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Human response to characteristic sound of drones

Session: Human Response to UAM Noise

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Abstract New aircraft mobility concepts feature the operation of drones close to locations where humans reside. Main applications currently include photography and video recording and hobbyists operating drones, but observation, inspection and package delivery are expected to become important future applications using drones. Residents close to operations of drones, will therefore be impacted by the increase of the sound events of these vehicles, either by larger drones and thus higher sound levels, or by the increased number of movements, or by both. Since the characteristics of drone sounds are different from other air vehicles, such as helicopters or airplanes, annoyance response is also expected to be different, even at similar loudness levels, as seen in recent studies where drones were considered more annoying than helicopters. Human perception studies with simulations of single event flyover sounds of drones and other vehicles provide insight into a human's reaction to these vehicles. A new perception study using both visual and auditory stimuli has been performed with similar peak sound levels for flyover events of different vehicles. The results of this study show that both aircraft and drones are rated louder in rural environments than in urban environments. Also, aircraft flyovers are considered more annoying than drone flyovers. No significant difference has been found between drones and helicopter flyovers. But with same peak sound level, drones are perceived significantly louder than Pipistrel Electro aircraft. Some of these results differ from earlier findings, possibly because of other sound characteristics, operational procedures, or different background environments.

Keywords: Noise Annoyance; Noise Perception; Aircraft Noise, Perception study, Drones.

1. INTRODUCTION

1.1 Drone concepts

Technological developments in electronics, information technology, battery technology and aerospace have made new kind of air vehicles a reality. One category of these vehicles are called Unmanned Aerial Vehicles (UAVs), also known as Unmanned Aerial Systems (UASs), or a more common term now used: drones. The concept where drones operate in (densely) populated cities is called Urban Air Mobility (UAM) (EASA, 2021). The concept where drones also operate between different cities is called Advanced Air Mobility (AAM) (Rizzi et al., 2020). These new aircraft mobility concepts feature the operation of drones close to locations where humans reside. Main applications of these drones currently include photography and video recording and hobbyists operating drones. But the named concepts of UAM and AAM are expecting to widen the usage of drones for inspection, and also delivery services are expected to become important future applications (Tojal et al., 2021). Some of these applications will require drones capable of carrying heavier payloads than the ones now used for e.g. camera surveillance. Residents close to operations of drones will therefore be impacted by the increase of the sound events of these vehicles, either by larger drones and thus higher sound levels, or by the increased number of movements, or by both. Since the nuisance of these vehicles can be bothersome, it can also hamper the introduction of new drone services if acceptability of drones is rejected by the general public due to noise annoyance (Aalmoes et al., 2022).

1.2 Drone sound characteristics

A representative, typical drone sound cannot be established easily. In this emerging market, there is a large variety of configurations that all meet the definition of a “drone”. Drones can roughly be categorized as either a multi-copter, a fixed wing aircraft, or a combination as either a tilt-rotor or a Fixed-Wing Vertical Take-Off and Landing drone (FW-VTOL) (Pollet et al., 2022). It is expected that the propulsion is the main noise source of these vehicles (Geyer & Enghardt, 2023). Each of these aircraft have different propulsion requirements as required thrust is not only different per drone type, but it can even be different depending on the type of operation (e.g. vertical lift or cruise phase). Also compared to the conventional aircraft industry, the number of manufacturers of either complete air vehicles, or even individual parts (engines or rotor blades), is much higher. This makes that drone sounds will differ depending on size, configuration, manufacturer (of parts), operating mode and so on. Nevertheless, most drone noise research is focused on multi-copter drones that generate sounds with typical high frequency sounds (sharpness) and high fluctuation strength (Gwak et al., 2020).

In previous studies by the authors, drone sounds were reported as being more annoying than helicopter sounds (Aalmoes et al., 2021; Aalmoes & Sieben, 2021). In the study of Aalmoes and Sieben, the sound of a lawnmower (often mentioned by people in earlier studies to be similar to drone sounds) was reported to be more annoying than drone sounds, though. Other studies report drones to be more annoying than aircraft (Gwak et al., 2020), while aircraft sounds themselves are considered more annoying than either rail or road traffic sounds (Miedema & Oudshoorn, 2001).

1.3 Factors influencing noise perception of drones

Not only the sound of the drone itself, at the source, should be considered when evaluation noise perception of drones, but also how is it perceived by the observer. The type of operation is one of the contributing factors in the perceived annoyance: whether it is a straight flyover or whether the drone is hovering above the observer. The authors found in a previous study that hovering drones are considered more annoying than drones that flyover in a straight line (Aalmoes & Sieben, 2021). For this reason, the way in which drones operate is important to consider if reduction of annoying is important.

There are also propagation effects that should be considered: the movement of the source and possibly also the observer (e.g. doppler effect), the geometric spreading, atmospheric absorption, and refraction. Also the locations and the objects close to the observer have influence due to diffraction along edges of objects, ground and façade reflections, and scattering. Finally, also the position of the head and the shape of the observer's ear determine how sounds are perceived. Some of these influence are less relevant due to close distance from drone to observer (e.g. refraction or atmospheric absorption) or not relevant when considering the free field (no buildings, so less or no reflections and scattering). But geometric spreading, doppler effect, and ground reflection should generally not be ignored for a reasonable reproduction of drone sounds at the observer.

Also of influence, but often not individually considered, is the personal hearing ability of the observer. The use of A-weighted metrics is the general accepted way to translate the perceived loudness for an observer, but there are more complex effects that are normally not individually addressed (Fastl & Zwicker, Eberhard, 2007). A perception study can help as multiple people with different hearing abilities are tested against similar sounds.

A final influence that has a dominating influence on the perception of (drone) noise is the effect of non-acoustical factors (Guski, 1999). Not only actual sound level or characteristics of sounds, but also people's noise sensitivity, their attitude towards the noise sound, or the authorities that enable production of the sound source and sound level, can shape people's perceived annoyance. Also, how people benefit from the services that causes the noise may determine the threshold for acceptance of the (annoying) noise. In case of a new type of air vehicle, such as drones, the acceptance may be even lower than for conventional aircraft as their use may not yet been proven. In the study where lawnmower sound was associated with or without a visual drone model (Aalmoes & Sieben, 2021), participants rated the event where a drone model was visible more annoying than the event where the model was not visible. This could be an indication of bias against drones, although this effect was not found with recorded drone sounds instead of lawnmower sounds. In a study to examine the attitude towards drones (Aalmoes et al., 2023), two groups evaluated drone sounds, where only one group watched an informational video on the usefulness of drones, while the others did not. In this study, this positively framed group did not report lower annoyance than the control group. It could be, though, that a negatively framed group (or people selected upon a negative bias versus drones) might report higher annoyance than a control group, but this was not studied. It was found in this study that the environment (rural versus urban) did have an influence, although it can be argued that this is partly also an acoustical effect due to (masking) sounds of the urban environment itself.

Also related to perception of drones, is how people experience drone flyovers. In a study by the authors that asked participants on the perceived loudness, threat, squeakiness, and tonality of drone sounds (Aalmoes et al., 2023), the loudness was an obvious predictor of annoyance scores. But the same was true for the perceived threat. Note that these studies also included a virtual reality visual simulation of the flyovers, which could strengthen the feeling of being threatened in this study.

2. METHODOLOGY

A sound perception study was developed to compare a drone flyover event with other aircraft in different environmental locations. The focus in this study is the sound characteristics comparison between these air vehicles. This study is combined with a similar study (Aalmoes et al., 2024) where two different propeller blade sounds are compared. This was done as the experiment set-up was similar and both this study and the propeller blade study required only a limited number of sound events. Even when combining these two studies, the total duration per participants was approximately 20 minutes. NLR's Virtual Community Noise Simulator (VCNS) was used (Aalmoes et al., 2018) to create a controlled environment for the perception of these sounds, and to report, by the participant, on the perceived loudness and annoyance. This simulator consists of a laptop computer, a virtual reality headset and some headphones. The computer runs an instance of the VCNS software. This simulator enables the researchers to combine environmental video and ambient sound recordings (without the sound events) with the flyover sound recordings. The flyover sounds were recorded at a different time and location. The simulator was configured to simulate both a visual and audible flyover procedure within two pre-recorded environments: a rural environment, with a highway in the distance at 500 meters, and an urban environment, with housing and a nearby local road with busy traffic. Both environments were recorded in and near a small city called Nieuwegein in the Netherlands. The recordings were done using a 360 degrees video recorder and a first-order ambisonics audio recorder. A separate sound level meter was used to record the actual environmental sound level and was used later to calibrate the environmental sound in the simulator (Aalmoes et al., 2024). The recorded flyover sounds that were evaluated are a DJI Matrice 600 hexacopter (with 6 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. The sound of the drone was chosen as it represents a common multi-copter configuration, but it also has a higher maximum take-off weight that allows for different kind of services, such as (large) camera surveillance and package delivery. All considered aircraft sounds in this study were recorded sounds, not auralized sounds. The sounds of the propeller events from the other study were auralized, but were not used in the analysis of this study. Also, an additional testing method, where sounds were alternated between the two auralized propeller sounds during one flyover, was not further considered in this publication. Geometric spreading was adjusted for the recordings where the proposed flight paths deviated from the original recordings. For the Boeing flyover, due to the higher simulated altitudes, also atmospheric absorption was applied. No corrections were made for the presented urban environment, so no additional scattering or reflections were considered. Note that for both the urban and rural environment, a location was chosen with (almost) full line of sight from the sound source to the observer, and only limited visual obscuring at the final part of the event for the urban environment.

Sound events were presented at sound levels of 60 and 65 dB(A) LA_{max} for the Pipistrel, 50 and 65 dB(A) LA_{max} for the Boeing 737, and only 65 dB(A) for the helicopter and the drone (note that in the article, the LA_{max} was measured with an interval time of one second, also known as "slow"). Therefore, all events were presented at least for the same 65 dB(A) peak sound level. But for both the Pipistrel and the Boeing, also a quieter sound level, with an accompanying higher flyover, was simulated. Flyovers with lower peak noise levels were simulated with a visually smaller sized aircraft model. The events can be found in Table 1. Events were randomly presented to the different participants to prevent any orderly bias. After each event, participants were asked, in the virtual reality environment, to rate their perceived loudness and annoyance on a 11-point scale. The left-most (lowest) value was named “not at all”, while the right-most (highest) value was named “extremely”. They used a handheld controller to make their selection.

Table 1. Events in perception study. Note that five events (using auralized propeller blades) were used as events but not displayed in this table, nor further evaluated in this publication.

no	Event	Visual model	Background	SPL dB(A)
1	Helicopter flyover 1000ft	Helicopter	RURAL	65
2	Boeing 737 10000ft	B737	URBAN	50
3	Boeing 737 3000ft	B737	URBAN	65
4	Boeing 737 10000ft	B737	RURAL	50
5	Boeing 737 3000ft	B737	RURAL	65
6	Pipistrel electric flyover 500ft	pipistrel	RURAL	65
7	Pipistrel electric flyover 1000ft	pipistrel	RURAL	60
8	Pipistrel electric flyover 1000ft	pipistrel	URBAN	60
9	drone-flyover 60ft	drone	RURAL	65
10	drone-flyover 60ft	drone	URBAN	65

3. STUDY EXECUTION

A total number of 21 participants were invited and were gathered from the NLR and from acquaintances of two of the authors. Most of the tests were executed at NLR premises in Amsterdam and Marknesse, The Netherlands, but as the system is fully portable, some tests were conducted by the authors at home locations (all in the Netherlands).
All participants filled in a consent form and a survey to gather the demographics of the study. The survey consisted of five questions on age, gender, level of education, living location, and affinity with aerospace. This final question was included as the authors expected, due to the recruiting locations, a large number of participants with knowledge in the aerospace domain. Both the consent form and the survey questions were in Dutch and all participants had at least a basic understanding of the Dutch language in reading. The questions in the simulator were given in English, but all participants understood that language as well.
The age of the participants was between 19 and 58 with an average age of 35.5. From the participants 62% were male and 38% female. Most of the participant were highly educated, as almost half (48%) of participants finished a university bachelor or master degree and 10% finished a PhD. 19% of participants finished an applied university (HBO) degree and 19% a secondary vocational education (MBO). 5% of participants obtained only a high school diploma. Most people, 76%, had affinity with aerospace, not unexpected as most participants were employees from NLR.

4. RESULTS

Mean and standard deviation results for reported annoyance and loudness for the rural events at 65 dB(A) LA_{max} are given in Table 2 and Table 3. Additional paired sample t tests show that the drone was significantly less annoying than the Boeing 737 at the same sound level (65 dB(A)) in the rural area, as seen in Table 4. The sound of the B737 was also rated as significantly louder than the drone at the same sound level in the rural area (see Table 4). Also in the urban environment, the B737 was significantly more annoying than the drone at 65dB(A), but not rated as significantly louder, as seen in Table 4.

Further paired sample t tests also show that the environment had an impact on the loudness scores for both the drone and the B737, with higher loudness scores in the rural environment. However, this effect was only found in annoyance for the B737 at 50 dB(A), with higher annoyance scores in the rural environment than in the urban environment, see Table 5. As for the B737 and the drone both at 65 dB(A), no differences were found in the urban environment and the rural environment (see Table 5).

Also, analyses show that the drone (*M* = 4.62, *SD* = 2.56) was rated significantly louder than the Pipistrel Velis electric aircraft (*M* = 3.48, *SD* = 2.16), both measured at 65 dB(A) in the rural environment, *t* = 2.68, *p* = .015. The drone (*M* = 4.29, *SD* = 2.26) was not significantly more annoying than the Pipistrel Velis electric aircraft (*M* = 3.67, *SD* = 2.08), *t* = 1.55, *p* = .137.

No (significant) differences in annoyance were found between the drone and the helicopter (*M* = 4.71, *SD* = 2.37), *t* = -1.14, *p* = .267. Also no (significant) differences in loudness scores were found between the drone and the helicopter (*M* = 4.57, *SD* = 2.40) *t* = 0.11, *p* = .911. Both events were analysed at 65 dB(A) in the rural environment.

Table 2. Reported annoyance mean and standard deviation values in rural environment for LA_{max} 65 dB(A) events.

Event	Mean	SD
Drone	4.29	2.26
Pipistrel	3.67	2.08
Helicopter	4.71	2.37
Boeing	5.52	2.14

Table 3. Reported loudness mean and standard deviation values in rural environment for LA_{max} 65 dB(A) events.

Event	Mean	SD
Drone	4.62	2.56
Pipistrel	3.48	2.16
Helicopter	4.57	2.40
Boeing	5.33	2.33

Table 4. Sample descriptives using t tests for equality of means in annoyance and loudness of the drone and B737

Sound events at 65dB(A)	Mean annoyance	Standard deviation annoyance	t test annoyance	Mean loudness	Standard deviation loudness	t test loudness

Drone in rural environment	4.29	2.26	**-3.83**	4.62	2.56	**-2.43**
B737 in rural environment	5.52	2.14		5.33	2.33	
Drone in urban environment	3.67	2.39	**2.36**	3.57	2.44	1.52
B737 in urban environment	4.81	2.54		4.24	2.32	

Bold: *p* < .05

Table 5. Sample descriptives using t tests for equality of means in annoyance and loudness of the different background settings of the drone and B737 sound events

Sound events	Mean annoyance	Standard deviation annoyance	t test annoyance	Mean loudness	Standard deviation loudness	t test loudness
B737 50dB(A) rural environment	2.19	1.66	**2.80**	1.95	1.50	**2.97**
B737 50dB(A) urban environment	1.38	1.60		1.24	1.34	
B737 65dB(A) rural environment	5.52	2.14	-1.83	5.33	2.33	**-2.77**
B737 65dB(A) urban environment	4.87	2.54		4.24	2.32	
Drone 65dB(A) rural environment	4.29	2.26	1.81	4.62	2.56	**3.13**
Drone 65dB(A) urban environment	3.67	2.39		3.57	2.44	

Bold: *p* < .05

5. DISCUSSION

This research evaluated different aircraft sounds and visuals in urban and rural environments in a perception study with headphones and virtual reality glasses. The tested drone noise was rated less annoying than an aircraft flyover at the same $\mathrm{LA}_{\mathrm{max}}$ sound level. This was an unexpected result in comparison with previous literature (Gwak et al., 2020), although this study only involved hovering drones. As another study (Aalmoes & Sieben, 2021) found that a hovering drone was considered more annoying than a flyover drone, a different conclusion could be made regarding flyover drones versus flyover aircraft sounds.

The environmental background does play an important role in the perception of loudness: sound events with the same SPL of the Boeing and the drone were both rated as more loud in the rural environment than in the urban environment. This does not necessarily lead to more annoyance, only the Boeing at 50 dB(A) LA_{max} was also rated as more annoying in the quieter, rural environment.

On the question of loudness in this study, the Boeing was also perceived louder than the drone, but this result was only significant for the rural background environment, not the urban environment. A reason for people considering the aircraft louder could be the difference between LA_{max} (peak) sound level and the Sound Exposure Level of the event: the aircraft noise is longer present than the drone noise, which may give rise to the perception that the aircraft is louder and more annoying than the drone. For this reason, additional metrics were calculated on the presented sound levels, see Table 6. Both the Sound Exposure Level (SEL) and the Effective Perceived Noise Level (EPNL) are calculated for the events. While LA_{max} and SEL were calculated using NLR noise applications, the EPNL was calculated using the SQAT open source toolbox (Felix Greco et al., 2023). The EPNL of the Boeing is almost 4 EPNdB higher than that of the drone, and the SEL also differs more than three decibels, and could justify a louder perceived sound. It may also explain why in the urban case, the significance of a louder event is not found with the aircraft noise, as these sound events are more masked by background sounds in the urban environment than in the rural environment.

Table 6. Sample sound metrics for the different flyover events, all normalized for 65 dB(A) peak sound level

Event	**LA_{max} (dB(A))**	**SEL (dB(A))**	**EPNL (EPNdB)**
Helicopter Eurocopter EC-135	65.0	72.4	74.7
Boeing 737-800	65.0	75.6	79.0
Pipistrel Velis Electro	65.0	70.3	76.9
Drone DJI Matrice 600	65.0	71.3	75.2

A subjective reason for participants to experience the aircraft as more annoying could be due to the negative perception of the impact on the environment and climate warming (Gössling & Upham, 2009) that is true for fossil-driven aircraft and not (electric) drones. However, due to the number of people with affinity for aerospace, it is unclear if this suggestions plays a role in this study. It could also be true that those people have an interest and a positive view of new forms of air vehicles, such as drones. As a recommendation, the question whether people have a negative perception about aircraft due to their negative effect on the climate could be added as a survey question for future studies, as well as a question on their view on new technological development like emerging drone vehicles.

A comparison between the drone noise and the Pipistrel electrical aircraft shows that the drone is significantly louder than the Pipistrel, but not significantly more annoying. The calculated metrics show that also here the louder perceived air vehicle (drone), also has a higher SEL value (71.3) than the quieter perceived aircraft (Pipistrel, 70.3), but the EPNL is lower (75.2 for the drone, and 76.9 for the Pipistrel). Note that here, the difference in SEL value is only one decibel and may not be a decisive factor. Also here, the affinity of most participants with aerospace may have an influence that they report a lower expected annoyance drones. But other factors, such as a different sound quality, may also have an influence on perceived annoyance (Boucher et al., 2023). The lower value of the EPNL for the drone, as EPNL includes tonality, could be an indication for that.

In an earlier study (Aalmoes & Sieben, 2021), with similar simulation set-up including virtual reality glasses, a contradiction was found compared to this study: in that study, the drone was perceived more annoying than the helicopter sound, while here the drone is reported less[1] annoying (although not significantly proven). A difference with the study of 2021 is that in 2021 only urban environments were considered, not also a rural environment as in this study. Also, different drones and helicopter sounds were used between these studies. Another study where multiple drones were compared to one helicopter (Aalmoes et al., 2021) did rate drones as more annoying than helicopters for sound events compared at equal SELs. In that study, it can be found that the different tested drones are also rated individually different on annoyance, but overall they are still considered more annoying than a helicopter. This would also provide an argument that other metrics related to sound quality may play an important role to determine annoyance for either drones or helicopters. Difference in annoyance between these vehicles may therefore differ depending on type of vehicle, their noise characteristics, their operations, and background environment.

6. CONCLUSION

A perception study has been conducted to evaluate drone noise compared to other air vehicles in both rural and urban settings, using virtual reality for additional visual feedback and to improve the immersion of the flyover experience. Drone sounds of a hexacopter have been compared to a conventional Boeing 737, a Eurocopter helicopter, and a Pipistrel Electro aircraft. Both annoyance and loudness were asked to be rated after each event. All sounds were presented with at least the equivalent peak sound level of 65 dB(A) LA_{max}. The Boeing and the drone sounds were tested in a rural and in an urban background environment. For both events, the sounds in the rural environment were reported louder than in the urban environment, even though they were both presented with the same sound level. However, only the 50 dB(A) Boeing sound was considered more annoying in the rural environment than in the urban environment.

The Boeing aircraft was rated both more annoying and louder than the drone flyover. In an earlier study (Gwak et al., 2020), a drone was found more annoying than an aircraft, although that was only done with a hovering drone. In the urban environment, the aircraft was not considered louder than the drone. Additional SEL and EPNL metrics measure higher values for the Boeing, possibly explaining the difference. Overall, when comparing different air vehicles for their annoyance, their noise characteristics, their operations, and background environment should all be considered.

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[1] Errata: In the original version of this paper, the article inadvertently stated that here the drone was more annoying. This should be less as corrected in this version.

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