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Effects of a hovering Unmanned Aerial Vehicle on urban soundscapes perception

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4 1 **Effects of a Hovering Unmanned Aerial Vehicle on Urban**
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6 2 **Soundscapes Perception**
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21 **Abstract**

22 Several industry leaders and governmental agencies are currently investigating the use of
23 Unmanned Aerial Vehicles (UAVs), or ‘drones’ as commonly known, for an ever-growing
24 number of applications from blue light services to parcel delivery. For the specific case of the
25 delivery sector, drones can alleviate road space usage and also lead to reductions in CO₂ and
26 air pollution emissions, compared to traditional diesel-powered vehicles. However, due to their
27 unconventional acoustic characteristics and operational manoeuvres, it is uncertain how
28 communities will respond to drone operations. Noise has been suggested as a major barrier to
29 public acceptance of drone operations in urban areas. In this paper, a series of audio-visual
30 scenarios were created to investigate the effects of drone noise on the reported loudness,
31 annoyance and pleasantness of seven different types of urban soundscapes. In soundscapes
32 highly impacted by road traffic noise, the presence of drone noise lead to small changes in the
33 perceived loudness, annoyance and pleasantness. In soundscapes with reduced road traffic
34 noise, the participants reported a significantly higher perceived loudness and annoyance and a
35 lower pleasantness with the presence of the same drone noise. For instance, the reported
36 annoyance increased from 2.3±0.8 (without drone noise) to 6.8±0.3 (with drone noise), in an
37 11-point scale (0-not at all, 10-extremely). Based on these results, the concentration of drone
38 operations along flight paths through busy roads might aid in the mitigation of the overall
39 community noise impact caused by drones.

40 **Keywords:** Drone Noise; Road Traffic Noise; Urban Soundscape; Audio-Visual Effects;
41 Listening Experiments.

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121 **1. Introduction**
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124 46 Due to the significant advancement on electrical power, battery and autonomous
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126 47 systems technology, the applications of Unmanned Aerial Vehicles (UAV), or ‘drones’ as
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128 48 commonly known, seem unlimited (Dorling et al., 2017). An ever-growing number of
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130 49 applications are currently under investigation in sectors such as construction, surveillance and
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132 50 parcel delivery (Yoo et al., 2018). With the continuous increase in consumer demand and cost
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134 51 and time savings in mind, several companies such as Amazon, UPS, Google, and Wal-Mart are
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136 52 testing multi-rotor UAV for delivering small packages or groceries (Alphabet, 2017; BI
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138 53 Intelligence, 2016; Rose, 2013; Vanian, 2017).

142 54 The need for reducing greenhouse gas emissions has led to a significant interest in
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144 55 electric propulsion for air vehicles (Schäfer et al., 2019). From the customers’ perspective,
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146 56 drone delivery is perceived as more environmentally friendly than delivery by truck, which
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148 57 makes it more appealing for customers who care about the environment (Yoo et al., 2018).
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150 58 Figliozzi (2017) states that UAVs are significantly more efficient for reducing carbon dioxide
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152 59 equivalent emissions than typical diesel delivery vehicles. Several authors suggest that in
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154 60 service zones close to the depot, a deployed UAV based delivery can reduce greenhouse gas
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156 61 and other environmental impacts compared to conventional diesel delivery trucks (Figliozzi,
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158 62 2017; Goodchild and Toy, 2018; Koitwanit, 2018; Stolaroff et al., 2018).

161 63 However, UAV sounds have been found more annoying than sounds of delivery road
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163 64 vehicles (Christian and Cabell, 2017). Although the authors highlighted the uncertainty as to
164
165 65 whether the differences in annoyance were due to the particular UAV manoeuvres measured
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167 66 (i.e. farther/slower than for road vehicles measurements) or qualitative differences between
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169 67 UAV and road traffic sounds, Christian and Cabell (2017) found an offset of 5.6 dB between
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171 68 UAV and road vehicles. This means that UAV sounds 5.6 dB lower in A-weighted Sound
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180 69 Exposure Level (SEL) than road vehicles sounds were reported equally annoying as the latter
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182 70 ones.

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185 71 The noise generated by UAVs does not qualitatively resemble the noise of conventional
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187 72 aircraft (Cabell et al., 2016; Christian and Cabell, 2017; Torija et al., 2019b; Zawodny et al.,
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189 73 2016); also, compared to contemporary aircraft, UAVs will operate much closer to the public.
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191 74 This is why there is an important uncertainty as to how the public will react to UAV noise.
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193 75 What is clear is that, if not appropriately addressed, noise issues might put at risk the expansion
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195 76 of the UAV sector in urban areas (Theodore, 2018).

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198 77 This paper is aimed to investigate the noise impact of UAV operations in urban
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200 78 soundscapes. The specific objectives of this research are: (1) Evaluate the impact of the noise
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202 79 generated by the hover of a small quadcopter on the reported loudness, annoyance and
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204 80 pleasantness of different urban soundscapes. (2) Assess the influence of the overall sound level,
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206 81 particular acoustics characteristics of the quadcopter (Cabell et al., 2016; Christian and Cabell,
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208 82 2017; Torija et al., 2019b; Zawodny et al., 2016) and non-acoustic factors such as visual scene
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210 83 (Liu et al., 2014; Ren and Kang, 2015; Viollon et al., 2002) on the perception of soundscapes
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212 84 with a hovering UAV. (3) Discuss the effect of ambient road traffic noise in masking UAV
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214 85 noise as a potential action for mitigating the noise impact of UAV operations in urban
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216 86 environments.

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218 87 Aural-visual scenarios were created to investigate the effects of the noise of a small
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220 88 quadcopter hover on the perception of seven urban soundscapes with varying sound level
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222 89 (L_{Aeq}), and with varying sound sources. The soundscapes evaluated include sites at varying
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224 90 distances from traffic roads (i.e. 5 m, 50 m and 150 m away) and a park with no influence of
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226 91 road traffic and dominant sounds from birds and a water stream. In order to assess the combined
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228 92 effect of road traffic (at varying levels) and drone noise on soundscape perception, the
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93 recordings were carried out in open spaces both alongside a busy traffic junction in city centre
94 and a busy road in the surroundings of the city. The selection of these two areas was to include
95 traffic under typical urban conditions, and also more fluid/high speed traffic. A combination
96 of audio and visual techniques was implemented to create a series of scenarios simulating the
97 operation of a small quadcopter hover in the different urban spaces tested. These audio-visual
98 scenarios provided realistic experiences to the participants of the experiments, allowing more
99 accurate information about the reactions to this novel noise source (Maffei et al., 2013, Ruotolo
100 et al., 2013). The perception of the overall environment is multisensory in its very nature, and
101 both audio and visual factors have been found highly influential in the reported annoyance of
102 transportation systems (Jiang and Kang, 2016; Jiang and Kang, 2017) and wind farms (Schäffer
103 et al., 2019; Szychowska et al., 2018).

104 This paper is structured as follows: Section 2 explains the acquisition of audio-visual
105 signals, describes the equipment, stimuli and methodology used for the development of
106 experiments, and introduces the data analysis techniques used; In Section 3 and 4 the
107 experimental results are presented and discussed respectively.

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109 **2. Material and methods**

110 **2.1. Data collection**

111 The stimuli used in the experiment reported in this paper contain audio and panoramic
112 video signals, which were extracted from a series of indoors and outdoors recordings. Audio-
113 visual recordings were made to capture representative samples of soundscapes with different
114 influence of road traffic noise (see Table 1). Due to the current legislation in the UK¹,

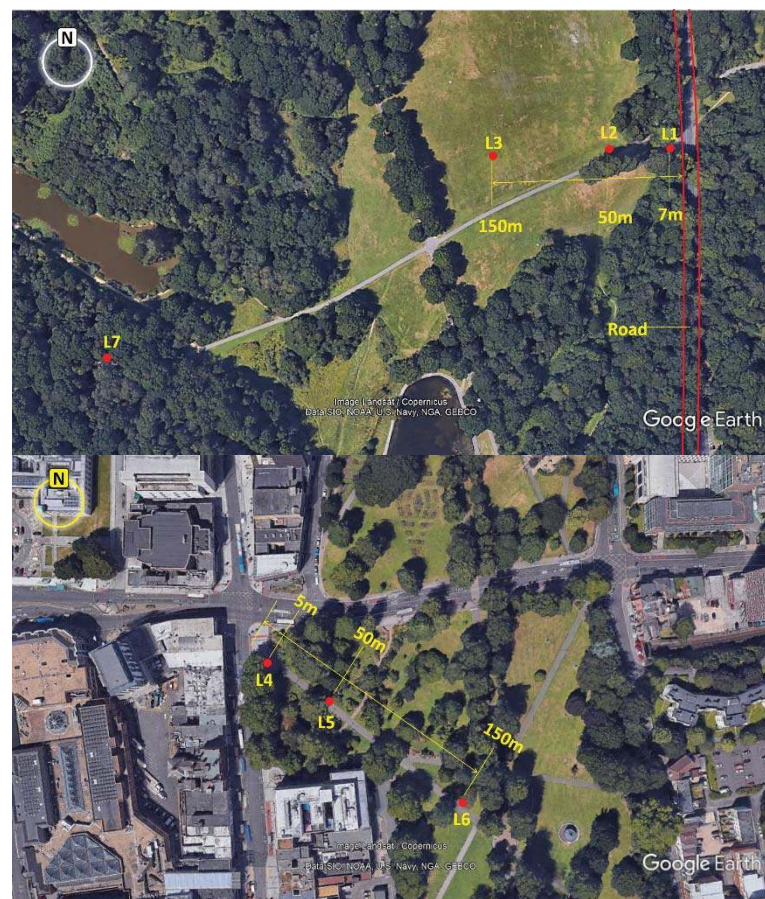
¹ Civil Aviation Authority (CAA) Air Navigation Order 2016, specifically Article 241 (endangering the safety of any person or property), Article 94 (small unmanned aircraft) and Article 95 (small unmanned surveillance aircraft).

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115 forbidding flying drones at least 50 m away from people and property, the audio-visual signals
116 of a small quadcopter were recorded in an anechoic chamber, used for aircraft noise and
117 aeroacoustics research. These audio-visual signals were combined with the audio-visual signals
118 recorded outdoors to generate the stimuli used in the experiment (described below). This
119 approach also allowed the analysis of the effects of exactly the same audio-visual drone
120 stimulus on different urban soundscapes.

121 2.1.1. Outdoors recordings

122 Fig. 1 shows the (audio-visual) field recording locations in the two areas selected in the
123 city of Southampton (UK).



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Figure 1. Audio-visual recording sites.

127 A panoramic camera (Ricoh Theta V) was used to record a high-quality 360° video (30
128 fps @ 3840 x 1920 pixels or 4K resolution with a data-rate of 56 Mbps; audio bit rate of 96

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357 129 kbps, audio sample rate of 48.000kHz; MPEG-4 type) in the seven locations selected: 4 in the
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359 130 Common park at varying distances (see Fig. 1) from a busy road with fluid/high speed traffic,
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361 131 and 3 in a park located in the city centre of Southampton (UK) at varying distances (see Fig.
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363 1) from a busy traffic junction (with pulsed-flow traffic conditions typical of urban areas). The
364 132 audio signals at these locations were recorded via four Micro Electrical-Mechanical System
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366 133 (MEMS) microphones integrated into the panoramic camera to independently record sound
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368 134 from four different directions. These four microphones are arranged as a tetrahedron to get 1st
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370 135 Ambisonic audio in A-format. Then the A-format audio was transferred to B-format using
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372 136 Ricoh Theta software. MEMS are stable and reliable small size microphones with low power
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374 137 consumption. MEMS has an excellent stability across a wide temperature range, and a
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376 138 consistent flat frequency response in the audio frequencies range (especially good at low
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378 139 frequencies) (Lewis and Moss, 2013).
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383 141 A calibrated class 1 sound meter (Brüel & Kjær 2260 Investigator) was also used to
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385 142 measure the A-weighted sound pressure levels (L_{Aeq}) at the site during the recording. The
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387 143 panoramic camera was placed on a tripod at a height of 1.6m from the ground while the sound
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389 144 meter was placed at a height of 1.2m from the ground. Fig. 2 shows a picture of one of the
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391 145 recording sites (location L1).
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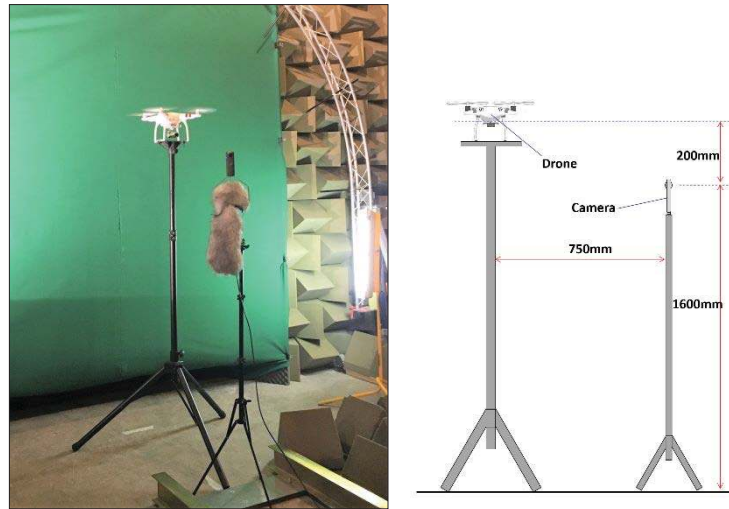


Figure 2. Picture of the recording site in location L1.

2.1.2. Anechoic recordings

The recordings of a small quadcopter (DJI Phantom 3 Standard) were carried out in the Anechoic Doak Laboratory at the Institute of Sound and Vibration Research (ISVR). This specific model has a full weight (battery and propellers included) of 1216 g, the max rpm of the propellers is about 7500 and the max load is 2.3 kg (including its own weight). This type of drone is a representative small consumer-level vehicle very promising to be used in construction inspection, surveillance, parcel delivery and traffic control. The quadcopter was fixed to a stand at a distance of 1.8 m above the ground such that only the four rotor blades could move. The same panoramic camera (with a four-channel built-in microphone) used in the recordings outdoors was placed on another tripod at a height of 1.6m from the ground and 0.75 m away from the tripod of the quadcopter. To ease the combination of the panoramic visual signals of the drone and soundscapes recorded, a 3m × 6m green cloth screen was fixed behind the quadcopter. To avoid sound reflection effects on the recorded audio signals, a green screen with high acoustic permeability was selected. During the measurements in the anechoic chamber no effect of the green screen was observed in the recorded sound levels. A picture

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475 163 and schematic diagram of the recording setup are shown in Fig. 3. During the recordings, the
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477 164 quadcopter was operated at full power.
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166 Figure 3. Picture and schematic diagram of the measurement setup at the Anechoic Doak
167 Laboratory at the Institute of Sound and Vibration Research (ISVR).
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501 168 2.2. Stimuli

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504 169 Two types of stimuli were used in this experiment, i.e. audio only (part 1 of the
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506 170 experiment) and panoramic video with the same audio signals of part 1 (part 3 of the
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508 171 experiment). The results of part 2 are not considered in this paper, as they fall out of its scope
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510 172 (see Section 2.3.3).
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513 173 2.2.1. Processing of the audio signals

514
515 174 A 15 s video excerpt with steady sound level to capture the ambient sound
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517 175 representative of each of the seven locations was selected from the each of the original
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519 176 panoramic video recordings. A 15 s video excerpt of the panoramic video recorded in the
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521 177 anechoic chamber with the drone operating at full power was also selected. The audio signals
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523 178 recorded in the field and in the anechoic chamber were extracted using the FFmpeg
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525 179 Import/Export library of the audio edit software Audacity (v 2.3.0).
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534 180 One of the objectives of this research is to assess the perception of urban soundscapes
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536 181 with a small drone hover and different road traffic sound levels. The underlying hypothesis is
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538 182 that road traffic noise can mask drone noise, and then mitigate the adverse effects of drone
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540 183 flyovers. The focus of this research is in the differences in the frequency spectra between road
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542 184 traffic and drone noise (see Fig. 14). For the sake of comparison between participants'
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544 185 responses, and in order to find conclusions statistically valid, it was required that all
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546 186 participants received exactly the same sound signal (i.e. sound level, frequency content, etc.)
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548 187 regardless of the movement of their head. For this reason, a monophonic headphone
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550 188 reproduction was preferred to other spatial audio techniques. In the stimuli simulating a drone
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552 189 hover presented to the participants, the small quadcopter is fixed in a steady position, with the
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554 190 other sound sources in the background. Spatial cues increase immersion and plausibility of
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556 191 sound scenes, and so, several spatial audio reproduction techniques have been proposed and
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558 192 tested to be applied in soundscape research (Hong, et al., 2019; Lam, et al., 2019). However,
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560 193 the spatial aspects of soundscapes are not within the scope of this research.
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565 194 As described above, the four-channel signal was recorded as a 1st order A-Format
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567 195 ambisonic, and then processed to 1st order B-Format. The monophonic signals used in the
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569 196 experiment was the W channel signal, which is a scaled version of the sound pressure at the
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571 197 centre of the microphone array as seen by an omnidirectional pressure microphone.
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574 198 The sound levels ($L_{Aeq,15s}$) recorded in the field for each 15 s audio except are shown in
575
576 199 Table 1. Three $L_{Aeq,15s}$ (i.e. 70, 60 and 55 dBA) were selected both to provide a wide range of
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578 200 sound levels and as representative of the different urban soundscapes recorded. The same sound
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580 201 levels, 70, 60 and 55 dBA, were assigned to the recorded locations with similar distances to
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582 202 road traffic, to investigate whether the different traffic patterns (e.g. urban vs. road traffic)
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584 203 might have effects on the results. Similarly, the location in the park, dominated by water and
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586 204 birds sounds, was set to 55 dBA to investigate the effect of natural sounds vs. distant
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205 background road traffic noise. The sound level (i.e. $L_{Aeq,15s}$) of each 15 s audio except recorded
 206 in the field was adjusted in amplitude, using audacity software, to the corresponding target
 207 sound levels shown in Table 1 (see $L_{Aeq,15s}$ (dBA) after adjustment in amplitude row). The
 208 sound levels of the ‘ambient plus drone’ stimuli (see $L_{Aeq,15s}$ (dBA) after adjustment in
 209 amplitude (‘ambient plus drone’ sounds) row) are the result of the energetic sum of the $L_{Aeq,15s}$
 210 (dBA) after adjustment in amplitude of each soundscape tested (see $L_{Aeq,15s}$ (dBA) after
 211 adjustment in amplitude row) and the $L_{Aeq,15s}$ (dBA) after adjustment in amplitude of the drone
 212 (i.e. $L_{Aeq,15s} = 65$ dBA).

213 The headphone reproduction was calibrated in sound pressure level using an artificial
 214 ear (Brüel & Kjær 4153 Artificial Ear) coupled to a class 1 sound level meter (Brüel & Kjær
 215 2260 Investigator), to the corresponding sound levels shown in Table 1 ($L_{Aeq,15s}$ (dBA) after
 216 adjustment in amplitude and $L_{Aeq,15s}$ (dBA) after adjustment in amplitude (‘ambient plus drone’
 217 sounds) rows), without altering neither temporal nor spectral characteristics.

219 **Table 1**

220 Sound level ($L_{Aeq,15s}$) for each 15 s audio excerpt.

Key	L1	L2	L3	L4	L5	L6	L7	Drone
$L_{Aeq,15s}$ (dBA) as recorded in the field	69.8	57.5	51.3	65.2	59.0	52.6	48.9	n.a.
$L_{Aeq,15s}$ (dBA) after adjustment in amplitude	70.0	60.0	55.0	70.0	60.0	55.0	55.0	65.0
$L_{Aeq,15s}$ (dBA) after adjustment in amplitude (‘ambient plus drone’ sounds)	71.2	66.2	65.4	71.2	66.2	65.4	65.4	n.a.

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The sound level ($L_{Aeq,15s}$) of the quadcopter was set at 65 dBA. This sound level was chosen on the basis of the results of a measurement campaign carried out by Cabell et al (2016) for a series of small quadcopters and hexacopters. Cabell et al (2016) found the sound level of small quadcopters at 15 m from the microphone ranging between 65 and 70 dBA. In the research presented in this paper it was assumed that a hovering altitude of 15-20 m is reasonable, and therefore, 65 dBA was selected as a representative sound exposure to a small quadcopter.

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The ‘ambient plus drone’ audio signals were created by combining with audacity software each of the seven field recorded 15 s excerpt and the 15 s drone audio signal recorded in the anechoic chamber. This resulted in fourteen audio signals (seven with ‘ambient’ sounds and seven with ‘ambient plus drone’ sounds) as the stimuli for this experiment.

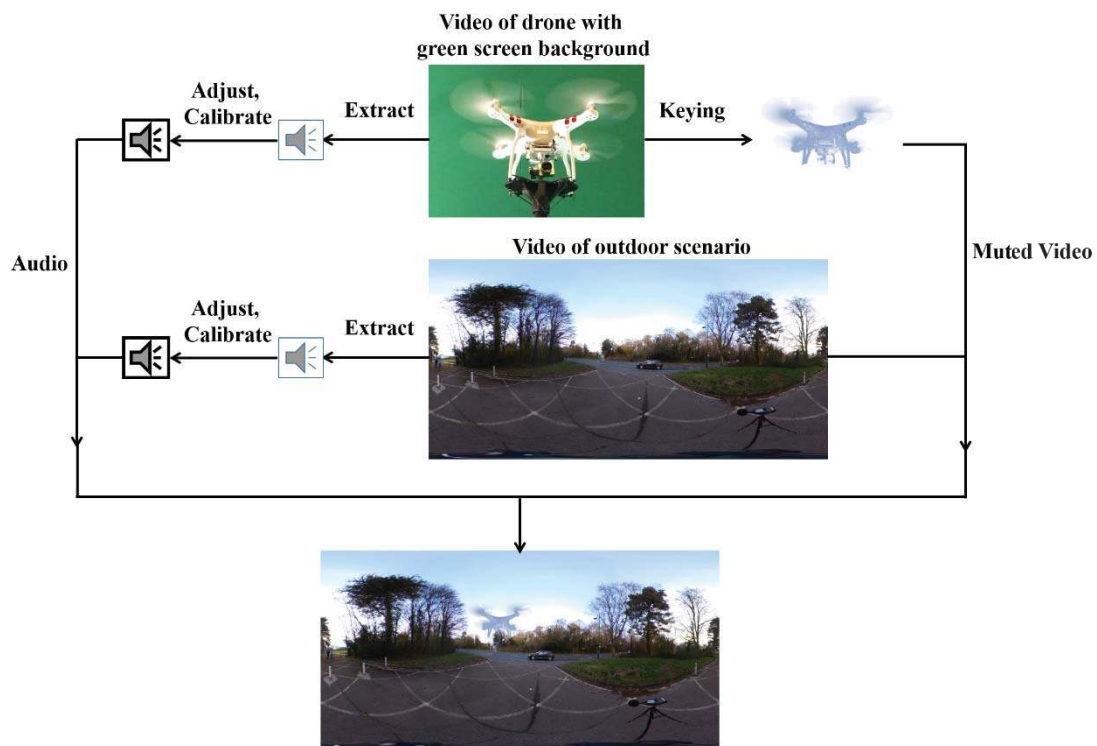
2.2.2. Processing of the panoramic video signals

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A series of panoramic videos simulating representative scenarios of all the seven urban soundscapes recorded were used as stimuli in the experiment. Altogether, 14 scenarios were assessed by the participants: the seven original urban soundscapes recorded, and the same seven urban soundscapes with the addition of a small quadcopter hover. The panoramic video of the quadcopter recorded in the anechoic chamber, with green screen background, was keyed out and added onto each of the seven recorded urban soundscapes using a video effects software, i.e. Adobe After Effect CC 2017. In this step, the videos were muted and the corresponding calibrated audio signals (see Section 2.2.1) were imported (see Fig. 4). Therefore, exactly the same sounds were presented to the participants in parts 1 and 3 of the experiment. Before the experiments, the experimenters checked that the reproduced levels in

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710
711 244 parts 1 and 3 were identical using an artificial ear coupled to a class 1 sound level meter (see
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713 245 Section 2.2.1).
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716 246 Fig. 5 displays a picture of the viewer's perspective for one of the locations tested
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718 247 (location L4), without and with the drone hover. In each of the seven panoramic videos
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720 248 produced for the 'ambient plus drone' scenarios, the drone was simulated in a fixed position
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722 249 (i.e. hover) showing fully operational propellers rotating at full power (see above max rpm).
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746 250
747 251 Figure 4. Overview of the processing to create the audio-visual stimuli with the quadcopter
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749 252 hover.
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Figure 5. Viewer's perspective for the location L4, without (top) and with the quadcopter hover (bottom).

2.3. Listening experiments

2.3.1. Participants

The listening tests were undertaken by 30 healthy participants (16 males and 14 females) aged between 21 and 59 years old (mean age = 30.5, standard deviation = 9.2, 57% between 20 and 29 years old, 31% between 30 and 39 years old, 6% between 40 and 49 years old, and 6% between 50 and 59 years old) who were recruited by email within university. A thank you gift of £10 for taking part was used to incentivize participation in the listening tests. Prior to participating in the listening test, each participant was required to confirm normal

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829 266 hearing ability and asked to fill out a consent form. This experiment was approved by the Ethics
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831 267 and Research committee of the University of Southampton.
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833 834 268 **2.3.2. Equipment for the presentation of stimuli** 835 836

837 269 The hardware setup used for the experiments consisted of a powerful desktop computer
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839 270 (Intel Core i7-2600 CPU @3.40GHz, 16.0 GB RAM, 64-bit Windows 10 Operating System)
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841 271 with a high-performance graphics card (NVIDIA GeForce GTX 1080), a USB
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843 272 DAC/headphone amplifier (Audioquest, DragonFly Red v1.2), a pair of open back headphones
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845 273 (AKG K-501), and a Facebook Oculus Rift S virtual reality head-mounted-display (VR HMD).
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848 274 The order of play was generated by the experimenters before each experiment using a
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850 275 random order generator software (i.e. The Hat Deluxe) to eliminate memory bias from prior
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852 276 judgments. In the first part, the audio stimuli were presented by the experimenter using the
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854 277 media player software VLC media player v3.0.6. In the third part, the participants were
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856 278 instructed to play back themselves the panoramic audio-visual stimuli using the VR video
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858 279 player DeoVR Video Player v5.8. Note that, as mentioned above, the second part of the
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861 280 experiments is not included in this paper. The volume level control on the desktop was blocked,
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863 281 so the reproduced sound levels were not altered after calibration. The tests were carried out in
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865 282 a very quiet environment (i.e. a small anechoic chamber at ISVR), with no interference from
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867 283 outside in order to avoid distractions. The background sound level in this small anechoic
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869 284 chamber was 15.1 dBA.
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872 285 **2.3.3. Experimental procedure** 873 874

875 286 This paper reports the results of two out of three parts of a listening experiment. As
876
877 287 described above, in the first and third parts of the experiment, only audio signals and audio-
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879 288 visual signals respectively simulating a drone hover in seven urban scenes were presented to
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881 289 the participants. In the second part of the experiment, a series of drone, road vehicles and
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889 290 aircraft sounds were played back, and the participants were requested to rank them by order of
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891 291 preference using a methodology developed by Torija et al. (2019a). The objective of this
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893 292 second part (of 40-min duration) was to compare subjective perception of drone flyovers with
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895 293 aircraft flyovers and road vehicles pass-byes. The data gathered in this second part are not
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897 294 included in the paper, as it falls out of its scope.

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900 295 The experiments involved a series of assessment tasks, where the participants reported
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902 296 their perception of loudness, annoyance and pleasantness induced by the sounds they heard
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904 297 (first part) or the panoramic videos they heard and watched (third part), using an 11-point scale
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906 298 (0-not at all, 10-extremely). In each part, i.e. only audio and audio plus panoramic video, 14
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908 299 15-second stimuli were rated, with a 20-second break in between.

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911 300 Panoramic video recordings and VR HMD were the stimuli and equipment chosen to
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913 301 present the participants with the different scenarios to be evaluated. A VR HMD provides
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915 302 important operational benefits compared to other reproduction equipment, such as big screens.
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917 303 Further, a panoramic video recording enables a better representation and simulation of the
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919 304 locations under study. The use of both panoramic video recordings and VR HMD made the
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921 305 participants more intuitively and better understand the scenarios presented.

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924 306 For the sake of comparison and statistical validity, all the participants were advised to
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926 307 look at front in order to focus on the area where the drone hover was simulated. During the
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928 308 20-second break the participants reported their answers, and then rested and waited for the next
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930 309 stimulus. The stimuli were presented (and rated) only once, in a random order. Before the start
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932 310 of the first part of the experiment, several audio samples were presented to the participants;
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934 311 similarly, before the start of the third part, several audio-visual samples were presented to the
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936 312 participants. The objective was to make the participants familiar with the tasks requested during
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938 313 the experiment (including the subjective ratings), and also with the equipment used.

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947 314 Specifically, audio samples of different loudness were used to instruct the participants in the
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949 315 rating using the 11-point scale, and panoramic video samples were used for the participants to
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951 316 learn how to use the VR video player. After the completion of the experiment, in an informal
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953 317 chat, the participants were inquired as to their views on both the experimental design and the
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955 318 audio/audio plus visual stimuli they heard/heard and watched.

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959 319 In the first part, the participants reported their responses in a paper questionnaire
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961 320 provided. In the third part, as the participants were wearing the VR HMD, they reported orally
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963 321 their rates after each stimulus, and it was the experimenter who wrote down their answers in a
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965 322 paper questionnaire.

968 323 Considering the training/introduction, experiment and debrief, the duration of each part
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970 324 1 and 3 was 20 min. Altogether, including the three parts of the experiment (second one not
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972 325 reported in this paper), the average total duration of the experiment was 1 hour and 20 min.

974 326 **2.4. Data Analysis**

977 327 The analysis of the influence of the overall sound level, particular acoustics
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979 328 characteristics of the quadcopter and non-acoustic factors such as visual scene on soundscape
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981 329 perception was addressed using multilevel modelling. Multilevel linear models (also known as
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983 330 mixed models) are a suitable approach to take into account individual responses of participants,
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985 331 as it is assumed that regression parameters (i.e. intercept and slopes) vary randomly across
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987 332 participants (Hox, 2010). As every participant might have a different interpretation of the rating
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989 333 scale, leading to different regression parameters, multilevel linear modelling was assumed an
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991 334 accurate approach to investigate the contribution of each acoustic and non-acoustic factors to
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993 335 the perception of the soundscapes tested. All the statistical analyses were carried out with the
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995 336 statistical package IBM SPSS Statistics 25.

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338 **3. Results**

339 **3.1. Perception of urban soundscapes with a hovering drone**

340 Fig. 6 shows the perceived loudness reported by the participants of the listening
341 experiments for the seven urban locations tested, with and without the presence of the noise
342 generated by a small quadcopter hover (e.g. L1 vs. L1D), also differentiating between the cases
343 with and without visual stimuli. In locations L1 and L4, the closest to road traffic, the presence
344 of drone noise has a limited effect with an increase in reported loudness of 9% and 15% (L4
345 and L1 respectively). As the distance from the road traffic increases, and therefore the ambient
346 sound level decreases, the effect of drone noise in reported loudness also increases, from 46%
347 in L5 to 99% in L3. The highest increase in reported loudness is observed in location L7 (park
348 with water and birds sounds), where the reported loudness with drone noise is 2.2 times the
349 one reported for the typical ambient sound. The visual stimuli seem not to have a clear effect
350 on the reported loudness. In locations with high ambient sound levels, i.e. L1 and L4, the
351 reported loudness decreases with visual stimuli. However, in the locations with low ambient
352 sound levels, the reported loudness is slightly higher with visual stimuli.

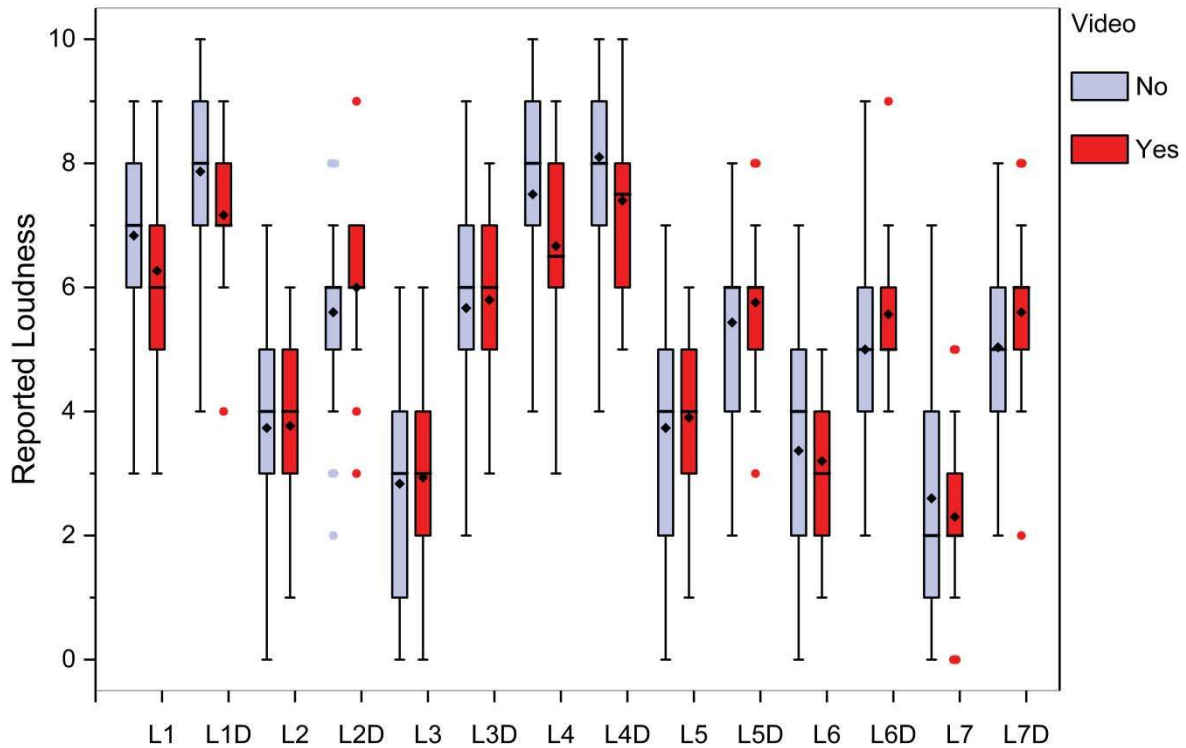
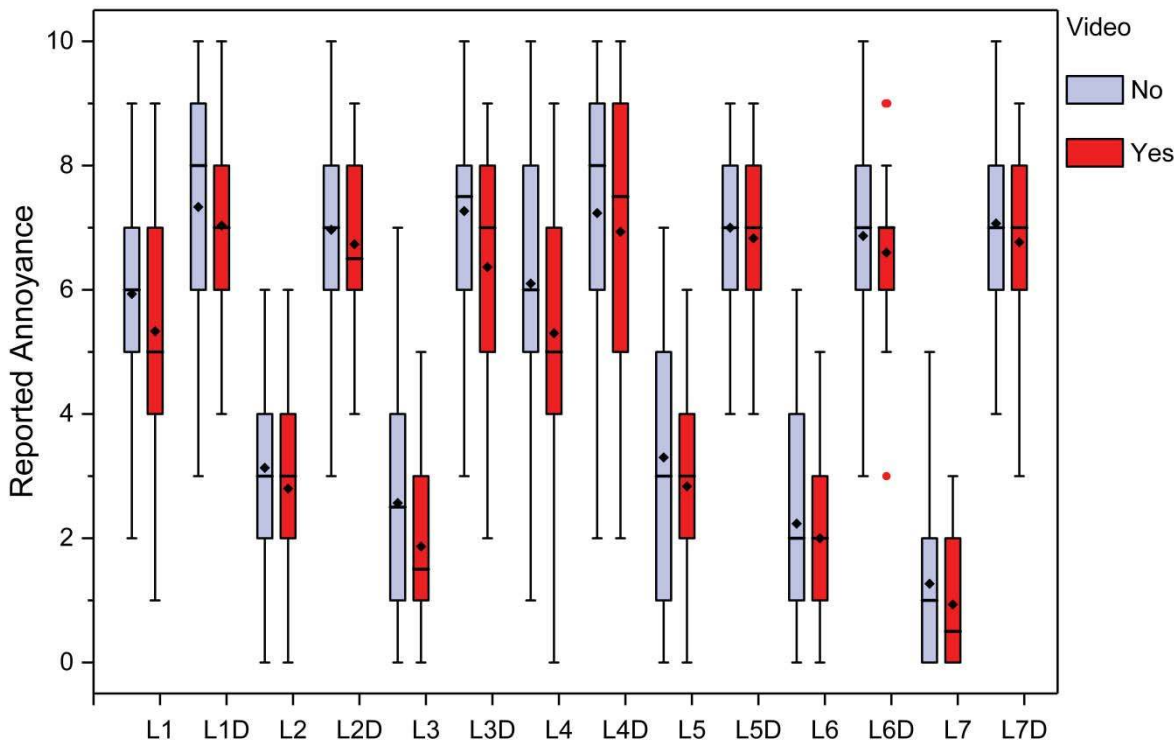


Figure 6. Reported loudness in each of the seven urban soundscapes evaluated without and with the noise generated by the drone hover (e.g. L1 vs. L1D), and without and with panoramic video.

In Fig. 7, it is shown the reported annoyance for the seven urban locations tested for the conditions with and without noise of a small quadcopter hover, and with and without visual stimuli. The reported annoyance increases between 24% and 28% (locations L4 and L1 respectively) with the presence of drone noise in locations with high ambient road traffic noise. In locations with little influence of road traffic noise, and consequently low ambient sound levels, significant increases in the reported annoyance are observed with the presence of drone noise. In these locations the increase in reported annoyance with drone noise ranges between 2.3 (locations L2 and L5) and 6.3 (location L7) times the reported annoyance for ambient noise. In fact, the median value of the reported annoyance in all the urban locations tested was about 7 (in a 11-point scale from 0 to 10) with drone noise, regardless the overall sound levels.

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367 Comparing the responses with and without visual stimuli, the reported annoyance is slightly
368 lower with visual stimuli in all the urban locations (8% lower than without visual stimuli).

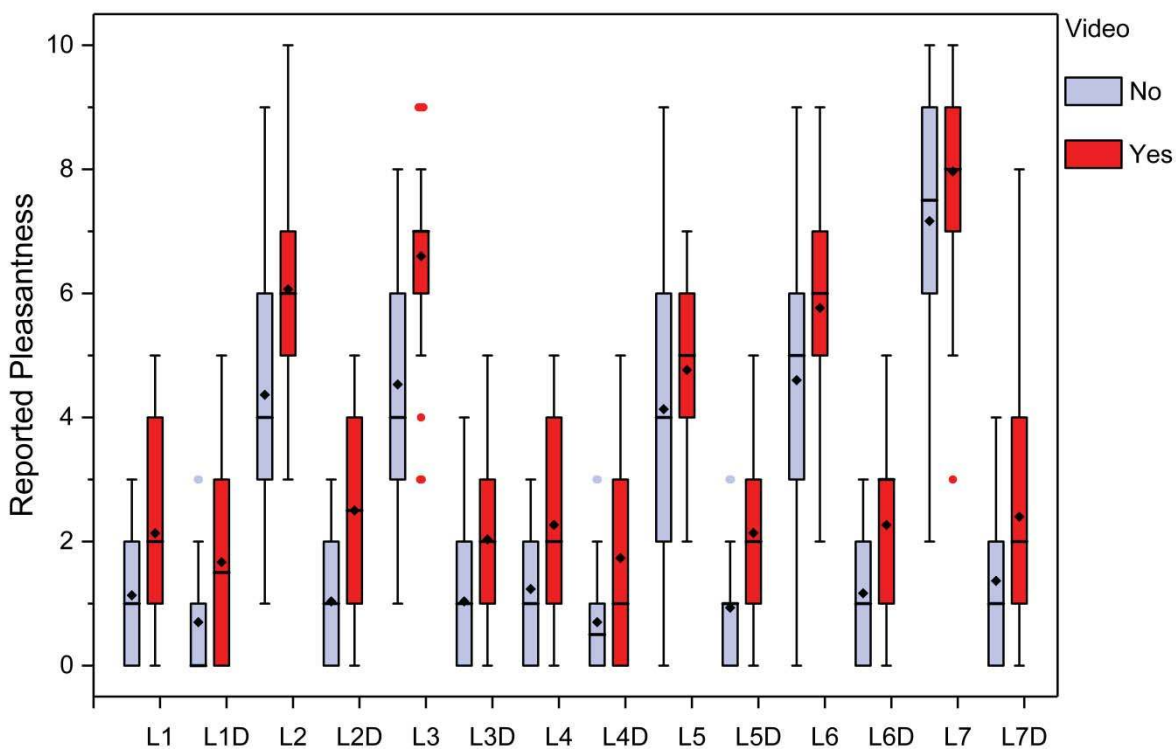


369
370 Figure 7. Reported annoyance in each of the seven urban soundscapes evaluated without and
371 with the noise generated by the drone hover (e.g. L1 vs. L1D), and without and with
372 panoramic video.

373 Fig. 8 shows the reported pleasantness for the seven urban locations tested with and
374 without noise generated by a small quadcopter hover, and also with and without visual stimuli.
375 The reported pleasantness, with and without drone noise, in locations with high road traffic
376 noise is similar, i.e. median = 0.8 and 1.5 with and without drone noise respectively. In
377 locations with reduced influence of road traffic noise, and also water and birds sounds (location
378 L7), the reported pleasantness without drone noise is significantly higher than with drone noise.
379 In these locations, the reported pleasantness without drone noise is from 2.9 (location L5) to
380 4.0 (location L7) times higher than with drone noise. The influence of the visual stimuli is
381 observed to have a larger influence than in the previous two cases (i.e. reported loudness and

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382 annoyance). Comparing the responses with and without visual stimuli, the reported
 383 pleasantness is notably higher with visual stimuli in all the urban locations (47% higher than
 384 without visual stimuli).



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 386 Figure 8. Reported pleasantness in each of the seven urban soundscapes evaluated without
 387 and with the noise generated by the drone hover (e.g. L1 vs. L1D), and without and with
 388 panoramic video.

389 **Table 2**

390 Results of the related-samples Friedman’s two-way analysis of variance by ranks. It is shown
 391 the pairwise comparisons with statistically significant differences ($p < 0.05$) between the
 392 conditions: C1 (‘ambient’, ‘only audio’), C2 (‘ambient plus drone’, ‘only audio’), C3
 393 (‘ambient’, ‘audio plus video’) and C4 (‘ambient plus drone’, ‘audio plus video’).

L1			
Pairwise Comparisons	Reported Loudness	Reported Annoyance	Reported Pleasantness

C1-C2	p<0.05	p<0.05	
C1-C3			p<0.05
C2-C4			p<0.05
C3-C4		p<0.05	
L2			
Pairwise Comparisons	Reported Loudness	Reported Annoyance	Reported Pleasantness
C1-C2	p<0.05	p<0.05	p<0.05
C1-C3			
C2-C4			p<0.05
C3-C4	p<0.05	p<0.05	p<0.05
L3			
Pairwise Comparisons	Reported Loudness	Reported Annoyance	Reported Pleasantness
C1-C2	p<0.05	p<0.05	p<0.05
C1-C3			
C2-C4			
C3-C4	p<0.05	p<0.05	p<0.05
L4			
Pairwise Comparisons	Reported Loudness	Reported Annoyance	Reported Pleasantness
C1-C2			
C1-C3			p<0.05
C2-C4			p<0.05
C3-C4		p<0.05	
L5			
Pairwise Comparisons	Reported Loudness	Reported Annoyance	Reported Pleasantness
C1-C2	p<0.05	p<0.05	p<0.05
C1-C3			
C2-C4			
C3-C4	p<0.05	p<0.05	p<0.05
L6			
Pairwise Comparisons	Reported Loudness	Reported Annoyance	Reported Pleasantness
C1-C2	p<0.05	p<0.05	p<0.05
C1-C3			
C2-C4			
C3-C4	p<0.05	p<0.05	p<0.05
L7			
Pairwise Comparisons	Reported Loudness	Reported Annoyance	Reported Pleasantness
C1-C2	p<0.05	p<0.05	p<0.05
C1-C3			
C2-C4			
C3-C4	p<0.05	p<0.05	p<0.05

A Friedman’s two-way analysis of variance by ranks was conducted to investigate whether there are statistically significant differences, in the responses of the participants about perceived loudness, annoyance and pleasantness, between four conditions: C1 (‘ambient’, ‘only audio’), C2 (‘ambient plus drone’, ‘only audio’), C3 (‘ambient’, ‘audio plus video’) and C4 (‘ambient plus drone’, ‘audio plus video’). As shown in Table 2, in locations with little

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1301 400 influence of road traffic noise (i.e. L2, L3, L5, L6 and L7) there are statistically significant
1302 401 differences ($p < 0.05$) in the reported loudness, annoyance and pleasantness between the
1303 402 conditions ‘with drone and ‘without drone’ noise, both without and with visual stimuli. In
1304 403 location L1 (by the side of a busy road), statistically significant differences in the reported
1305 404 loudness and annoyance are observed between the conditions ‘with drone’ and ‘without drone’
1306 405 noise, with only audio stimuli; and statistically significant differences in the reported
1307 406 annoyance between the conditions ‘with drone’ and ‘without drone’ noise, with audio plus
1308 407 visual stimuli. In location L4 (by the side of a street with busy traffic), statistically significant
1309 408 differences in the reported annoyance are observed between the conditions ‘with drone’ and
1310 409 ‘without drone’ noise, with audio plus visual stimuli. In locations L1 and L4, statistically
1311 410 significant differences in the reported pleasantness are also observed between the conditions
1312 411 ‘only audio stimuli’ and ‘audio plus visual stimuli’, both with only ‘ambient’ noise and with
1313 412 ‘ambient plus drone’ noise. As described above, in these locations, the perceived pleasantness
1314 413 reported by the participants with visual stimuli is notably higher than with only audio stimuli.

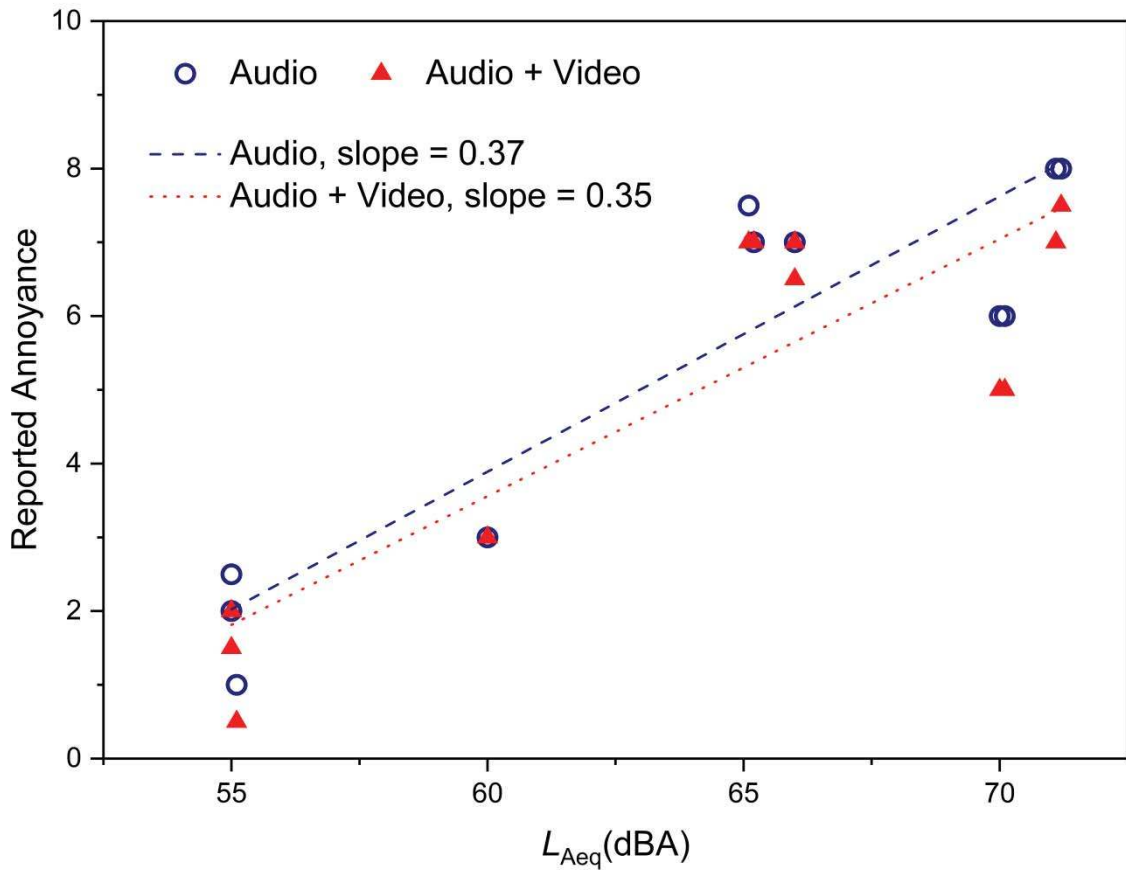
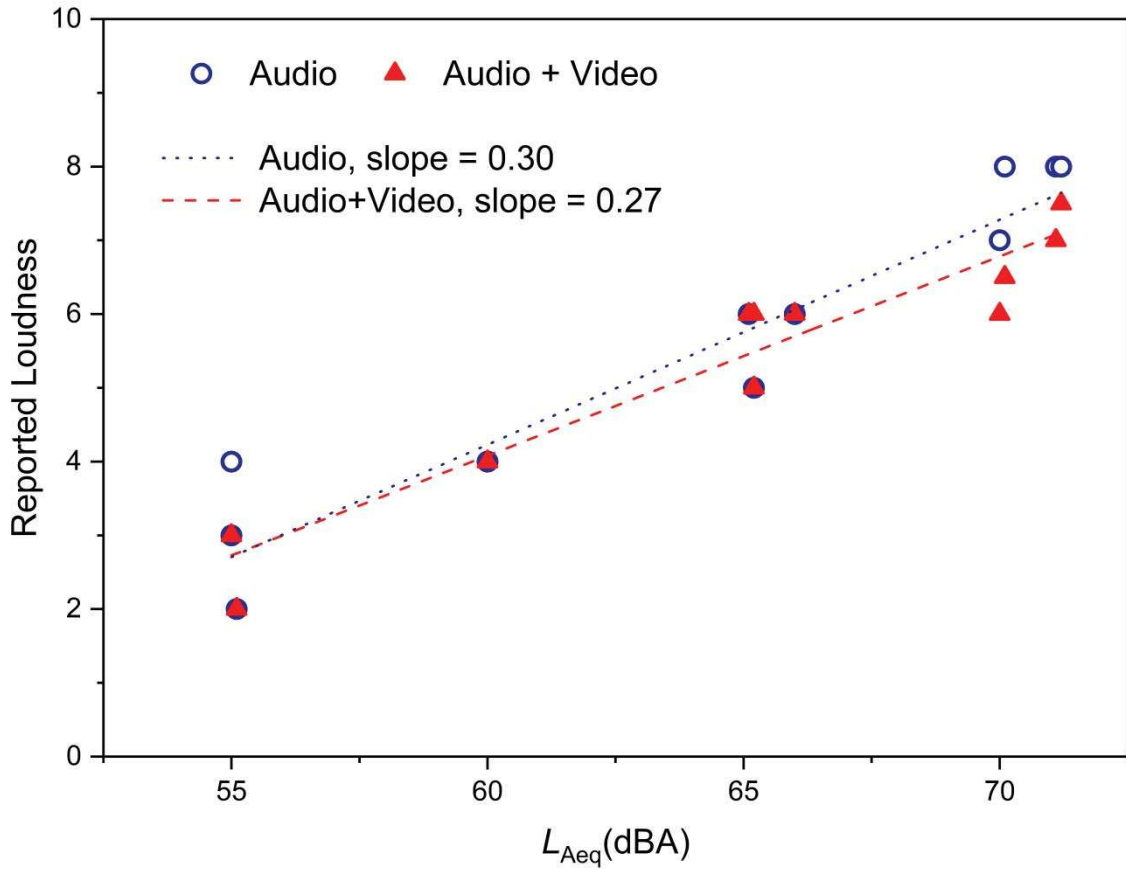
1331 414 **3.2. Relationship between L_{Aeq} and subjective ratings for urban soundscapes with a** 1332 415 **drone hover**

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1334 416 The sound levels (L_{Aeq}) set for each of the seven urban location tested, with and without
1335 417 drone noise (14 scenarios in total), range from 55 dBA to 71.2 dBA (see Table 1). The
1336 418 relationship between L_{Aeq} and reported loudness, annoyance and pleasantness for the whole set
1337 419 of urban soundscape scenarios evaluated is shown in Figs. 9 and 10. The values of reported
1338 420 loudness, annoyance and pleasantness displayed in Figs. 9 and 10 for each scenario evaluated
1339 421 correspond to the median value calculated from all participants’ responses.

1340 422 Fig. 9 shows the relationship between L_{Aeq} and reported loudness (top), annoyance
1341 423 (middle) and pleasantness (bottom) for the conditions ‘only audio’ (circles) and ‘audio plus

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424 video' (triangles). As observed in Fig. 9 – top, the slope (i.e. $s = \Delta$ subjective rating / ΔL_{Aeq})
425 in the relationship L_{Aeq} vs. reported loudness is similar for both condition 'only audio stimuli'
426 ($s = 0.30$) and condition 'audio plus visual stimuli' ($s = 0.27$). For the relationship L_{Aeq} vs.
427 reported annoyance (Fig. 9 – middle), the slopes of both conditions (i.e. 'only audio' and 'audio
428 plus video') are almost the same ($s = 0.37$ and 0.35). However, in this case an offset of 1.2 dB
429 is observed between both conditions, i.e. for a given value of reported annoyance, the L_{Aeq} of
430 the condition 'audio plus visual stimuli' is 1.2 dB higher than for the condition 'only audio
431 stimuli'. For the relationship L_{Aeq} vs. reported pleasantness (Fig. 9 – bottom), the slope is
432 similar for both condition 'only audio stimuli' ($s = -0.34$) and condition 'audio plus visual
433 stimuli' ($s = -0.38$). An offset of 3.9 dB is observed between both conditions, i.e. for a given
434 value of reported pleasantness, the L_{Aeq} of the condition 'audio plus visual stimuli' is 3.9 dB
435 higher than for the condition audio stimuli. This significant offset seems to indicate (as
436 described above in Section 3.1) that the visual stimuli influence the perceived pleasantness.



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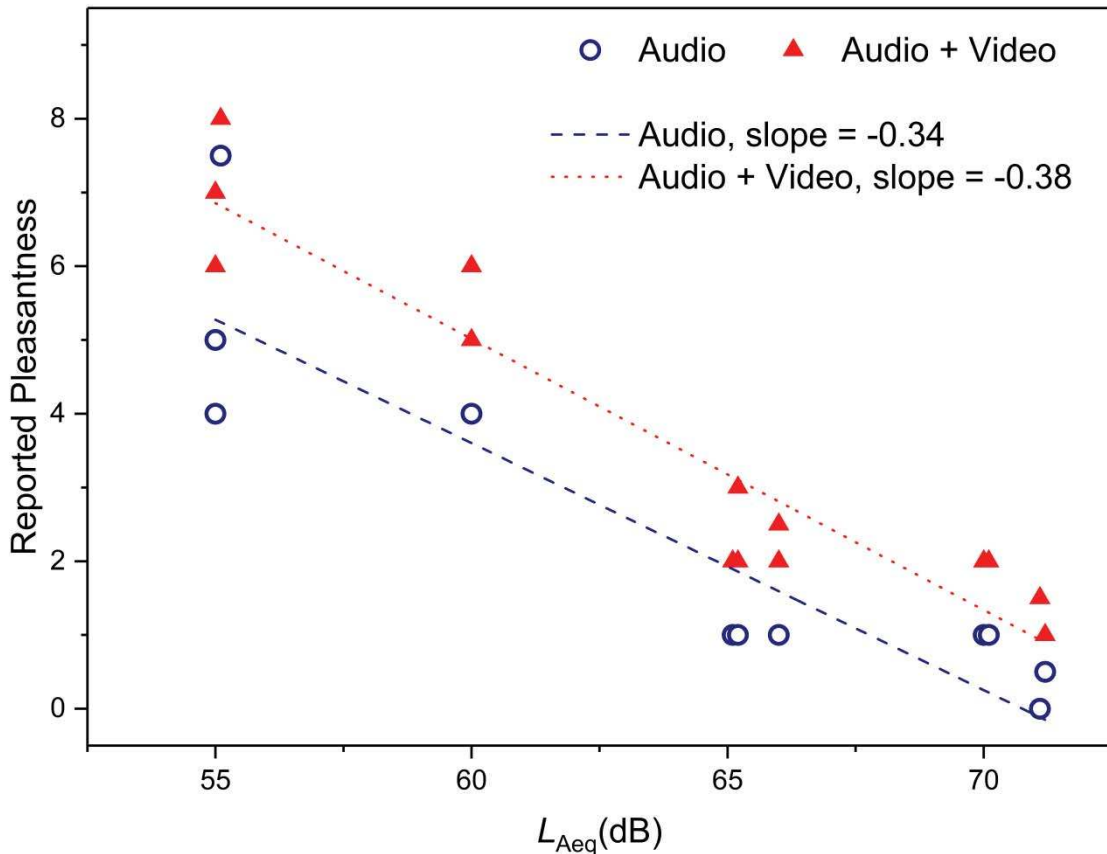
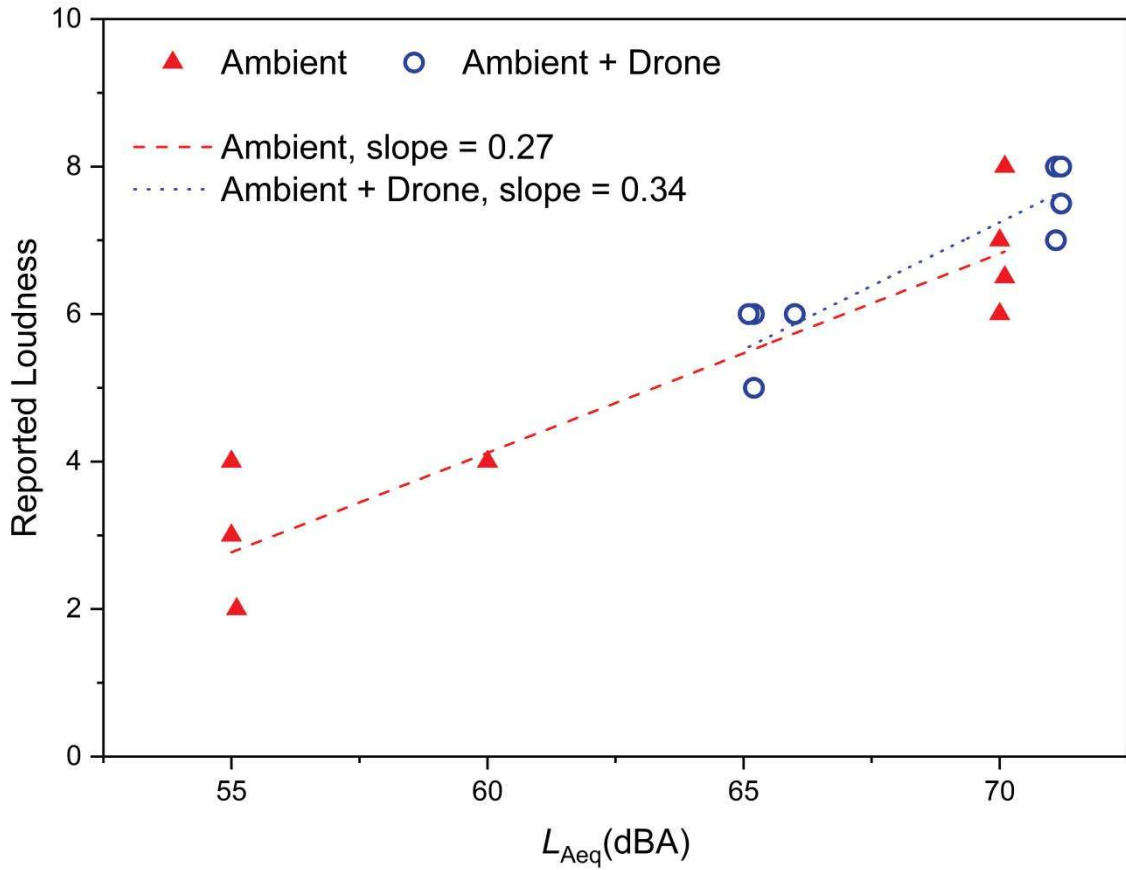


Figure 9. L_{Aeq} vs. reported loudness (top), annoyance (middle) and pleasantness (bottom) for the conditions ‘only audio’ (circles) and ‘audio plus video’ (triangles).

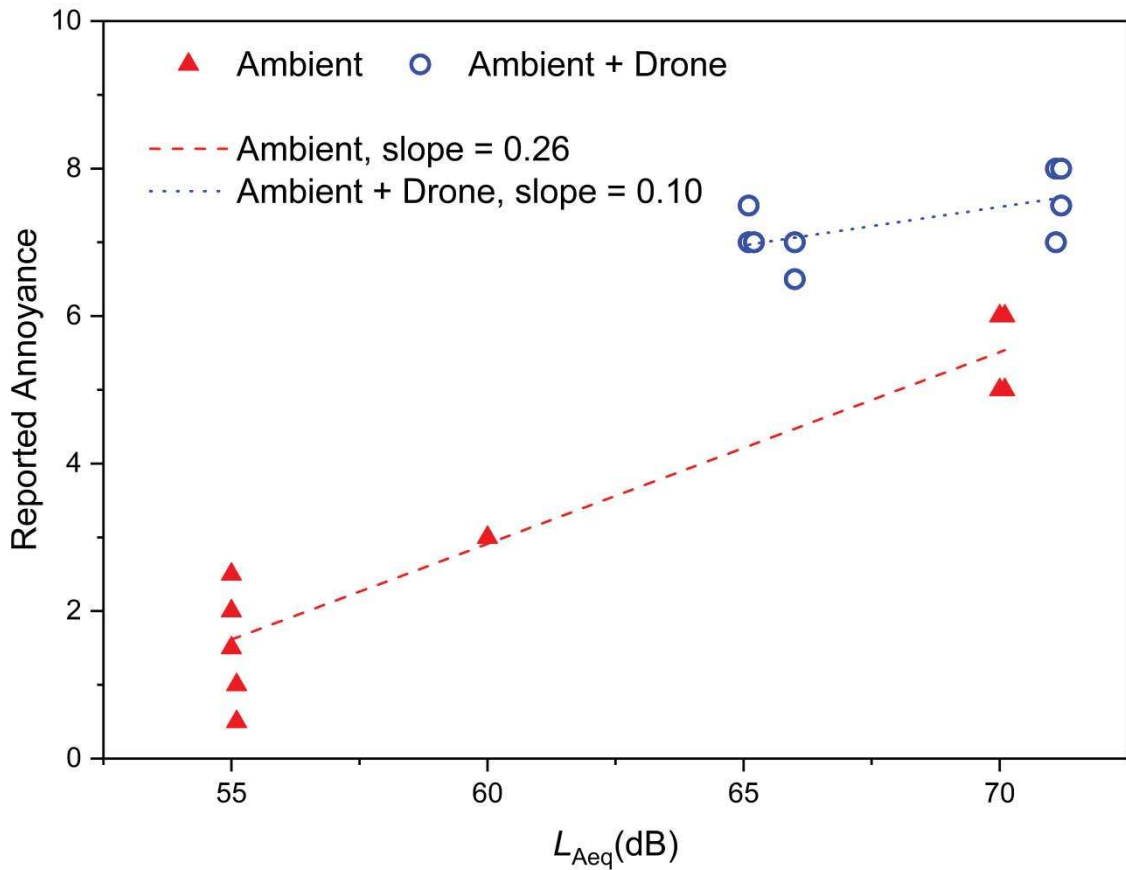
The relationship between L_{Aeq} and reported loudness (top), annoyance (middle) and pleasantness (bottom) for the conditions ‘ambient’ (triangles) and ‘ambient plus drone’ (circles) is shown in Fig. 10. Fig. 10 – top, i.e. relationship between L_{Aeq} vs. reported loudness, shows that the slope for the condition ‘ambient plus drone’ is higher ($s = 0.34$) than for the condition ‘ambient’ (i.e. without drone) ($s = 0.27$). For both conditions, the responses on perceived loudness seem mainly driven by L_{Aeq} . The relationship between L_{Aeq} vs. reported annoyance (Fig. 10 – middle), seems mainly driven by L_{Aeq} for the condition ‘ambient’ ($s = 0.26$). However, for the condition ‘ambient plus drone’, the reported annoyance is about 7 in all locations regardless of the L_{Aeq} . If we assume that the relationship between annoyance and L_{Aeq} is approximately linear in the sound level range between 50 dBA and 75 dBA, the

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452 difference between two curves at the 65 dBA reach about 2 units, yielding a difference of 6 dB
453 equivalent. This suggests that the participants' responses on perceived annoyance are highly
454 influenced by acoustics factors, other than sound level, particularly characteristic of small
455 quadcopter noise (Cabell et al., 2016; Christian and Cabell, 2017; Torija et al., 2019b; Zawodny
456 et al., 2016), or non-acoustics factors such as visual scene (Jiang and Kang, 2016; Jiang and
457 Kang, 2017; Schäffer et al., 2019; Szychowska et al., 2018) and expectation (Bruce and Davies,
458 2014; Perez-Martinez et al., 2018). Fig. 10 – bottom shows that the relationship between L_{Aeq}
459 vs. reported pleasantness seems also driven by L_{Aeq} for the condition 'ambient' ($s = -0.32$). As
460 for the case of reported annoyance, the participants' responses on perceived pleasantness for
461 the condition 'ambient with drone' seems highly influenced by acoustics or non-acoustics
462 factors associated to drone noise. In Fig. 10 – bottom, it is also observed a higher degree of
463 variability in the responses on perceived pleasantness, which might be due to the effect of
464 visual stimuli on the reported pleasantness, as described above (Section 3.1).



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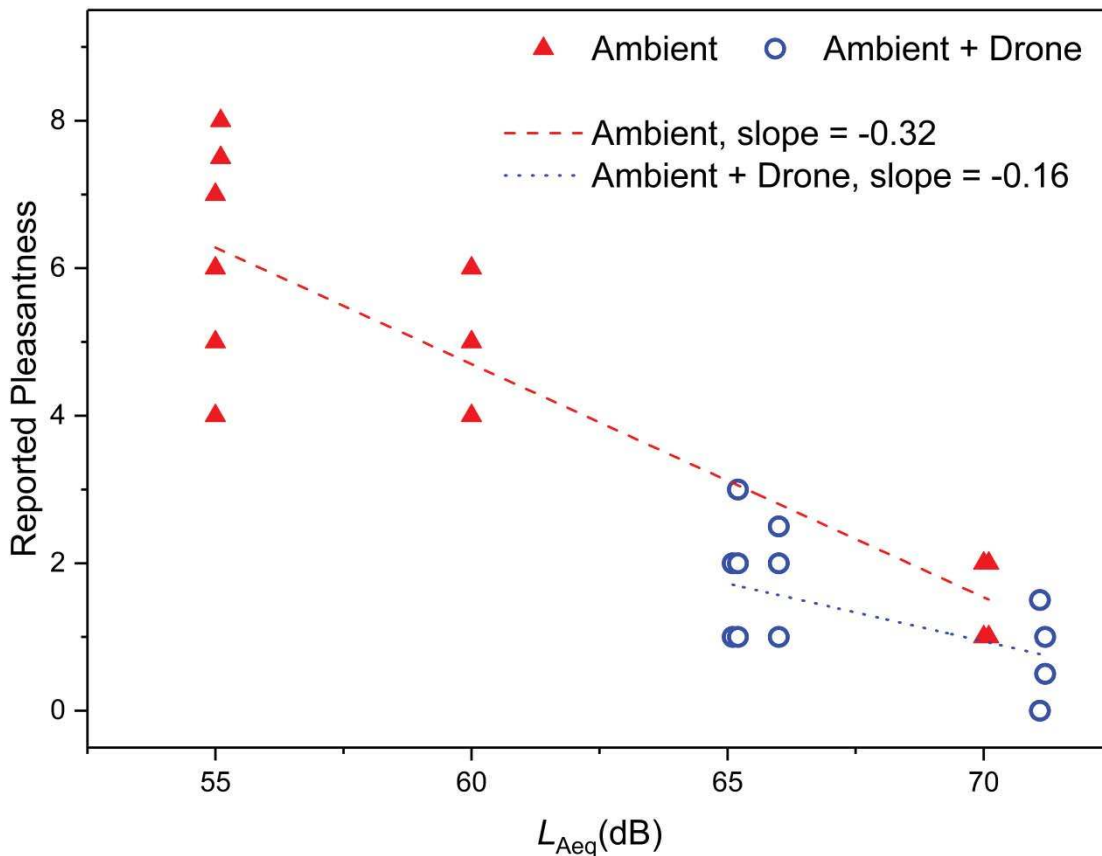


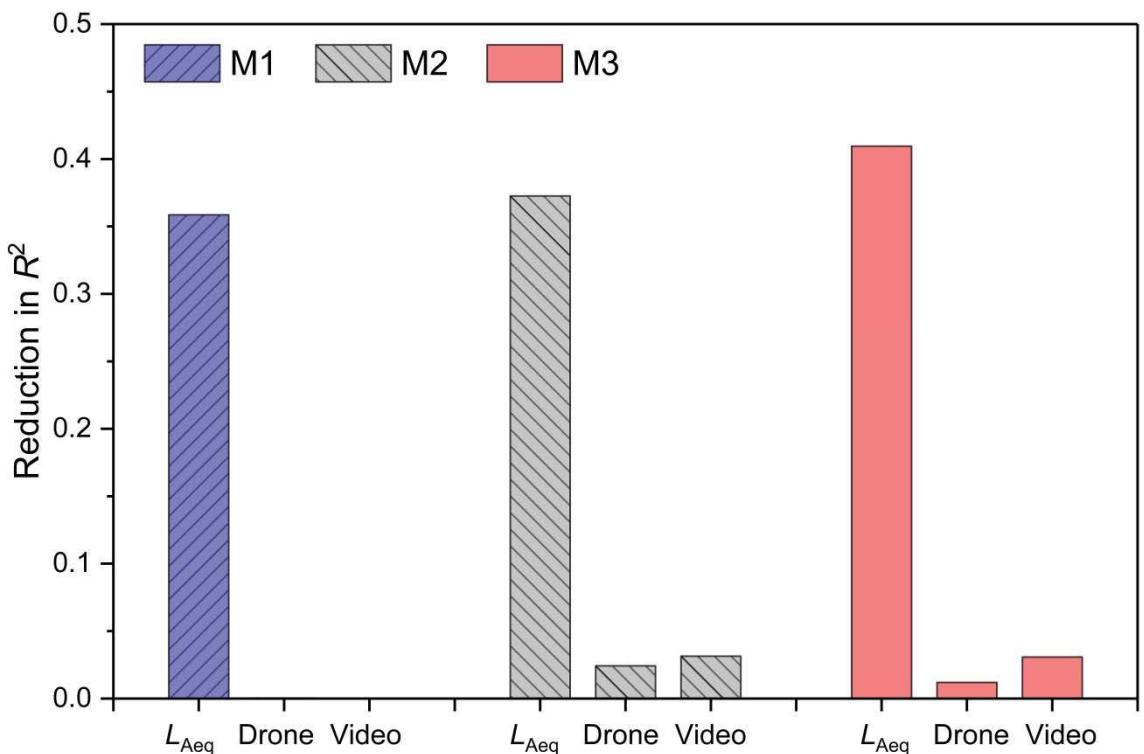
Figure 10. L_{Aeq} vs. reported loudness (top), annoyance (middle) and pleasantness (bottom) for the conditions ‘ambient’ (triangles) and ‘ambient plus drone’ (circles).

3.3. Importance of acoustics and non-acoustics factors of drone noise on urban soundscapes perception

The importance of each factor, i.e. L_{Aeq} , drone noise source and visual scene, on the reported loudness, annoyance and pleasantness was evaluated using a “one-off” approach. In this approach, the importance of each factor is assessed based on model accuracy when removing it from the analysis (Boucher et al., 2019). Three multilevel linear regression models were tested, M1 (fixed intercept, fixed slopes), M2 (fixed intercept, variable slopes) and M3 (variable intercept, variable slopes). The variable parameters in models M2 and M3 represent random effects. Based on models’ results, it is first observed that participant is a significant factor, and after participant is taken into account, reported loudness, annoyance and

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480 pleasantness are more accurately estimated. Thus, with all three parameters included, the
 481 conditional R^2 -value increases from model M1 to M3, for the three subjective ratings
 482 considered: $R^2 = 0.54$ (M1), 0.76 (M2), 0.80 (M3); $R^2 = 0.60$ (M1), 0.83 (M2), 0.84 (M3); and
 483 $R^2 = 0.59$ (M1), 0.76 (M2), 0.78 (M3), for reported loudness, annoyance and pleasantness
 484 respectively.



485
 486 Figure 11. Reduction in conditional R^2 when subtracting L_{Aeq} , drone and video factors from
 487 the multilevel linear regression models M1 (fixed intercept, fixed slopes), M2 (fixed
 488 intercept, variable slopes) and M3 (variable intercept, variable slopes) for estimating the
 489 reported loudness.

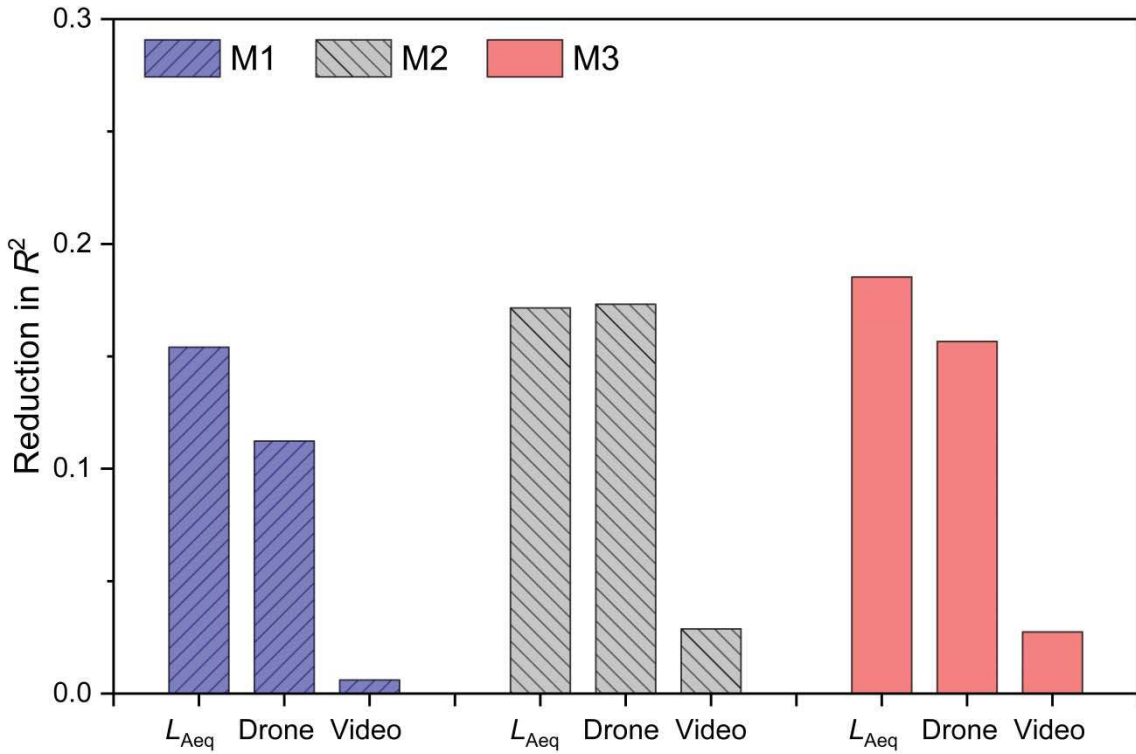


Figure 12. Reduction in conditional R^2 when subtracting L_{Aeq} , drone and video factors from the multilevel linear regression models M1 (fixed intercept, fixed slopes), M2 (fixed intercept, variable slopes) and M3 (variable intercept, variable slopes) for estimating the reported annoyance.

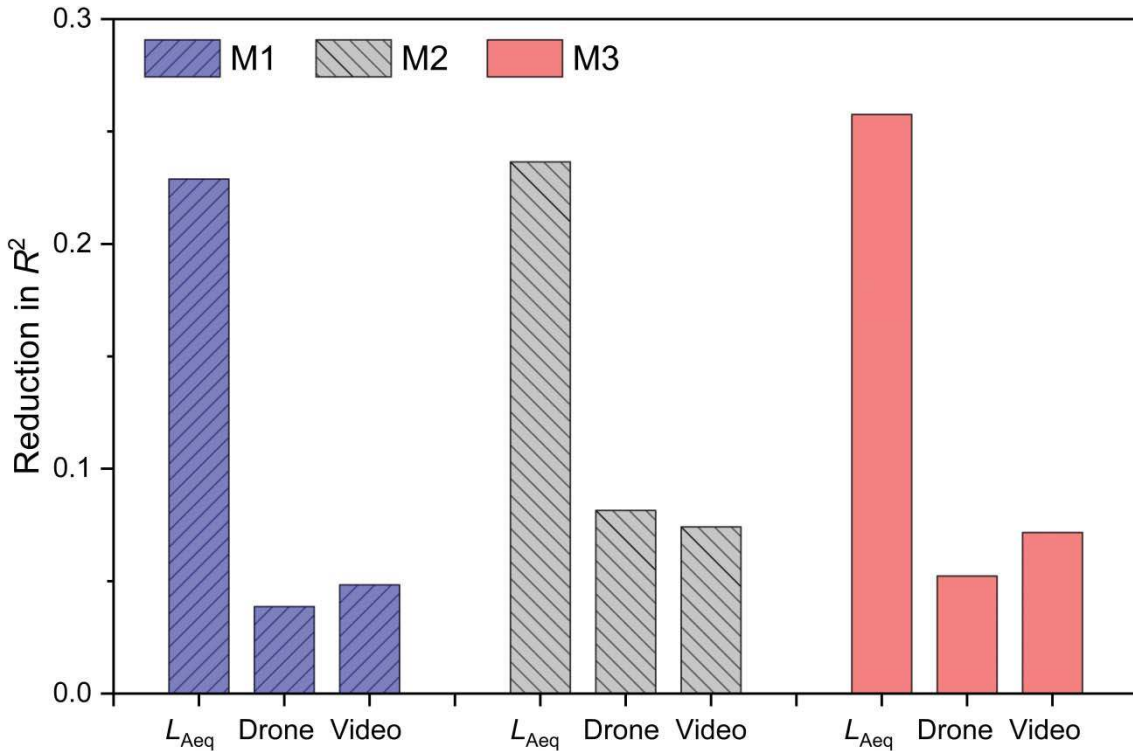


Figure 13. Reduction in conditional R^2 when subtracting L_{Aeq} , drone and video factors from the multilevel linear regression models M1 (fixed intercept, fixed slopes), M2 (fixed intercept, variable slopes) and M3 (variable intercept, variable slopes) for estimating the reported pleasantness.

As shown in Fig. 11, and in line with Fig. 9 – top, the estimation of the perceived loudness, as reported by the participants, is highly determined by L_{Aeq} (reduction in R^2 between 0.36 and 0.41). The estimation of reported annoyance is equally determined by the factors L_{Aeq} (reduction in R^2 between 0.15 and 0.19) and drone noise source (reduction in R^2 between 0.11 and 0.17) (Fig. 12). As described above (see Fig. 9 – middle), this finding confirms that participants' responses on perceived annoyance are also greatly influenced by acoustics (other than sound level) or non-acoustics factors associated to a small quadcopter noise source. Fig. 13 shows that L_{Aeq} primarily determines the reported pleasantness (reduction in R^2 between 0.23 and 0.26). However, the factors drone noise source and, especially, visual stimuli

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509 (reduction in R^2 between 0.05 and 0.07) influence the participants' responses on perceived
510 pleasantness.

511

512 **4. Discussion**

513 **4.1. Influence of visual scenes on soundscape perception**

514 Several authors (Hong et al., 2017; Puyana-Romero et al., 2017; Viollon et al., 2002)
515 have confirmed the influence of visual scenes on soundscape perception. In the results
516 presented in this paper (see Section 3.1), it is observed a decrease of the reported annoyance,
517 in all urban scenarios tested, when visual stimuli is also presented. The use of visual stimuli
518 leads also to a clear increase in the reported pleasantness, although statistically significant
519 differences were only found in the noisiest locations (L1 and L4). In these locations, with high
520 influence of road traffic noise, the visual scene modifies the soundscape perception towards an
521 increase in perceived pleasantness (Pheasant et al., 2010). The human perception is
522 multisensory by its very nature (Cassidy, 1997; Iachini et al., 2009; Pheasant et al., 2010), and
523 therefore bi-modal stimuli (i.e. aural and visual) are essential for a full characterisation of
524 soundscapes (Pheasant et al., 2010). Taking into account audio-visual interaction factors has
525 been found to improve the reliability of studies evaluating the perception of soundscapes
526 (Maffei et al., 2013, Ruotolo et al., 2013).

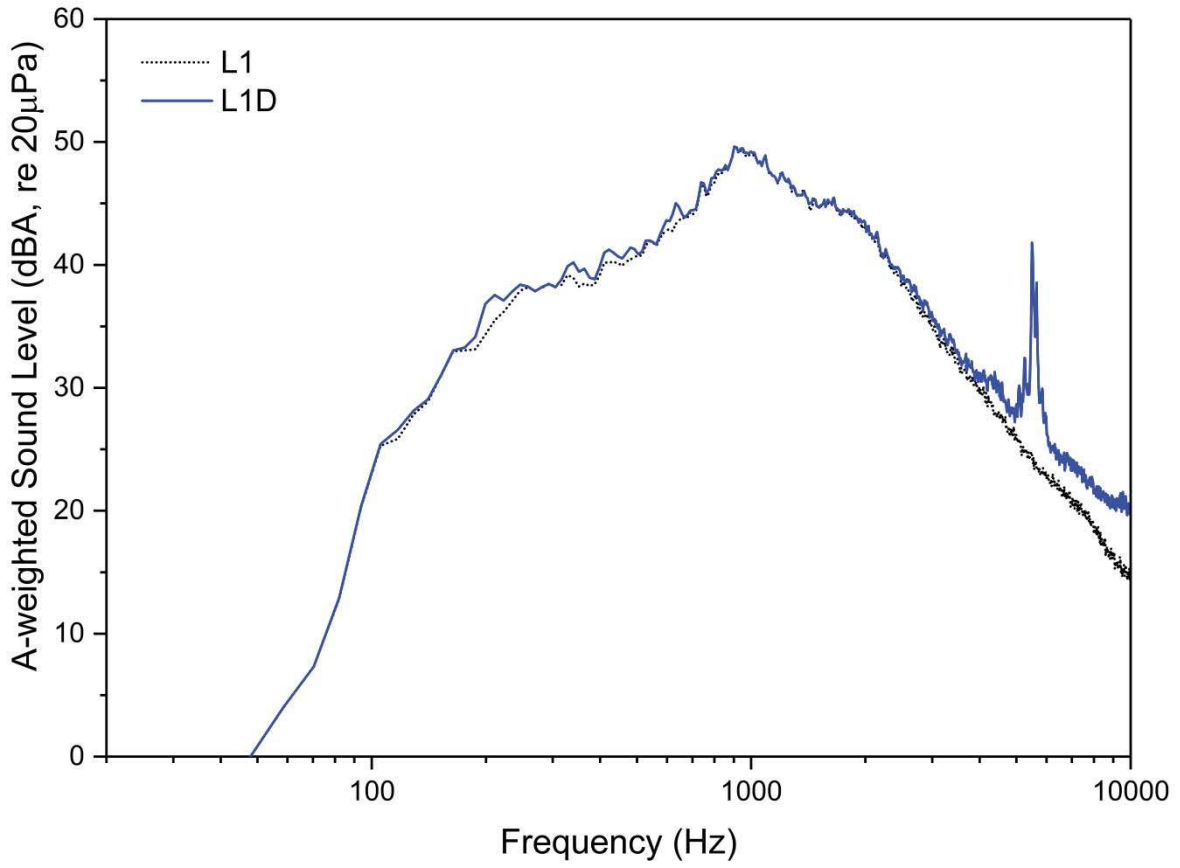
527 **4.2. Combined effects of road traffic and drone noise**

528 In locations with reduced influence of road traffic, statistically significant differences
529 ($p < 0.05$) in reported loudness, annoyance and pleasantness are found between soundscapes
530 with and without the noise of a small quadcopter hover (Table 2). In these locations, the
531 presence of drone noise lead to significant increases in the reported annoyance and loudness,
532 and significant decreases in reported pleasantness. Statistically significant differences in the

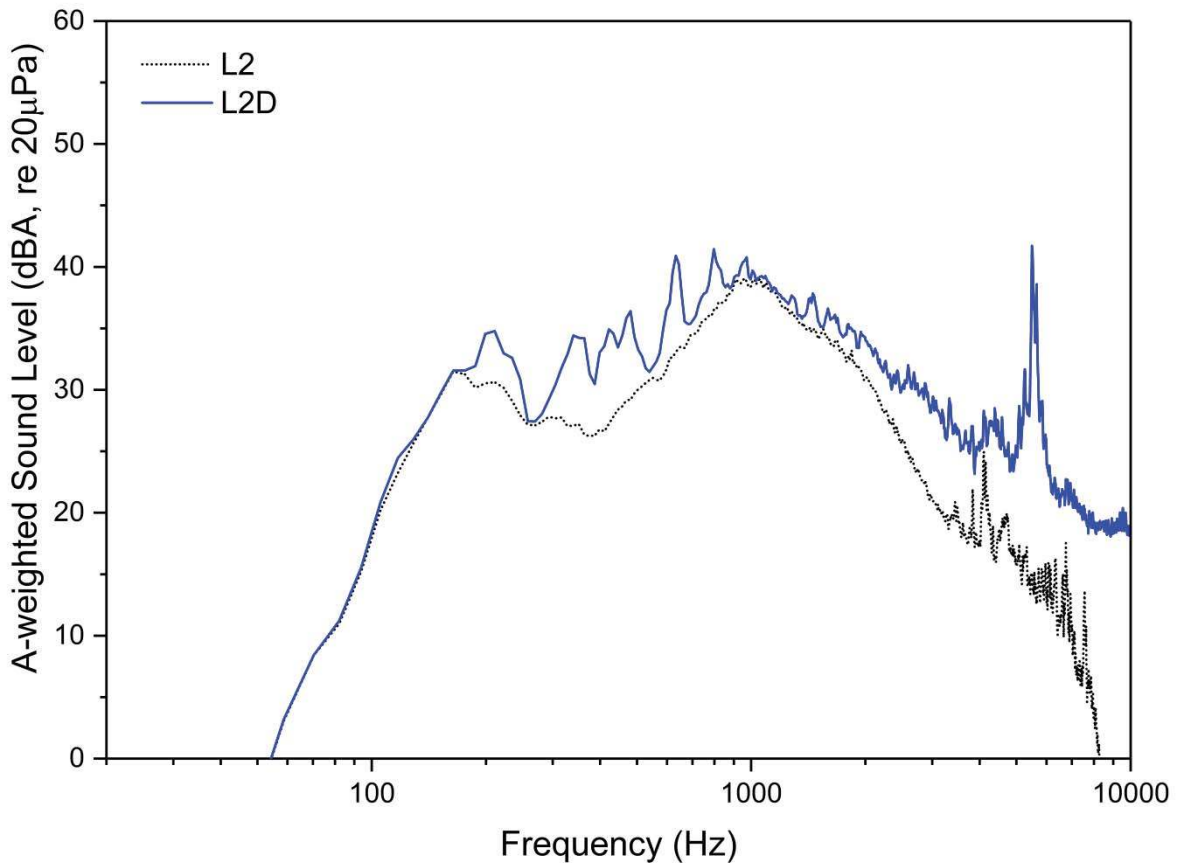
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533 perceived annoyance, reported by the participants, between soundscapes with and without
534 drone noise are found in all locations tested. However, in the locations closest to road traffic
535 (L1 and L4), the increase in reported annoyance with drone noise is very reduced, i.e. only
536 about 1.3 times higher than without drone noise. In locations with little influence of road traffic
537 noise (L2, L3, L5, L6 and L7), the reported annoyance with drone noise is up to 6.4 times
538 higher than without drone noise.

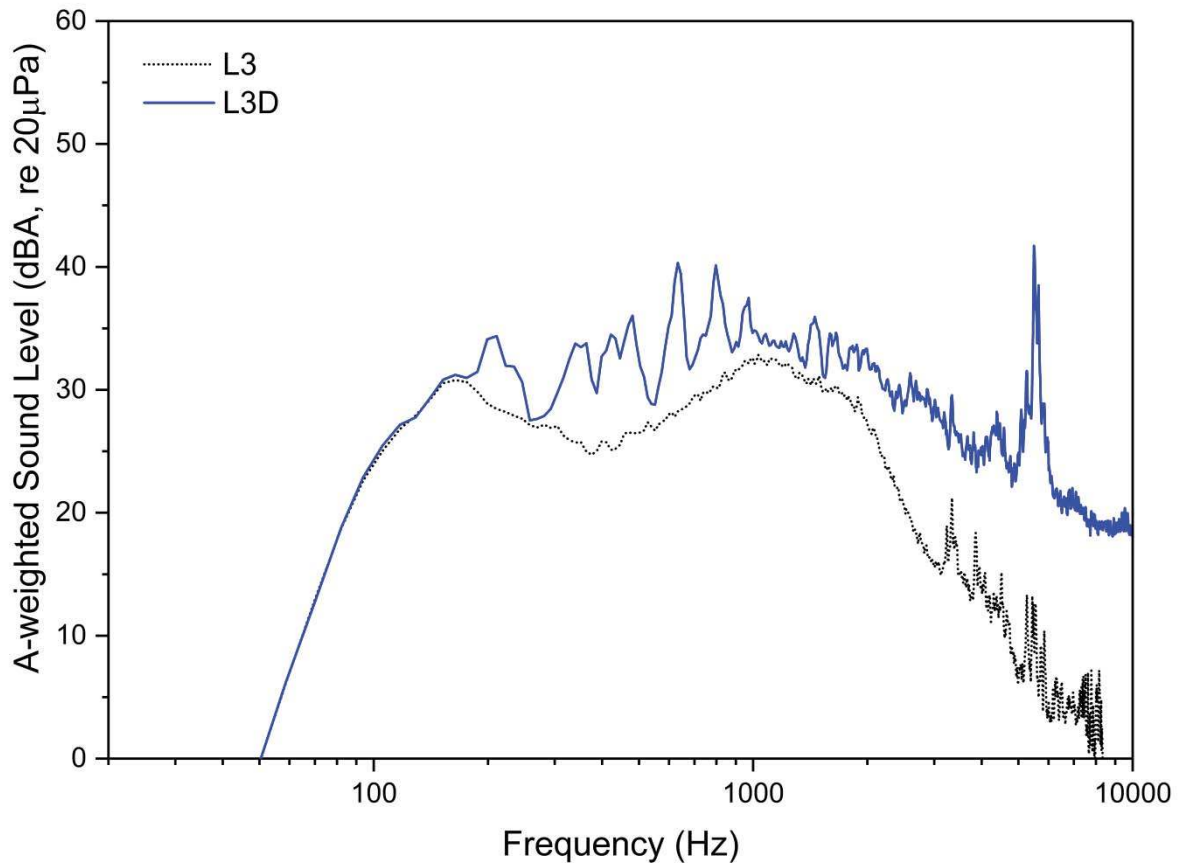
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 542 Figure 14. Frequency spectra (A-weighted Sound Pressure Level (dBA, re 20µPa)) measured
 543 in locations L1 (top), L2 (middle) and L3 (bottom), without (dotted line) and with (solid line)
 544 noise of the small quadcopter.

545 The overall sound level (L_{Aeq}) is the primary factor in determining the reported loudness
 546 for both soundscapes with and without drone noise (see Section 3.3). In determining reported
 547 annoyance for soundscapes with drone noise, the factor drone noise source is as important as
 548 L_{Aeq} (see Fig. 12). In determining reported pleasantness for soundscapes with drone noise, L_{Aeq}
 549 is the primary factor, but factor drone noise source, and especially visual factor influence the
 550 participants' responses. In Sections 3.2 and 3.3, it is hypothesised that the participants'
 551 responses on perceived annoyance and pleasantness for soundscapes with drone noise might
 552 be highly influenced by acoustics factors particularly characteristic of a small drone
 553 (quadcopter). The noise generated by a small quadcopter is mainly tonal in character, with a

2125
2126
2127 554 series of tones at harmonics of the blade passing frequency (BPF) of the rotors distributed
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2129 555 across the frequency spectrum, and with a significant content in high frequency content
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2131 556 consequence of the operation of the electric motors (Cabell et al., 2016; Torija et al., 2019b).
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2133 Both the tonal and high frequency content are of significant importance for the subjective
2134 557 response to aircraft noise (Torija et. al, 2019a). Neither the tonality nor the very high frequency
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2136 558 (above 4000 Hz) noise are taken into account in the L_{Aeq} metric, which might be the reason of
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2138 559 its poor performance in assessing the reported annoyance (and pleasantness) of soundscapes
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2140 560 with drone noise (see Fig. 10). As shown in Fig. 14, in locations close to a road (Fig. 14 – top),
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2142 561 the road traffic noise masks the noise generated by the small quadcopter, with the exception of
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2144 562 the very high frequency noise. Under outdoor conditions, with flyovers at a particular altitude
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2146 563 (e.g. 15-30 m and up to 100 m (Christian and Cabell, 2017)), the very high frequency noise is
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2148 564 rapidly attenuated by atmospheric absorption. At locations further away from road traffic, with
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2150 565 lower levels of road traffic noise, the tonal and high frequency content of the small quadcopter
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2152 566 becomes more dominant (Fig. 14 – middle and bottom). Under these conditions, and assuming
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2154 567 a linear relationship between the subjective ratings evaluated and L_{Aeq} , the participants’
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2156 568 responses (on perceived annoyance and pleasantness) are mainly driven by the noise features
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2158 569 of the small quadcopter, and are almost independent of the overall L_{Aeq} in the location. In these
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2160 570 locations, the perceived annoyance is reported as high as in locations with higher overall L_{Aeq}
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2162 571 (see Fig. 10 – middle).
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2168 573 These results suggest that, notwithstanding the potential safety issues, the development
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2170 574 of corridors along busy roads for drone fleets to operate might reduce the overall community
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2174 576 Merchan et al., 2015).
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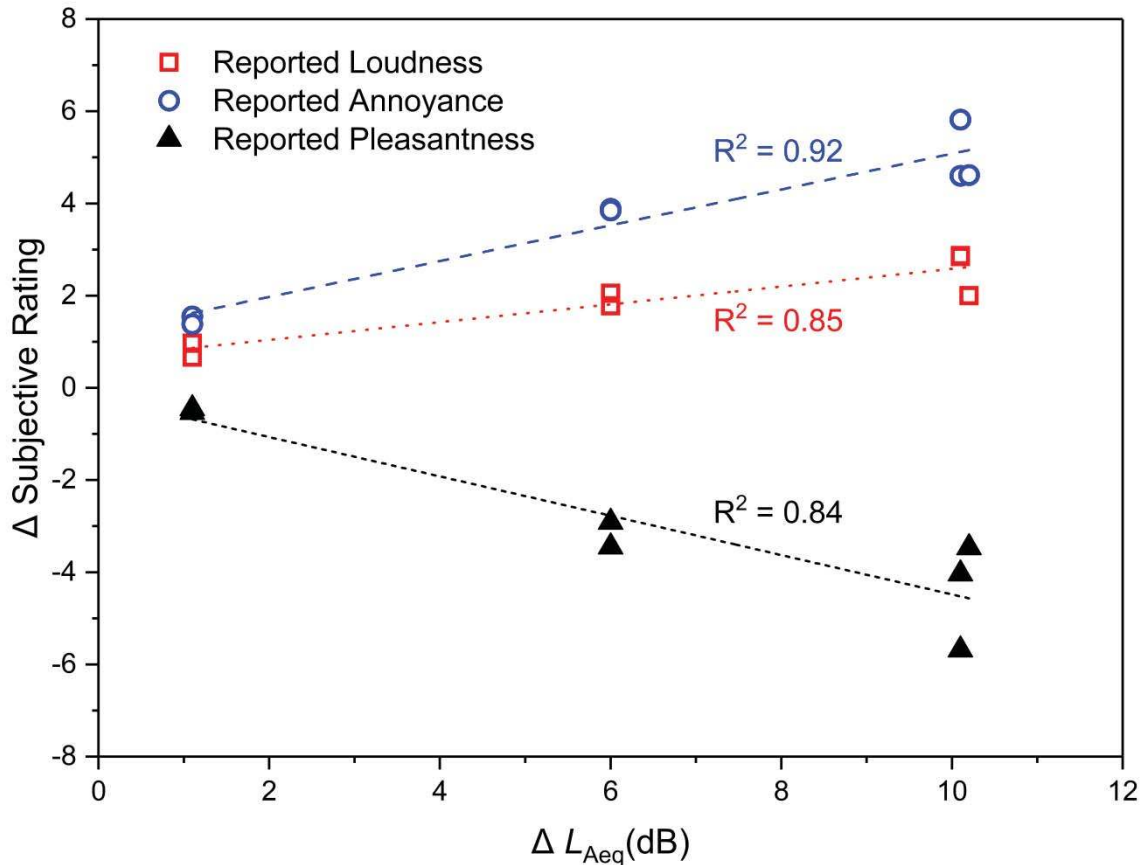


Figure 15. Changes in the subjective ratings loudness (squares), annoyance (circles) and pleasantness (triangles), and in the L_{Aeq} without and with the noise generated by the drone hover, in the seven locations tested.

As seen in Fig. 15, the change in the reported loudness, annoyance and pleasantness between the soundscapes without and with drone noise is highly correlated with the increase of L_{Aeq} generated by the small quadcopter over the ambient noise. Moreover, Fig. 15 shows that for all the locations tested, the increase in reported annoyance with drone noise is higher than the increase in reported loudness, which also suggests the influence of the tonal and high frequency content of drone noise (in addition to loudness) on the participants' responses.

In Sections 3.2 and 3.3, it is also hypothesised that the responses on perceived annoyance might be influenced by non-acoustics factors associated to the drone noise source. Although this research does not provide enough evidence to test this hypothesis, the

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590 participants' responses on perceived loudness and annoyance in location L7 (park without
591 influence of road traffic, dominated by birds and water sounds) seem to suggest some influence
592 of non-acoustics factors. Thus, in Fig. 15, the increase in reported annoyance and decrease in
593 reported pleasantness with drone noise is notably higher and lesser, respectively, compared to
594 the increase/decrease in locations with similar ΔL_{Aeq} . In this location, there is probably an
595 expectation of tranquility and relaxation, and the presence of drone noise is more penalised
596 (Pheasant et al., 2008).

4.3. Constrains and limitations

598 The design of this research was carefully planned to investigate the perception of the
599 same drone operation (a small quadcopter hover) on several urban soundscapes with a varying
600 level of road traffic noise (and varying sound sources). The underlying hypothesis is that road
601 traffic could mask drone noise, and thus corridors for drone fleets might be defined along road
602 infrastructure to alleviate the noise impact of residents. A single drone was used in this
603 research, a small quadcopter, whose size and characteristics resemble with drones currently
604 under investigation for several applications from parcel delivery to surveillance. The focus of
605 this research is the changes in sound level and frequency spectral when a drone operation is
606 introduced in a typical urban soundscape. To simplify the achievement of this objective, a
607 hover operation was selected, with the drone in a fixed position working at full power. Under
608 these conditions, the influence of varying operational regimes, doppler effect and atmospheric
609 absorption was avoided, and only the drone sound emission was assessed. As no drone
610 movement was simulated, and the focus was on a steady positioned drone with other sources
611 in the background, the experimenters decided to use a monophonic signal to present stimuli to
612 the participants.

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613 The findings of this paper refer to a drone hover with a steady frequency spectrum.
614 Under flyover conditions, or with significant influence of atmospheric disturbances such as
615 wind gusts, the flight control system varying rotor rotational speeds to maintain vehicle
616 stability will create an unsteady acoustic signature (Cabell et al., 2016; Torija et al., 2019b).
617 Furthermore, during the landing and take-off maneuvers, the changes in power setting and rotor
618 rotational speeds will change sound directivity and frequency spectra. Both the unsteadiness
619 of the acoustic signature and the changes in directivity and frequency spectra are likely to affect
620 the audibility of the drone noise, and therefore, might alter the road traffic noise vs. drone noise
621 combination effects described above.

622 Under the assumption of a linear relationship between the subjective ratings evaluated
623 and L_{Aeq} , Fig. 10 suggests that the annoyance and pleasantness reported by the participants are
624 mainly driven by the noise features of the small quadcopter. The comparison between drone
625 noise and other transportation noise at the same sound level (L_{Aeq}) will provide further insight
626 into the effects of the particular noise features of drones on sound perception.

627 After the main principles of the effects of drone noise are understood (as described in
628 this paper), further investigation on the effects of drones operating in (a wider diversity of)
629 urban environments on the perceived soundscape would require the simulation of flyovers (and
630 take-off and landing maneuvers) to account for both emission and propagation factors. A wider
631 range of drones would need to be assessed, accounting for differences in size, power, and
632 configuration (fixed wing vs. multicopter). From the soundscape perception point of view,
633 the use of spatial reproduction techniques (e.g. headphone-based First-Order-Ambisonic
634 (FOA) tracked binaural or FOA 2D speaker arrays), would allow the immersion and
635 plausibility of simulations with moving sources (Hong, et al., 2019; Lam, et al., 2019). As
636 masking is a complex phenomenon influenced by not only sound levels and frequency, but also
637 spatial cues (Cerwén et al., 2017), the use of spatial audio reproduction techniques would

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2363 638 increase the fidelity of simulations with combined road traffic and drone noise sources,
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2365 639 allowing a more refine evaluation of the masking capabilities of road traffic.
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2371 641 **5. Conclusions**

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2373 642 This research represents a first approach to quantify the effect on urban soundscapes of
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2375 643 introducing drone operations. The paper presents the results of a series of experiments aimed
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2377 644 to investigate the effects of drone noise on a diversity of urban soundscapes. An audio-visual
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2379 645 recording of a small quadcopter, recorded in an anechoic aeroacoustics laboratory, was added
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2381 646 to audio-visual recordings taken in seven urban locations of different type. Both audio and
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2383 647 audio plus panoramic video stimuli (using VR techniques) were presented to a series of
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2385 648 participants, who were asked to report their perceived loudness, annoyance and pleasantness
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2387 649 for each one. The soundscapes of the seven locations evaluated differed in the influence of road
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2389 650 traffic noise. In locations close to busy roads, road traffic noise seems to mask the noise
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2391 651 generated by the small quadcopter (with the exception of very high frequency noise). In these
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2393 652 locations, the reported annoyance for the soundscapes with drone noise is only 1.3 times higher
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2395 653 than without drone noise. In locations with little influence of road traffic noise, the specific
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2397 654 characteristics of drone noise (i.e. series of tones at harmonics of rotors' BPF and high
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2399 655 frequency noise) dominate the soundscape. In these locations, the participants reported a
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2401 656 perceived annoyance with drone noise up to 6.4 times higher than without drone noise. In these
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2403 657 locations with low influence of road traffic noise, the reported annoyance was about 7 (scale
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2405 658 from 0 to 10) with drone noise, regardless the overall L_{Aeq} in the location. These results have
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2407 659 two main implications: (1) The annoyance reported for the soundscape with the drone present
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2409 660 was highly influenced by the particular characteristics of drone noise. The descriptor L_{Aeq} does
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2422 662 for providing an effective assessment of drone noise impact in urban settings. (2)
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2425 663 Notwithstanding any potential safety issue, the operation of drone fleets through corridors
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2427 664 along busy roads might significantly mitigate the increase of community noise impact caused.
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2429 665 The use of panoramic video had little influence on the responses on perceived loudness.
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2431 666 However, the reported annoyance and pleasantness of the soundscapes tested with panoramic
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2433 667 visual stimuli were notably different than with only audio stimuli. As previous studies suggest,
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2435 668 the simulation of audio-visual scenes can aid a more accurate assessment of the noise impact
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2438 669 of transportation systems on urban soundscapes.
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2440 670 The results presented in this paper should be taken with caution, as only one quadcopter
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2443 671 model in a fixed position is assessed. This single drone noise condition was enough for the
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2445 672 purposes of this paper, as the emphasis was to assess the noise impact of the same drone noise
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2447 673 in different urban soundscapes, with varying influence of road traffic. However, in future
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2449 674 research, a variety of flyover maneuvers (with different airspeed and altitude) of a wider range
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2451 675 of drones will be investigated for a more comprehensive analysis of drone noise impact on
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2453 676 urban areas. Further work will investigate different conditions with visual cues, where the
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2455 677 drone is visible, partly visible and not visible, also taking into account different distances (i.e.
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2457 678 flyover altitudes).
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2463 680 **Acknowledgements** 2464 2465

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2467

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686 **Supplementary material**

687 The data (including audio and panoramic visual stimuli) used for this research will be
688 provided by the authors upon request.

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