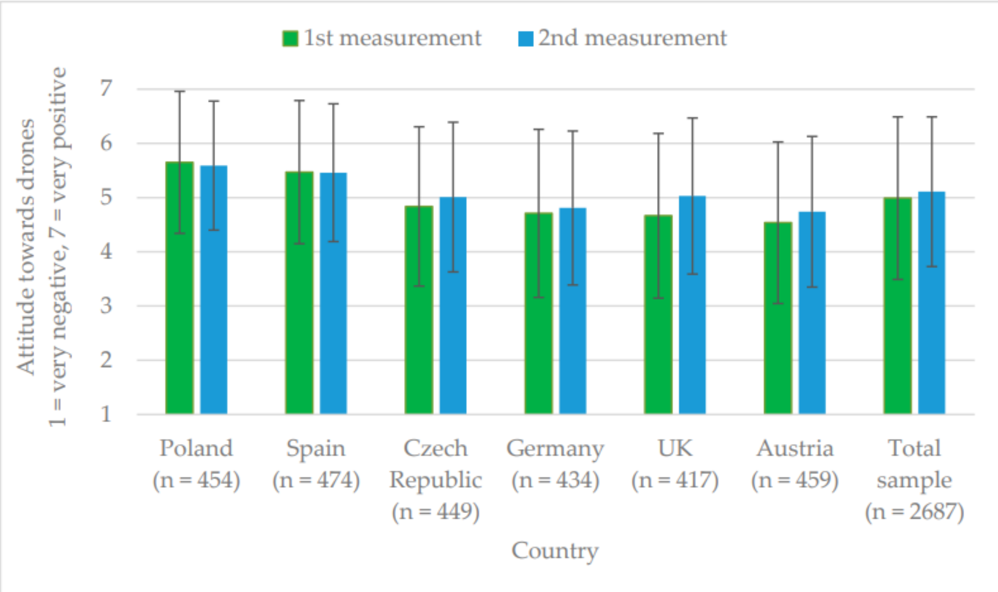

Figure 7: Mean values of attitude toward drones at the beginning and end of the survey for the participating countries and the total sample. Whiskers indicate standard deviations.

4.17 There was a slight increase in attitude scores at the end of the study, for all countries except Poland and Spain. Statistical analyses indicated that there was a significant improvement between the first and second measurements for the overall sample.

4.18 In terms of use cases, disaster management, monitoring transport networks and energy supply were more accepted by people than the use cases ranging from photos and videos for news reports to passenger transport, which were moderately accepted. The use cases were grouped into civil and public use, and private and commercial use.

- Civil and public use cases: disaster management, research, agriculture, medical use, civil protection.
- Private and commercial use cases: photos and videos for news reports, parcel delivery, hobby, photos and videos for advertisement, passenger transport (air taxi).

4.19 A paired t-test revealed significant differences ($t = 46.31$, $p < 0.001$, $n = 2572$) between public and civil ($M = 5.62$, $SD = 1.24$) and private and commercial drone applications ($M = 4.53$, $SD = 1.47$) in the total sample. There were also significant differences between countries as shown in Figure 8.

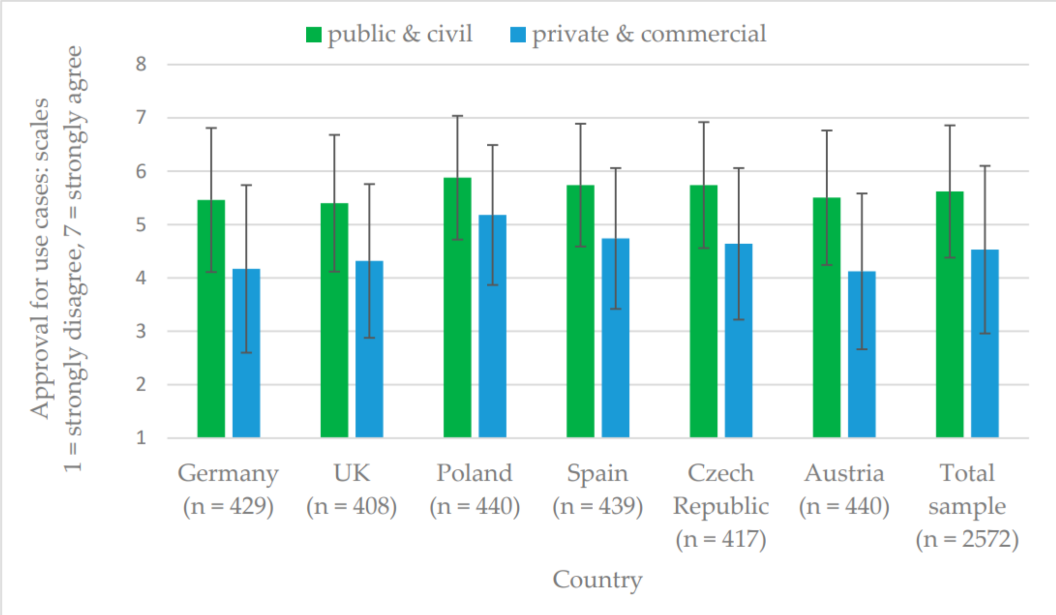

Figure 8: Approval for public and civil use cases compared to approval for private and commercial use cases in the different countries.

4.20 Further statistical analysis revealed a significant difference for both private and commercial and public and civil use cases between the countries.

4.21 When analysing data relating to concerns of participants, the authors found that people were moderately to intensely concerned about different aspects. The biggest concern was that drones might violate citizens' privacy or be misused for criminal actions. Participants were least concerned about drone noise. This is illustrated in Figure 9.

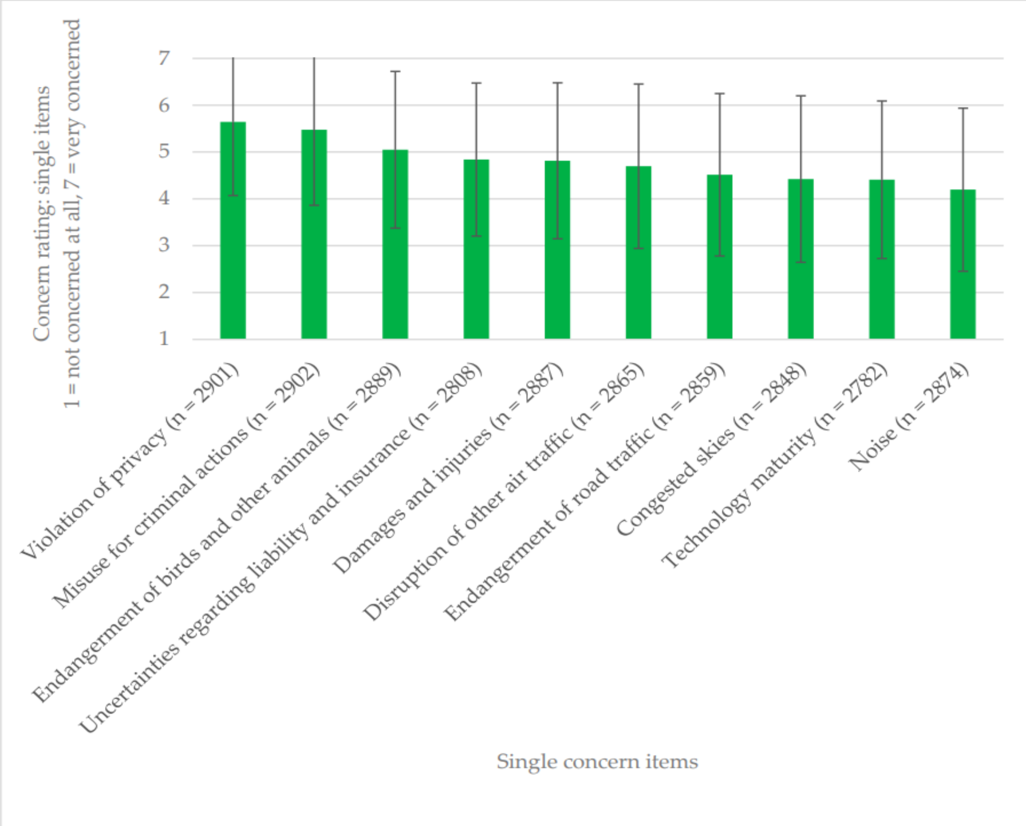

Figure 9: Participants' single concerns about drones. Whiskers indicate standard deviations.

4.22 Participants answered open questions regarding their concerns, and the resulting concern-related statements were analysed according to the frequency of content-bearing keywords. The five most common concern-related words of each subsample were presented. The authors explain that the word 'privacy' was mentioned most often across all countries and confirm that the results are consistent with the findings from the previous analysis, which indicates privacy concerns and concerns about criminal abuse are most important.

4.23 The relative frequency of people with no concerns was 28% for the whole sample, and 34.5% for the UK sample. Poland (35%) and the UK had the highest percentage of people with no concerns, with the Czech Republic displaying the lowest number of no concerns at 16.2%.

4.24 The participants were also asked about the acceptability of locations where drone flight might occur. The data indicated that drone flight was most acceptable in uninhabited regions, acceptance was moderate for sparsely populated areas and small towns and was negative for medium-sized and big cities.

4.25 The authors analysed the data for insights into personal and demographic factors that influence acceptance of drone flight. Knowledge and interest in modern technology were the strongest predictors of the general attitude toward drones and approval for different use cases. They found that knowledge is more relevant for attitude and approval for private and commercial use cases. An interest in technology is the more important factor for approval for public and civil use cases. In terms of having concerns, age was the most important factor, and the authors present several theories as to why this may be, including possible higher concern around safety, risk around reduction of social interactions and higher privacy concerns.

4.26 **Eißfeldt and Stolz** published findings from their study on public perception of air taxis in Germany. This was part of a larger telephone survey on drone acceptance, conducted at the end of 2022, (**End et al**, referred to in CAP 2692) and contained a dedicated section on air taxis. The authors aimed to obtain a view of the individual differences that occur in noise perception and use open question formats to gain insight into perceived risks and benefits and how these relate to perceptions of air taxis. They were also interested in perceptions of the noise aspect of air taxis and how this relates to acceptance.

4.27 1001 participants were surveyed, ranging in age from 18 to 94 years old and this section of the wider study contained ten questions on air taxis. The authors refer to the report by EASA (2021), which stated that after safety concerns, noise is the second main concern expressed by European citizens about UAM. EASA also reported that in listening tests, the tonal quality of eVTOLs with their multi-rotor drives is experienced as more disturbing than that of conventional aircraft at the same sound pressure.

4.28 Participants were asked about their general attitude towards air taxis, and the results were split into the following categories: very positive (7.6%), rather positive (37.4%), rather negative (35.4%), very negative (19.1%) and don’t know (0.6%). The benefits and risks of air taxis were assessed firstly using closed questions, and the results are presented in Figure 10. The same was assessed via open questions, with software being used to collate the top fifty most frequent responses. The words accidents, environment, people, traffic, and transportation were mentioned in the context of benefits and risks, indicating relevance for both topics.

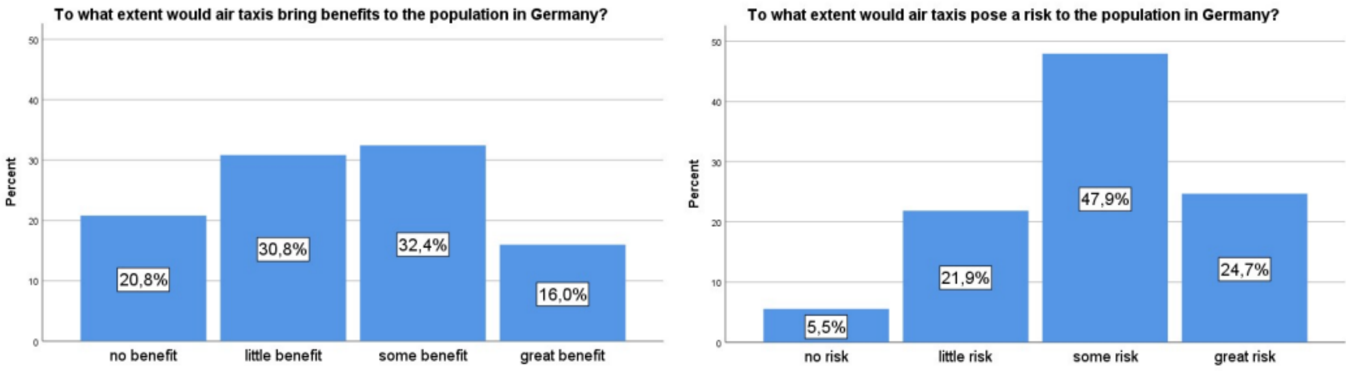

Figure 10: Expected benefits (left) and risks (right) of air taxis for the population in Germany.

4.29 Attitude towards air taxis correlated strongly with both expectations, positively with expected benefits (Spearman's $\rho = .659$, $p < .001$) and negatively with expected risks ($\rho = -.495$, $p < .001$). Although expected risks are more pronounced (72.6% indicated "some risk" or "great risk"), expected benefits correlated more strongly with the attitude towards air taxi.

4.30 The study also investigated noise sensitivity. About 20% of respondents described themselves as very sensitive to noise. 33% indicated they lived near a busy road and/or railroad line, and about 62% stated they heard aircraft and/or helicopter noise daily. On a drone-related question, about 53% indicated being not or rather not concerned about drone noise.

4.31 Further analysis revealed that attitude towards civilian drones correlated positively with attitude towards air taxis. Noise sensitivity showed a stronger negative correlation with civilian drones than air taxis, and the same was found for noise concerns. Measures of neighbourhood traffic noise (living nearby busy roads or railroad lines or audible air traffic) did not correlate with attitudes towards drones or air taxis.

4.32 **Vaughn and Christian** published findings on individual response trends to UAM noise in a laboratory setting. The aim of the study was to investigate the relationship between noise level and number of events on individual annoyance responses to UAM noise. The authors explain that by understanding individual responses in more depth, more protective measures for vulnerable groups may be considered when trying to minimise the impacts from UAM noise.

4.33 The psychoacoustic study was conducted at NASA in early 2023 and included thirty-eight participants who were exposed to various acoustic scenarios, with UAM flyovers varying in number. Participants responded to a total of fourteen scenarios with repeats included.

4.34 Multilevel linear mixed effects (LME) regression was used to calculate the best fit for the relationship between noise level and annoyance for the whole study population, which is shown in Figure 11.

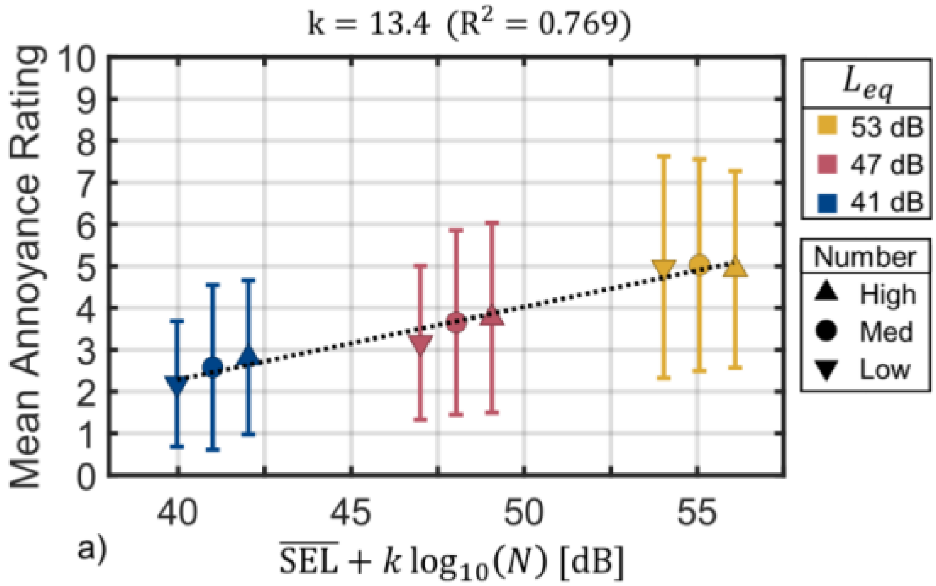

Figure 11: LME model fit for the overall study population.

4.35 Data from individuals were then compared to the whole study population and statistically grouped into four clusters.

- Cluster 1: Differs most from the population result. Overall, this cluster has the largest number of individuals, and they seem more annoyed by the average noise level of the flyover events rather than the number of events.
- Cluster 2: Appears close to the population result.
- Cluster 3: Also appears close to the population result. Individuals in this cluster exhibit greater annoyance to the number of events than suggested by the population result.
- Cluster 4: This is the second largest cluster of individuals. Inconclusive as to whether they are more annoyed by noise level or number of events.

4.36 The authors concluded that the results indicated that individuals could employ different strategies for listening and responding to the various noise scenarios. They explain that using the data for the whole population to create noise policy may impact on several individual groups differently and some people may become disproportionately affected. They suggest further investigation into trends of individuals in community noise studies may reveal similar trends that can help guide future noise mitigation for those sections of the population that differ in their processing of noise and number trade-offs.

4.37 **König et al** published their study on the prediction of annoyance due to drone noise and looking at technical, operational and psychoacoustic parameters. This study investigated the following questions:

1. Which versions of psychoacoustic metrics most accurately predict the annoyance of electric drone noise and how do these compare to A-weighted sound pressure level (SPL)?
2. Do sociocultural aspects, such as continental region or age, influence the perception of electric drone noise?
3. How effective are technical and operational parameters in predicting annoyance levels compared to psychoacoustic metrics?
4. To what extent can design modifications reduce annoyance through adjustments in operational and technical parameters, and what are the effects on the performance of drones?
5. Are psychoacoustic metrics reliable measures of evaluating the annoyance associated with a given design solution?

4.38 The authors investigated these questions through creation of a sound database from experiments conducted in a hover-test-bench and real flights using a Rubina X8 drone, operated indoors. These experiments involved a wide range of parameter variations and operational conditions. Annoyance responses to the measured sounds was determined in a global digital user study, conducted via a smartphone app with participants (N = 578) from the field of paid crowdsourcing. Participants were selected from an even distribution across continents (Europe, Asia, and America), age groups (18–32, 33–47, 48–62). A total of 161 samples of the hover-test-bench and 46 samples of the real flights were included in two separate studies.

4.39 The context provided to listeners was a scenario involving parcel delivery within a city setting. Participants were asked to state which sound they preferred from a choice of A or B for each pairwise presentation. Each participant conducted 100 pairwise comparisons of sound samples, which took around 35 min to complete.

4.40 The results on annoyance and acoustic parameters indicated differences in variable importance of psychoacoustic metrics depending on the applied version/norm of metric that was used. The data showed an improvement in annoyance through the reduction of the analysed psychoacoustic metrics of loudness, sharpness, tonality, and roughness or fluctuation strength. Loudness was the best predictor of annoyance, which confirms the results of Lotinga et al, who also found loudness was the main contributor to annoyance. The authors suggest that the results show the importance of carefully choosing the version/norm of a metric, as it impacts variable importance and the outcomes of annoyance models.

4.41 To investigate sociocultural aspects, the authors analysed the sociocultural groups in terms of age, gender, continent, size of town, technical affinity, noise sensitivity, and drone ownership. The results indicated that similar overall characteristics of the dependencies of annoyance on psychoacoustic metrics were found. The authors suggest that the findings of this study indicate that annoyance from drone noise is perceived the same way independent from sociocultural factors.

4.42 Technical and operational parameters were also investigated in terms of their impacts on annoyance, in particular when reducing the speed of the blade tip. It was found that a 20% reduction in tip speed still showed acceptable drone performance while beneficially targeting annoyance.

4.43 The authors suggest that further work should evaluate existing annoyance models for electric drone noise, considering different psychoacoustic metrics and flight phases.

4.44 **Stolz et al** published their work on a virtual reality methodology to identify factors that influence public acceptance of drones in city environments. The study included ten participants, who were shown drone flight scenarios via virtual reality environments, including different types of drones with varying purposes in four urban areas: an industrial area, a city centre, a residential area, and a park.

4.45 The aim of the study was to use an explorative approach and collect data to generate hypotheses. The focus of the study was primarily on collecting qualitative data, which were collected through interviews. In addition, subjective data from questionnaires and objective data were also collected. The aim was to generate results that provide a comprehensive picture of the acceptance of drone flights. The authors posed the following research questions:

- Which factors determine the acceptance of UAS fights in urban environments?
- Which aspects related to the acceptance of UAS fights in urban environments need (further) investigation in the future?

4.46 The study was conducted at the DLR, Germany and used the new state-of-the-art pedestrian simulator, with a motorised treadmill that can go in any direction, combined with a VR headset and associated controllers. It is explained that a complex environment with separated focus areas was created based on the outline of Cremlingen, a small city near Brunswick. This included an industrial area/business park, a city centre, a residential area, and a park. The intention was to make small, self-contained sections that can be fully experienced for 15 minutes.

4.47 Different UAS types and use cases were presented in urban scenarios, including air taxis, rescue drones, quadcopters with private or commercial missions, and delivery drones. For the quadcopters and delivery drones, suitable open-source sound samples were used. In each scenario, different UAS types representing different use cases were shown. Various types of drones with different purposes were presented in the simulation. These included a small quadcopter, an octocopter, a UAV helicopter, and a VTOL with two seats.

4.48 The results indicated that various factors influenced the likelihood of drone acceptance. The authors produced a diagram to summarise the main aspects that contribute to acceptance, which is shown in Figure 12.

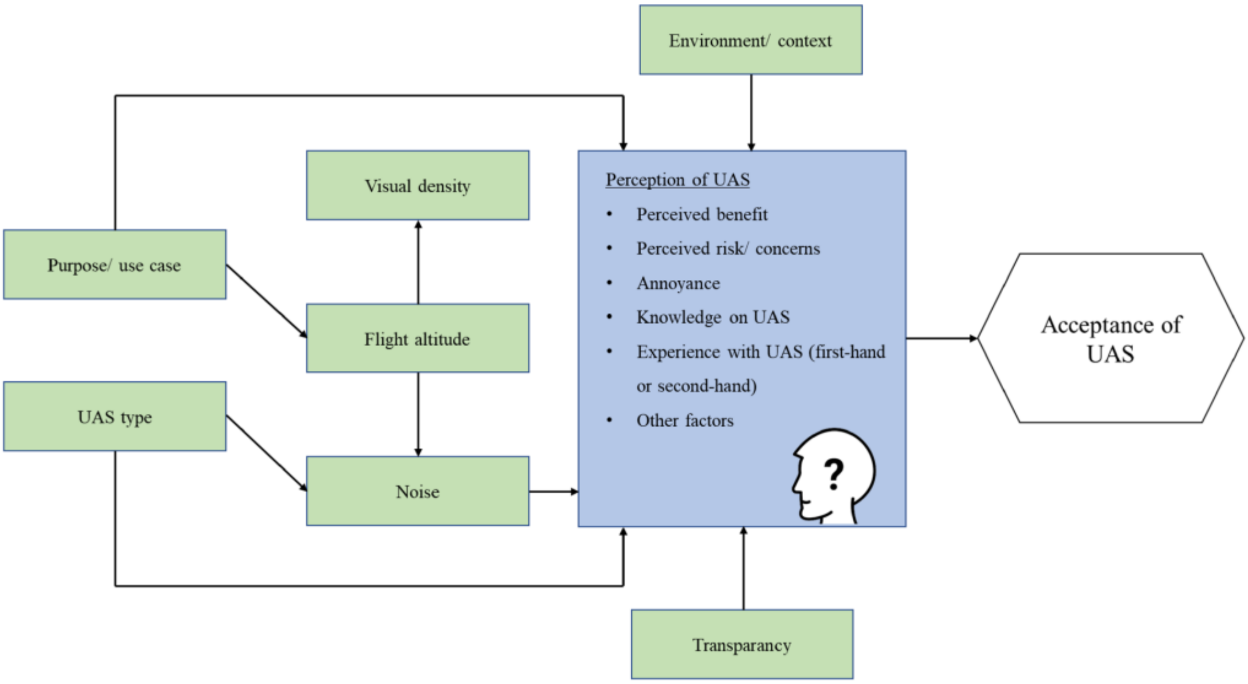

Figure 12: Path diagram of UAS acceptance based on the study findings and previous research.

4.49 The blue box represents people and how they perceive the various stimuli around them, with arrows indicating relations (not statistical) and their direction. In this study, the participants experienced UAS fights in various urban settings, leading to the finding that UAS fights are more tolerable in certain city areas. They are more acceptable in industrial or business parks and city centres than in residential areas and parks. Participants expressed the most discomfort in the residential area, while UAS fights were least disruptive in the industrial area of the study, hence Figure 12 showing the influence of environment on acceptance. The relationship with noise is also shown. The interviews revealed that UAS flights are more expected in industrial parks, and the UAS sound is less disturbing due to the existing noise in these types of areas. The results also indicated that public applications of UAS are more acceptable to people than private or commercial ones.

4.50 The authors suggest further study with larger sample sizes is required and could involve the use of structural equation models (SEMs) which could further analyse the relationships between the variables involved in acceptance of drones. They also suggest examining the impact of experience and knowledge about UAS on its acceptability more thoroughly. The sample in this study was highly experienced and informed about UAS and its possible applications, so examining a study population with less experience and knowledge would be of interest. It is suggested that further exploration on whether acceptance changes when people receive more detailed information about the use case would be of use.

4.51 **Wang et al** published findings from their study on experts' perceptions on factors influencing drone acceptability. This study is part of a larger research project consisting of three main workstreams: a scoping literature review (Wang et al 2023, reported in CAP 2692), an expert survey (from drone experts in Switzerland), and semi-structured interviews with domain experts. The authors aim to answer the following questions:

- how do experts evaluate the acceptance of drones in different contexts and applications?
- What do these experts identify as key challenges for successful drone implementation from the societal acceptance perspective?

4.52 The aim was to identify the key factors that either improve or hinder drone acceptance, by gathering what experts believed to be the most significant challenges and potential solutions in terms of drone acceptance. An online survey was used to gain responses from 117 drone experts within Switzerland. The authors included experts as people involved with drones on a professional level, including (1) private sector members, such as aviation or robotics industry, (2) public sector institutions, such as governmental and non-governmental organisations, and (3) academia, such as research institutions and universities of applied sciences.

4.53 The survey consisted of thirty-two main questions, with some containing follow-up questions. The data was analysed in terms of descriptive analysis, factor analysis and thematic approaches to the data.

4.54 The authors provide a detailed description of the different types of responses, but broadly concluded that experts highlighted operational details such as financial viability and resource allocation as pivotal to both the success of drone projects and their societal acceptance. They stated that concerns over themes such as noise and visual pollution, or design and human control, were not the most notable features in the study.

4.55 The findings also highlighted the important role of public awareness and education, which the authors describe were raised as a central strategy to foster more informed public policy on urban drones, and their benefits and potential risks. Themes of privacy, safety, and regulation were recurring throughout the study. Trust towards different institutions deploying drones varies, while the need for dedicated awareness and education efforts to inform public understanding was also a theme. The authors concluded that there is an inter-connected number of challenges that require governance to have consideration of all stakeholders' viewpoints and complexities when integrating drones into society.

4.56 The University of Birmingham led two studies in the UK, namely a public dialogue study and a national representative survey. The work was funded by UK Research and Innovation (UKRI) Future Flight Challenge, and delivered by Innovate UK and the Economic and Social Research Council (ESRC) and aimed to explore and understand public views on drones, electric vertical take-off and landing vehicles (eVTOLs), and electric or hydrogen regional air mobility.

4.57 The public dialogue study, which was supported by UKRI's Sciencewise programme and delivered by Thinks Insight & Strategy aimed to understand the publics' hopes and fears around Future Flight technologies, systems and services as well as their expectations for regulation and decision-making. The study included 43 participants from the UK, who were asked to attend seven workshops which covered views on existing transport methods, the three Future Flight technologies, views from experts on their selected topics and then discussing the main principles they wished to see taken forward.

4.58 The authors found there were fourteen main principles that came out of the study, which are summarised here:

i. **Future Flight technologies must be used for public good – they should only be rolled out if there are more positive impacts than negative ones for society.** There was a strong consensus that Future Flight technology should benefit the whole population and consider the rural communities as well as cities.

ii. **Research and testing must be carried out to make sure that policy and regulation for Future Flight technologies aligns with these principles.** The desire for policies on wildlife, noise and visual pollution, privacy, social inclusion and accessibility to be in place before roll-out.

iii. **The development of Future Flight technology and services must involve collaboration with specialists and the public.** In particular, for flight path planning, wildlife and those with accessibility/health issues.

iv. **Future Flight developers and operators must be held to account by independent bodies.** For issues around safety, sustainability, wildlife, surveillance concerns, and social inclusion.

v. **Future Flight technology and development must be transparent.** For example, in the ethics of production and overall sustainability of the technologies.

vi. **The roll-out of Future Flight technologies must be properly resourced.** Participants wanted enough resources in place to ensure human accountability at all times in terms of safety and managing airspace.

vii. **The UK as a whole must benefit from leading in Future Flight technologies, behaving ethically through international co-operation.** Economic benefits for the UK from the development and deployment of these technologies should be distributed across society, rather than limiting benefits to profitmaking companies.

viii. **Future Flight technologies must be managed safely and held to the same level of, or higher, safety standards as existing technology.** The need for certainty and reassurance around safety for passengers and non-passengers, including considerations of fuel and batteries.

ix. **Flight paths must limit the negative impact of noise pollution and visual congestion on people.** Participants stressed flight paths and transport hub placement should be designed with the potential benefits and negative impacts of noise pollution and visual congestion in mind, balancing the two along with public input. Maximum noise level regulation.

x. **Future Flight vehicles and operations must be designed with accessibility in mind from the start.** Improvement of the accessibility and social inclusion of public transport.

xi. **Future Flight services must be affordable to the public.** Strong feeling that Future Flight services should not only be available for the wealthiest in society, when there are negative consequences for the rest of the public, funded by the taxpayer.

xii. **Limiting negative impacts of Future Flight on wildlife must be a priority, avoiding tick-box exercises**. Desire for independent research and experts to have input into decision-making about Future Flight technology, with a priority on the avoidance of impact to wildlife.

xiii. **Future Flight job opportunities must be available in a fair and accessible way.** Importance of training and job opportunities to be open to all.

xiv. **The use of drones for surveillance must be proportionate to the level of the potential threat, with clear guidelines.** Participants wanted case-by-case decisions on use to be made, with regulation and oversight carried out by an independent organisation.

4.59 The authors concluded that although there were initial reservations around the introduction of this new technology, participants were soon able to understand the benefits that may be afforded by some of the use cases. They suggest that further public engagement would be valuable to build trust and maintain transparency going forward. They also stress the need to set up and have in place independent bodies, regulation, and the means for consultation to be successfully conducted by government.

4.60 The field study was conducted between March and April 2024 among a representative sample of 3,279 adults aged 18+ living in the UK. All respondents who took part in the survey were drawn from the YouGov panel of over 400,000 active panel members who live in the UK. Authors ensured representativeness, and quotas were set during fieldwork on age, gender, social grade, urban/rural status and region.

4.61 The authors found that awareness of drones is high with (95%) of people stating they have heard of them. This was reduced for advanced air mobility (28%) and electric or hydrogen regional air mobility (24%) technologies, with men having a higher incidence than women in terms of awareness.

4.62 For perceptions of future flight technologies, the authors concluded that the benefits were perceived to outweigh the reservations and concerns, particularly the benefits to emergency services and the ability to reach isolated communities. Drawbacks included cyber security, impacts on wildlife, safety, congestion, privacy and potential inequality of access. For both drones and eVTOLs, respondents were more likely to perceive them to be beneficial in remote and rural areas compared to urban and suburban ones.

4.63 Participants expressed a preference for investment in sustainable ground transport ahead of future flight technologies. Regional electric or hydrogen flight across the UK or in rural/remote areas were seen as higher priority than electric flight in urban areas.

4.64 The authors found that a large proportion of participants would like a greater involvement of government in technology and transport sectors, along with addressing climate change. The feeling was that government should regulate private companies to ensure they act on climate change, and that it is the role of the government to ensure that the benefits of new technologies benefit all. People generally reported low levels of trust in both local and national government to accurately explain and mitigate the impacts of technology on society, as well as ensuring that future flight technologies are safe. It was proposed that such low levels of trust could be avoided by an independent body acting as a link between government, industry and the UK public which has the public's support.

4.65 It was found that people envisaged non-passenger carrying drones to be commonly used in the next ten years, but this was lower for eVTOLs. People expressed they would be willing to be passengers in eVTOLs once they had been operating safely for several years.

Chapter 5
Summary

5.1 This report has provided an overview of the research between March 2024 and March 2025 into the potential effects of noise from emerging aviation technology on people. The main relevant findings presented at the Quiet Drones and Internoise conferences have been summarised, and findings which have been published in the literature over this twelve-month period have been described.

5.2 This area of research continues to expand rapidly, with particular attention paid to the understanding of different sound quality metrics such as loudness, sharpness, roughness, tonality, fluctuation strength and impulsiveness, to further understand which acoustic characteristics impact annoyance and listener perceptions.

5.3 The use of listener experiments and virtual reality scenarios have been employed to gain insight into which aspects of drone noise are perceived as more annoying, and to provide comparisons with known transportation noise such as conventional aircraft.

5.4 Public dialogue studies have enabled researchers to gain a detailed analysis of people’s thoughts and perceptions of such new aviation technology and allowed for exploration and discussion of a wide range of factors such as benefits, concerns, acceptance and governance of eVTOLs and drones going forward.

5.5 It is intended that update CAP reports will be produced on an annual basis, and will include findings presented at relevant conferences, and from published work in this growing area of research. Understanding the role of non-acoustic factors, and impacts on sleep and health effects, alongside the work on sound quality metrics and annoyance, will continue to be important for developing noise policy and legislation for this new aviation technologies, and for the protection of the people exposed to noise from them.

Chapter 6

References

Aalmoes, R. and Sieben, N. (2024) Human response to characteristic sound of drones. *Quiet Drones.*

Barrado, C., Kuljanin, J. et al. (2024) Insights of the citizens perception during a 3-days outdoors flight demonstration. *Quiet Drones.*

Bauer, M.W. Bartels, S., Redmann, D. (2024) UAM Community Noise Impact Studies in Project PAULA. *Quiet Drones.*

Cotton, C., Gosschalk, K. (2024) The University of Birmingham and Future Flight Challenge: Future Flight Survey 2024. YouGov, UKRI, Innovate UK, ESRC.

Eißfeldt, H. & Stolz, M. (2024) Public perception of air taxis in Germany: anticipated risks, benefits, and noise sensitivity. *Proc. Mtgs. Acoust*. 54, 040004

Evensen, K.B., Hauge, L.H., Gjestland, T. (2024) Directional Perception and its Influence on Noise Annoyance from Unmanned Aerial Vehicles. *Internoise.*

Green, M. and Torija Martinez, A. (2024) Soundwalking in Salford: A Soundscape Approach to Drone Noise Assessment. *Quiet Drones.*

Green, N., Torija, A. J. (2024) Comparing the Human Response of Unmanned Aircraft System Noise and Other Transportation Noise. *Quiet Drones.*

Green, M., Torija, A.J. (2024) A Deep Learning Approach to Predicting Aircraft Sound Annoyance. *Internoise.*

Green, N., Ramos-Romero. C, Torija, A.J. (2024) Comparison of the Noise Perception of Conventional Aircraft and Unmanned Aircraft Systems. *Internoise.*

Kawai, C., Jäggi, J., Georgiou, F. et al. (2024) How annoying are drones? A laboratory study with different drone sizes, maneuvers, and speeds. *Quiet Drones.*

König, R., Babetto, L., Gerlach, A. et al. (2024) Prediction of perceived annoyance caused by an electric drone noise through its technical, operational, and psychoacoustic parameters. J. Acoust. Soc. Am. 156 (3).

Lingham, S.N., Franssen, M. et al. (2024) Challenges and Future Directions for Human Drone Interaction Research: An Expert Perspective. *International journal of human-computer interaction*. https://doi.org/10.1080/10447318.2024.2400756

Lotinga, M.J.B., Green, M.C., Toríja, A.J. (2024) How do flight operations and ambient acoustic environments influence noticeability and noise annoyance associated with unmanned aircraft systems? *Quiet Drones.*

Masulo, M., Gravina, N., Iaderosa, R. (2024) An investigation on the effects of drone noise in an urban context. *Quiet Drones.*

Merino-Martínez, R., Yupa-Villanueva, R.M., von den Hoff, B. (2024) Human response to the flyover noise of different types of drones recorded in field measurements. *Quiet Drones.*

Stolz, M., Papenfuß, A. et al. (2024) Harmonized Skies: A Survey on Drone Acceptance across Europe. *Drones*. 8, 107

Stolz, M., Rehm, M., Papenfuß, A. et al. (2024) See it, hear it, feel it: an explorative virtual reality study to identify factors determining public acceptance of drones in different city environments.

Straub, D., Schade, S. et al. (2024) Novel Approach to assess the link between engine design parameters and noise perception. *Quiet Drones.*

Thinks & Insight Strategy. (2024) Framework for Future Flight in the UK: Principles from a deliberative Public Dialogue.

Vaughn, A.B. and Christian, A.W. (2024) Individual response trends to Urban Air Mobility vehicle noise in a laboratory study. *Proc. Mtgs. Acoust.* 54, 040011

Wang, N., Mutzner, N., Blanchet, K. (2024) ‘We Need Time…’: An Expert Survey on Societal Acceptance of Urban Drones. *Science and Public Policy*, 00, 1–19.

Woodcock, J. Thomas, A., McLeod, L. (2024) Influence of operational and contextual factors on the human response to drone sound. *Quiet Drones.*