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## **Nature and the City: Audiovisual interactions in pleasantness and psychophysiological reactions**

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► **To cite this version:**

V.B. Bogdanov, Catherine Marquis-Favre, Marylise Cottet, Brice Beffara Bret, Fabien Perrin, et al.. Nature and the City: Audiovisual interactions in pleasantness and psychophysiological reactions. Applied Acoustics, 2022, 193, pp.108762. 10.1016/j.apacoust.2022.108762 . hal-03924495v2

**HAL Id: hal-03924495**

**<https://hal.science/hal-03924495v2>**

Submitted on 14 Nov 2024

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1 **Nature and the City: audiovisual interactions in pleasantness and**  
2 **psychophysiological reactions**

3

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20 **Abstract**

21

22 The presence of natural elements in the urban environment improves wellbeing. Comparisons  
23 of different psychophysiological reactions to both auditory and visual perceptions of urban  
24 environments are employed as a method for shedding light on the mechanisms involved in  
25 audiovisual interaction, by which visual context influences auditory perception, and vice versa.  
26 Combining psychophysical and physiological methodologies is likely to improve our  
27 understanding of the perceptual consequences of variations in the presence of nature in the  
28 city. In the present study, 61 participants, mainly students, were exposed to urban  
29 soundscapes accompanied by street scenes. Audio excerpts of bird song or road traffic were  
30 paired with images with or without vegetation. Half of the participants (n=30) were asked to  
31 judge the auditory pleasantness after each audiovisual presentation, whereas the other half  
32 (n=31) judged the visual pleasantness of the scene. Heart rate, pupil area, gaze fixations and  
33 electromyography of the eyebrow muscle (*corrugator supercillii*) were concurrently recorded.  
34 We demonstrated a strong perceptual audiovisual interaction: auditory pleasantness was  
35 higher when accompanied by a natural visual context, and visual pleasantness was higher  
36 when accompanied by natural sounds. Electromyography and heart rate were particularly  
37 sensitive to the presence of nature in the soundscapes, whereas gaze behavior discriminated  
38 only visual nature elements. The natural sounds were associated with lower heart rate and  
39 less *corrugator supercillii* electromyographic activity, whereas natural images were associated  
40 with slower gaze behavior. Pupil area was sensitive to both auditory and visual stimulations.  
41 The pupil was relatively constricted by all natural stimuli and discriminated different unpleasant  
42 traffic noise samples and the modulation of visual pleasantness by these sounds. This  
43 suggests a distinctive role of arousal level in the modulation of pupil reactions, which appear  
44 well suited to study audiovisual interactions and the perceptual effects of natural elements in  
45 urban environments.

46 **Keywords:** audiovisual, nature, pleasantness, arousal, attention

## 47 **1. Introduction**

48

49 The densification of urban areas, activities generated by economic growth and  
50 transportation, are some of the main driving forces for noise pollution, which is considered as  
51 a major environmental health problem. Studies have highlighted various adverse impacts of  
52 noise exposure on well-being and health, such as sleep disturbance (e.g., Muzet, 2007),  
53 effects on children's cognition and health (e.g., Clark et al., 2013), annoyance (e.g., Miedema  
54 & Oudshoorn, 2001), myocardial infarction (e.g., Babisch et al., 2005), diastolic blood pressure  
55 and hypertension (e.g., Petri et al., 2021). Noise exposure incurs a financial burden on society  
56 (e.g., World Health Organization. Regional Office for Europe, 2011). Urban areas are typically  
57 exposed to a multitude of noise sources (e.g., road traffic noise, railway noise, road traffic  
58 noise, recreational noise). Road traffic noise is one of the prominent threats to wellbeing in  
59 cities, causing emotional stress, impeding work performance, and forming a risk factor for  
60 sleep disturbance, cardiovascular diseases and hypertension (e.g., Singh et al., 2018). The  
61 exposure of city dwellers to noise pollution is thus an important issue. The presence of nature,  
62 whether visually perceived (e.g., the presence of plants, trees, or a river) or heard (e.g., bird  
63 song, water lapping, wind in trees), is known to improve wellbeing (e.g., Franco et al., 2017).  
64 Soundscape studies have shown that when natural sounds like bird song or water sounds are  
65 combined with road traffic noise, they improve judgments of auditory pleasantness of urban  
66 environments (Lavandier & Defréville, 2006, Jeon et al., 2012). Natural sounds increase the  
67 perceived tranquility of urban areas (Cassina et al., 2018), and are thought to play an important  
68 role in nature-based rehabilitation (Cerwén et al., 2016). From a visual perspective, looking at  
69 vegetated scenes was demonstrated to bring important benefits, such as stress reduction and  
70 better psychological restoration (Kaplan, 1995). For example, it was shown that green spaces  
71 are favorable for stress reduction as indicated by a reduced cortisol level (Ward Thompson et  
72 al., 2012). However, there is still much that remains to be learned about the specific pathways  
73 linking green spaces to health (Markevych et al., 2017). In particular, previous studies  
74 indicated that audiovisual interactions (here defined as the perceptual phenomenon according

75 to which visual context influences auditory perception, and vice versa) were observed in  
76 pleasantness judgments, especially when nature is present. Actually, it is known that the  
77 presence of nature in the visual context affects auditory judgments (e.g., Preis et al., 2016).  
78 For example, the auditory unpleasantness due to road traffic noise in urban areas was judged  
79 to be about 20-30 % less when auditory stimuli were combined with a visual context of natural  
80 scenes compared to the context of a scene with apartment blocks only (Viollon et al., 2002).  
81 Similar findings were also highlighted in studies dealing with noise annoyance (e.g., Chau et  
82 al., 2018). Outdoor vegetation visible from the living room window reduces noise annoyance  
83 (e.g., Van Renterghem & Botteldooren, 2016). However, not all studies confirmed such  
84 findings when noise annoyance was assessed in a visual context with or without vegetation  
85 (Sun et al., 2018). Thus, the mechanisms linked to the impact of natural factors and  
86 audiovisual interactions on wellbeing in the context of the urban environment are therefore far  
87 from clear. Several psychological and physiological human responses deserve when exploring  
88 these mechanisms. In particular it could be promising to compare how the changes in  
89 parameters of audiovisual excerpts of urban environments cause variations in emotional  
90 valence, arousal and attention. In this manner, it may be possible to identify the key processes  
91 by which the presence of nature in the urban environment can modify human behavior.  
92 Pupillary dilation is known to be sensitive to rapid arousal (Bradley et al., 2008), slowing of  
93 heart rate is evidence of an experienced threat, and an increase in the activity of *corrugator*  
94 *supercilii* face muscle has been interpreted as evidence of discrimination between negative  
95 and positive emotional valence (Bradley & Lang, 2000). Gaze behavior reveals changes in  
96 visual attention. A reduced number of gaze fixations and longer fixation durations may be  
97 physical manifestations of altered attentional states that have been characterized as  
98 involuntary sustained attention or fascination (Berto et al., 2008). Such parameters could  
99 therefore be of interest for revealing the basic mechanisms of audiovisual interactions and for  
100 helping us to understand the wellbeing effects of nature in urban environments.

101 The present study aimed to explore the mechanisms involved in perceptual audiovisual  
102 interactions observed during the auditory and visual appraisal of urban environments in the

103 presence of nature. Sixty-one participants, mainly students, were exposed in laboratory  
104 conditions to audiovisual stimuli stemming from urban environments. This study presented the  
105 following main features:

106 (1) Both the auditory and visual pleasantness of urban environments was studied while  
107 varying the degree of nature elements present in the audiovisual stimulation.

108 (2) A combined psychophysical and physiological methodology was used to investigate  
109 both the auditory and visual perceptions of urban environments.

110 (3) Audiovisual interactions in either auditory or visual perception was highlighted, i.e.  
111 the influence of the visual scenery on auditory perception, and vice versa.

112 (4) Various peripheral psychophysiological measures were used to probe changes in  
113 emotional valence, arousal and attention during audiovisual stimulation.

114 Our hypothesis was that both the audible and visible presence of nature in urban  
115 environments would not only induce greater auditory or visual pleasantness but also affect  
116 certain physiological measures.

117

## 118 **2. Method**

119

### 120 **2.1 Participants**

121

122 Sixty-one healthy adults between 19 and 57 years-of-age (mean age 27.93, SD=10.33)  
123 were recruited through advertisements sent via the institutional mailing list of the Graduate  
124 School of Civil, Environmental and Urban Engineering (ENTPE – Lyon, France), where the  
125 research experiment took place. This sample size corresponded to the number of participants  
126 used in previous studies with a similar design (Berto et al., 2008; Bradley et al., 2008; Bradley  
127 & Lang, 2000; Viollon et al., 2002). The critical sample size calculated for our study was 26  
128 participants, and obtained with G\*Power 3 (Faul et al., 2007) for an effect size (f) 0.33, power  
129 of 0.80,  $p < 0.05$  and four measures in repeated measures ANOVA, assuming no overall  
130 correlation between the measures.

131 Participants were students and staff of the aforementioned School. They declared to  
132 have normal or corrected-to-normal vision, with self-reported absence of neurological,  
133 psychiatric, cardiovascular, respiratory, and auditory disorders. This study followed the  
134 standards of the Declaration of Helsinki and was approved by the regional ethics committee  
135 (Sud-Ouest et Outre-Mer III) on 01/08/2018, Research protocol n° 2018/58, ID-RCB: n°2018-  
136 A01621-54. Each participant gave written informed consent and was reimbursed for  
137 participation with a gift certificate worth 10 Euros.

138

## 139 **2.2 Auditory and visual stimuli**

140

141 The protocol used two categories of auditory stimuli: 18 urban road traffic noise samples  
142 ranging from 48 to 62 dB(A) and 18 samples of bird song ranging from 40 to 45 dB(A), each  
143 sample lasting for 4 seconds. All noise samples stemmed from recordings made using the  
144 ORTF technique (devised at the former Office de Radiodiffusion Télévision Française), with  
145 Schoeps MSTC 64 microphones equipped with Schoeps BBG windfields, and a Tascam  
146 portable recorder with 24-bit resolution and a sampling frequency of 44.1 kHz (Morel et al.,  
147 2012). The road traffic noise samples consisted of vehicle pass-bys (light vehicles, buses,  
148 heavy vehicles or motorcycles/mopeds) recorded by Morel and colleagues (Morel et al., 2012).  
149 These samples were previously used in studies dealing with noise annoyance (Gille et al.,  
150 2016). The bird song samples were recorded on the ENTPE campus site (Vaulx-en-Velin,  
151 France). A 300-Hz high-pass filter was applied to the bird song samples to remove low  
152 frequency content resulting from the background noise of suburban Lyon and to insure good  
153 sound reproduction quality in the quiet experimental room. For the sound reproduction, the  
154 mean sound pressure levels of all sound stimuli were set to the levels of the noise sources  
155 measured on site. A 200-ms amplitude fade-in and a 500-ms fade-out with a quadratic  
156 progression kernel were applied to all 36 sound stimuli.

157 The experimental protocol also used two categories of visual stimuli: 18 images  
158 representing vegetated scenes and another 18 images depicting non-vegetated scenes

159 (examples in **Fig. 1**). These visual stimuli were pictures of urban scenery in and around Lyon  
160 (France) taken specifically for this experiment during the spring and summer seasons. The  
161 camera used to take the pictures was a SONY© DSC-HX10V, with exposure of 1/400-1/1000  
162 s, ISO 100, and automatic white balance.

163 There was no overall significant difference in eye illuminance between the vegetated  
164 and non-vegetated images when displayed on the screen during the experiment (11.0 lux, SD  
165 = 1.1, n = 18 and 10.9 lux, SD = 1.2, n = 18, respectively,  $p=0.81$ , t-test). The initial resolution  
166 was 4896 x 2752 pixels, while the size of the images on the screen was 45.3 x 25.5 cm with  
167 a resolution of 1632 x 918 pixels. All photographs were taken in the same manner: the  
168 photographer stood at the intersection of two streets with their back turned towards the  
169 intersection and the lens pointing in the opposite direction. This protocol was followed to avoid  
170 visual and auditory incongruities. All photographs were taken in good weather in the city of  
171 Lyon and its suburbs.

172

### 173 **2.3 Laboratory setup**

174

175 Participants were seated in front of a desk (Fig. 1, A3) supporting a computer monitor  
176 and eye-tracking equipment (described in 2.6) inside a dark sound-proof room with a  
177 background noise level of 18.5 dB(A). A computer mouse for making responses was available  
178 on the desk. The LCD monitor used (Lenovo ThinkVision LT2423WC, 24-inch FHD LED  
179 Backlit Monitor, TN technology) had a resolution of 1920 x 1080 with a typical contrast ratio of  
180 1000:1. The viewing distance was about 50 centimeters. Given that the width/height of the  
181 display was 53/30 centimeters, it subtended approximately 30 degrees of visual angle  
182 vertically and 50 degrees of visual angle horizontally. Sound stimuli were reproduced using  
183 two active loudspeakers (Dynaudio BM5A Actif), and one subwoofer (Dynaudio Acoustics  
184 BM9S) to ensure good reproduction of low frequencies of the road vehicle pass-by noise  
185 samples. The loudspeakers were located behind the seated participants at a height of 1.50  
186 with the subwoofer on the floor between them. The center of the participant's interaural axis



187 and the loudspeakers formed an equilateral triangle with sides measuring 1.5 m. Thus, the  
188 sounds were reproduced in such a way that the participants perceived the vehicles to pass  
189 behind their backs, and therefore the noise sources would have been outside of their field of  
190 vision.

191

## 192 **2.4 Experimental paradigm**

193

194 The PsychToolbox application (Brainard, 1997; Pelli, 1997) in MATLAB was used for  
195 implementing the experimental paradigm based on 2 categories of sounds (18 bird song and  
196 18 road traffic noise samples) and 2 categories of visual scenes (18 vegetated and 18 non-  
197 vegetated urban pictures). To ensure that physiological measures were reliable, stimuli were  
198 presented with short duration and repeated conditions (e.g., Bradley & Lang, 2008) using  
199 different samples per condition to avoid habituation (e.g., Groves & Thompson, 1970). During  
200 each audiovisual presentation, the participants were simultaneously exposed to one picture  
201 and one sound for a duration of 4 s. Four paradigm conditions resulted from the 2-by-2  
202 categories of sounds and images: bird song and vegetated image; bird song and non-  
203 vegetated image; traffic noise and vegetated image; traffic noise and non-vegetated image.  
204 Each of the 36 visual stimuli was randomly presented twice, once paired with a bird song  
205 sample and once with a traffic noise sample. Each of the 4 conditions was repeated using 18  
206 trials with different image-sound combinations, giving a total of 72 audiovisual stimulations  
207 (see **Fig. 1, A1 and A2**). Whether participants assessed the auditory or visual pleasantness  
208 of the audiovisual combination was randomly determined before the start of the experiment  
209 and constituted a between-subjects factor (**Fig. 1, B**).

210 During the experiment, heart rate, pupil size variations, gaze fixations, and EMG activity  
211 of the *corrugator supercillii* (eyebrow muscle) were recorded. The systems used for these  
212 physiological measures are described in sections 2.6 to 2.8.

213 After each presentation, a 4-s blank screen with a fixation dot was shown. Subsequently,  
214 participants made their response by judging the auditory or visual pleasantness of the

215 presented urban environment (depending on the task required – cf. instructions in section 2.5).  
216 They gave their rating using a bipolar continuous visual-analogue scale. The scale displayed  
217 numerical labels from 0 to 10, with two opposite end points “unpleasant” and “pleasant”, to  
218 facilitate ratings along the continuum (cf. Fig. 1, B3), as typically used in studies recording  
219 affective reactions (e.g., Bradley & Lang, 2000; Frederickson & Dunsmuir, 2009). Participants  
220 were instructed to move the mouse cursor from the center of the screen to the location on the  
221 scale reflecting the pleasantness felt. Placing the mouse on the line made a white spot appear  
222 at that position, thus providing feedback on a successfully registered judgment. The mouse  
223 cursor then had to be brought back to the center of the screen so that the next judgment  
224 started from about the same hand position. Participants had 4 s to make their response.  
225 Subsequently, a fixation dot was displayed for a random duration between 6 and 14 s before  
226 the next trial commenced.

227 Before the experiment, participants completed four training trials to get acquainted with  
228 the task and the rating scale. The trials included all four experimental conditions and were  
229 randomly composed of 4 sound excerpts (2 bird songs and 2 traffic noises) and 4 images (2  
230 vegetated scenes and 2 non-vegetated scenes). These stimuli were not used in the main  
231 experiment. The experimental session took about 30 minutes.

232

## 233 **2.5 Judgment task instructions**

234

235 The instructions given to the participants were similar to those used in a previous study  
236 on audiovisual interaction (Viollon et al., 2002).

237 Approximately half of the participants (n=30) were randomly assigned to the “auditory  
238 task”. They received the following instructions in French: «*L’expérience vous propose des*  
239 *extraits audiovisuels d’environnements urbains. Imaginez-vous à chaque fois dans le lieu*  
240 *représenté par l’image. Si vous étiez dans ce lieu, comment jugeriez-vous l’environnement*  
241 *sonore et uniquement l’environnement sonore ?*», which translate as “During the experiment,  
242 you will be exposed to audiovisual excerpts of the city environment. Imagine yourself each

243 *time at the place shown in the image. If you were at this place how would you judge the sound*  
244 *environment and only the sound environment?”.*

245 The other half of the participants (n=31) were assigned to the “visual task”. They  
246 received the same instructions except for the last question which was: “*Si vous étiez dans ce*  
247 *lieu, comment jugeriez-vous l’environnement **visuel** et uniquement l’environnement **visuel** ?*»,  
248 *which translates as “If you were at this place how would you judge the **visual** environment*  
249 *and only the **visual** environment?.”*

250

## 251 **2.6 Eye-tracking**

252

253 The gaze position and pupil area of both eyes were recorded using an Eyelink® Portable  
254 Duo eye-tracker (SR Research Ltd., Mississauga, Ontario, Canada) with a sampling frequency  
255 of 1 kHz. This eye-tracker operated in remote mode as a head-free system with a target  
256 sticker: a standard cue placed on the forehead of the participants and automatically identified  
257 by the eye-tracking system. This setup allows recording of eye position without restraining the  
258 head position. The test phase was preceded by a standard nine-point calibration procedure  
259 for mapping gaze position to screen position. The targets used for calibration were the default  
260 targets of the Eyelink® apparatus.

261

## 262 **2.7 Eye-tracking preprocessing**

263

264 Pupil area and gaze position data were analyzed using MATLAB. The algorithm for the  
265 preprocessing of pupil size data and automatic artifact rejection followed recommendations  
266 proposed in the Pupil Size Preprocessing Code (Kret and Sjak-Shie, 2019). This routine sets  
267 certain criteria for the rejection of samples associated with blinks. First dilation speed outliers  
268 and edge artifacts were identified as pupil size samples that were outside of a predefined  
269 feasible range. Second, measurements with abnormally large deviations (caused by eye-  
270 blinks) from a smooth trend line were removed. To detect dilation speed outliers, the median

271 absolute deviation was used, this is a robust and outlier resilient data dispersion metric.  
272 Finally, short-series eye-tracking samples separated from the rest of the recording by long  
273 temporal intervals were removed before analyzing the data.

274 This preprocessing was applied to both right-eye and left-eye data. If the proportion of  
275 rejected samples was more than 10% higher in one eye than in the other, the eye with the  
276 most rejected samples was not used in further analysis; otherwise the valid samples of the  
277 two channels were averaged for pupil size and gaze position. Subsequently, the pupil size  
278 data that were rejected were replaced with cubic-interpolated samples. Depending on the  
279 number and duration of blinks, the quantity of rejected data varied from a few samples to  
280 several seconds. A typical blink duration was about 300-400 ms.

281

## 282 **2.8 Electrophysiological recording**

283

284 Electromyography (EMG) and electrocardiography (ECG) were continuously recorded  
285 during the experiment using AgAgCl electrodes at a 1024-Hz sampling rate (16 bits) and the  
286 MicroMed SD64 electrophysiological system (Micromed, Treviso, Italy). As recommended for  
287 recording of the EMG activity of the *corrugator supercillii* muscle (Fridlund & Cacioppo, 1986),  
288 the electrodes of a bipolar channel were placed over the right eye-brow (**Fig. 1, A3**). For ECG  
289 recording, the electrodes of the other bipolar channel were placed on the left and right wrists  
290 (or on the left ankle as a function of the detectability of the R peak, the most important peak  
291 of the ECG). The ground electrode was placed on the left side of the forehead. In both cases,  
292 the skin was cleaned, gently abraded with gel (NUPREP; Weaver and Co.) and for better  
293 contact, a conductive adhesive gel (Tensive; Parker Laboratories) was placed under each  
294 electrode. The electrode impedances were kept below 5 kOhm. During the acquisition a band-  
295 pass filtering of 0.1-8 Hz and 0.1-1 Hz was applied to the EMG and ECG channels  
296 respectively, using the BRAIN QUICK recording system. The electrophysiological signal was  
297 amplified 1000 times.

298

## 299 **2.9 EMG preprocessing**

300

301 The EMG signals were preprocessed in a similar way as in other recent studies  
302 examining the activity of the corrugator supercilii muscle during emotional experiences  
303 (Golland et al., 2018). The EMG spectrogram was estimated with a short-time Fourier  
304 transform. The Fourier-transform segment length was 100 ms, with adjoining segments  
305 overlapping by 50 ms. For each segment, the sum of the natural logarithms of the power  
306 spectral densities was computed for the frequencies 10 – 200 Hz, excluding the range of 45-  
307 55 Hz to suppress power line noise. Then, the time series were interpolated to the initial  
308 sampling rate (1 kHz) with shape-preserving piecewise cubic interpolation.

309

## 310 **2.10 ECG preprocessing**

311

312 The ECG signals were filtered using fast Fourier transformation, excluding the range of  
313 45-55 Hz. Then, 20-ms moving-average smoothing was applied. R-peak times were detected  
314 using a wavelet approach similar to the one reported in (Sundarasekar et al., 2018) and  
315 following the recommendations in MATLAB guidelines (*R Wave Detection in the ECG -*  
316 *MATLAB & Simulink*, n.d.).

317 The RR intervals, that is the intervals between R peaks, were then interpolated to a 1-  
318 kHz sampling rate to obtain a whole-session RR-interval time series. Finally, the time series  
319 were smoothed using a 1-s moving average.

320

## 321 **3. Results**

322

### 323 **3.1 Behavior**

324

325 The individual behavioral responses were collected for the 4 experimental conditions in  
326 auditory or visual tasks. The mean pleasantness scores for all the four conditions for either

327 task are shown in **Figure 2, A1-A2**. These individual scores were used in 2\*2 repeated-  
328 measures analyses of variance (RM-ANOVAs), with the within-subject factor “Sound category”  
329 (2 levels: bird song, denoted later by B, and road traffic noise, denoted by T) and the within-  
330 subject factor “Image category” (2 levels: vegetated scene, denoted by V, and non-vegetated  
331 scene, denoted by nV). RM-ANOVAs were performed separately for the two tasks (i.e., judging  
332 the pleasantness of the auditory or the visual environment, hereafter referred to as the  
333 “auditory task” and “visual task”, respectively). To estimate the effect size, partial eta squared  
334  $\eta_p^2$  was calculated, a parameter frequently reported for RM-ANOVA designs (Bakeman, 2005).

335 As expected, the auditory or visual environments that were more natural were judged to  
336 be more pleasant than those that were less natural. An effect of the main factor “Sound  
337 category” on the pleasantness score during the auditory task was unsurprisingly observed  
338 ( $F(1,29) = 241.6, p < 0.001$ , partial eta squared  $\eta_p^2 = 0.89$ ; **Fig. 2, B1**). The effect of the main  
339 factor “Image category” on visual pleasantness was also highly significant in visual task  
340 ( $F(1,30) = 34.49, p < 0.001, \eta_p^2 = 0.53$ ; **Fig. 2, B2**).

341 Strong perceptual audiovisual interaction was also observed in both tasks: the visual  
342 context affected auditory ratings and vice versa. The effect of the main factor “Image category”  
343 on auditory pleasantness was highly significant ( $F(1,29) = 17.56, p < 0.001, \eta_p^2 = 0.37$ ),  
344 demonstrating that pleasantness in the auditory task was increased by the presence of  
345 vegetation in the depicted environment (see **Fig. 2, B1** and the red dotted contour to highlight  
346 the perceptual audiovisual interaction). The effect of the main factor “Sound category” on  
347 visual pleasantness was highly significant ( $F(1,30) = 20.33, p < 0.001, \eta_p^2 = 0.40$ ), showing that  
348 the natural auditory context, represented by bird song, made the visual scenery more pleasant  
349 in the visual task (see **Fig. 2, B2** and the red dotted contour to highlight the perceptual  
350 audiovisual interaction). Both contextual effects provided evidence of perceptual audiovisual  
351 interaction in both auditory and visual pleasantness judgments.

352

353

### 354 3.2 Pupil area, EMG and heart rate

355

356 The following processing and analyses were applied to pupil, EMG and heart rate  
357 physiological responses. First, for each participant, seventy-two epochs were extracted, each  
358 spanning from 4 s prior to the onset of the 4-s audiovisual presentation until 4 s after its end.  
359 A correction was applied to the 72 epochs by subtracting a baseline. For heart rate and EMG,  
360 the baseline was the average of the physiological measurements recorded during the 10 s  
361 before the stimulus onset. For pupil area, the baseline was the average of the physiological  
362 measurements during the 2 s before stimulus onset. The statistical noise level was estimated  
363 as a minimum to maximum range during the 20-s segment around presentation onset, and  
364 the 14 noisiest epochs of each participant were excluded from further analysis. Additionally,  
365 those pupil size epochs, in which more than 40% of samples were rejected because of blinks  
366 in the 20-s segment around the presentation onset, were rejected. There were up to three  
367 such trials in the recordings of the majority of the participants, whereas 8% of participants  
368 (5/61) had more than seven trials rejected, with the maximum number of rejected trials per  
369 participant being 27.

370 Second, the average epoch time-series from 4 s prior to the stimulus onset until 4 s after  
371 its end, was down-sampled by a factor of 100 (i.e. to 10 Hz) for each of the 4 audiovisual  
372 conditions and each of the 61 participants. When compared with the pleasant counterparts,  
373 the unpleasant conditions, namely traffic noise or non-vegetated scenes provoked  
374 pronounced pupil dilations and smaller EMG and heart rate effects. From these individually  
375 averaged temporal physiological responses, the dynamic physiological response difference  
376 was considered to highlight the potential change in physiological responses due to the  
377 variation in the extent of nature within the sound and image categories of the audiovisual  
378 stimulations (i.e., bird song vs road traffic noise, and vegetated images vs non-vegetated). To  
379 illustrate the differences in dynamic physiological responses for pupil area, EMG and heart  
380 rate, they were averaged over the participants of each group (i.e., for auditory and visual tasks,  
381 respectively) and are presented in **Figure 3, A-C**. The effect of the variation in nature presence

382 within the sound category (i.e., bird song vs. road traffic noise) is referred to as the auditory  
383 effect [B-T], while the effect of the variation in nature presence within the image category (i.e.,  
384 vegetated vs non-vegetated images) is referred to as the visual effect [V-nV].

385 For either of the two groups, a median-based 1000-iteration-bootstrap bias-corrected  
386 and accelerated percentile 95%-confidence interval (DiCiccio & Romano, 1988) was  
387 estimated for each timepoint of the differential responses. Then, the average differential  
388 response for every participant was computed within the window of interest of 4 s-audiovisual  
389 stimulation. These individual scores were used in group-level summary statistics with the  
390 median-based bootstrap technique and RM-ANOVAs. Furthermore, medians and bootstrap  
391 group-level 95%-confidence intervals (CI) were also considered for the differential scores of  
392 pleasantness, to simultaneously illustrate the significance of the effect of audiovisual  
393 stimulation on both pleasantness judgments and physiological reactions. The **Figures 4 and**  
394 **5** display the median values and 95%-CIs to highlight the auditory effect [B-T] (i.e., Bird song  
395 vs. Traffic noise) and the visual effect [V-nV] (i.e., Vegetated vs. non-Vegetated) on the  
396 differential pleasantness scores (**Fig. 4, A**) and the differential physiological responses (**Fig.**  
397 **4, B to Fig. 5, C**). In these figures, a significant effect can be considered to have occurred  
398 when the confidence interval does not embrace the zero line.

399 RM-ANOVAs with the factors “sound” (i.e., Bird song vs. Traffic noise, [B-T]) and “image”  
400 (i.e., Vegetated vs. non-Vegetated, [V-nV]) were performed for the auditory and visual tasks,  
401 respectively, to give the magnitudes of significant effects according to  $\eta_p^2$ .

402 The median and 95% CI results show that pupil area was higher when the participant  
403 was presented with traffic noise rather than birdsong, both in the auditory task and in the visual  
404 task. This is highlighted in **Figure 5, A** by the significant auditory effect [B-T] on pupil area  
405 during both the auditory and visual tasks. This effect is also observed in the RM-ANOVA  
406 results ( $F(1,29) = 30.6, p < .001, \eta_p^2 = 0.51$  for the auditory effect [B-T] on pupil area during the  
407 auditory task, and  $F(1,30) = 10.8, p = .003, \eta_p^2 = 0.27$  during the visual task). Pupil area was  
408 also higher after observing non-vegetated scenes than after observing vegetated scenes (**Fig.**



409 **5, A**). The visual effect [V-nV] was significant in the RM-ANOVAs, both when the sound  
410 environment was judged ( $F(1,29) = 10.0, p=.004, \eta_p^2 = 0.26$ ) and when the visual environment  
411 was evaluated ( $F(1,30) = 5.9, p=.021, \eta_p^2 = 0.16$ ).

412 The bootstrap method indicated that the *corrugator supercilii* muscle (EMG) appeared  
413 to be more strongly activated during traffic noise than during bird song, in both the auditory  
414 task and the visual task (**Fig. 5, B**). This significant auditory effect [B-T] is also observed in  
415 the RM-ANOVA results ( $F(1,29) = 8.6, p=.006, \eta_p^2 = 0.23$  during the auditory task, and  $F(1,30)$   
416  $= 5.1, p=.031, \eta_p^2 = 0.15$  during the visual task). In contrast, image content had no significant  
417 differential effect on the EMG (**Fig. 5, B**). Heart rate showed a slight elevation only when  
418 unpleasant sound content was presented in the visual task (**Fig. 5, C**), with the auditory effect  
419 [B-T] showing statistical significance in the RM-ANOVA ( $F(1,30) = 6.2, p=.019, \eta_p^2 = 0.17$ ).

420

### 421 **3.3. Relationships between pupil reactions and behavior**

422

423 The results reported so far have shown that pupil dilations were obtained in response to  
424 the less pleasant sound and image categories. Beyond this finding we wanted to explore  
425 whether pupil size during exposure was linked to the subsequent behavioral judgments on  
426 samples within sound and image categories. Differences in pleasantness and physiological  
427 reactions within the image category will be presented in a forthcoming study dedicated to  
428 visual perception. Our investigation therefore concerns the potential effect of variation in  
429 auditory pleasantness on the pupil size within each sound category. As there was negligible  
430 variation in pleasantness judgments for the different bird song samples stemming from the  
431 Lyon area, we focused on differences in reactions to the urban road traffic noise samples (light  
432 vehicle, bus, heavy vehicle, and motorcycle/moped pass-bys). To investigate the potential  
433 effect on pupil size, two sub-conditions of traffic noise samples were considered: traffic noise  
434 samples with high unpleasantness scores versus samples with low unpleasantness scores.

435           Given the variation in auditory pleasantness judgments across the 18 traffic noise  
436 samples used (data from n=30 participants), five sound samples were selected for high  
437 unpleasantness (mostly motorcycle/moped pass-by noises) and five samples for low  
438 unpleasantness (mostly light vehicle pass-by noises). These subsamples are shown in **Fig. 6,**  
439 **A1** in terms of their median pleasantness ratings relative to median bird song pleasantness  
440 ratings during the auditory task.

441           We then examined whether these two selected sets of traffic noises differed in their  
442 effects on pleasantness judgments in the visual task. As shown in **Fig. 6, A2**, we found lower  
443 visual pleasantness relative to bird song during presentation of highly-unpleasant traffic noise  
444 samples (HT) in comparison with presentation of less-unpleasant traffic noise samples (LT).  
445 This significant perceptual audiovisual interaction is displayed in **Fig. 6, A2** in terms of median  
446 ratings and 95%CIs relative to bird song.

447           Following the same rationale as the one used for the analysis described in section 3.2,  
448 the response differences due to the two sets of traffic noises (Less-unpleasant Traffic noise  
449 vs. Highly-unpleasant Traffic noise, i.e. [LT – HT]) are hereafter used in the group-level  
450 summary statistics with the median-based bootstrap technique and RM-ANOVAs, and  
451 displayed in **Fig.6, A2-B1-B2**.

452           The highly-unpleasant traffic noise samples exerted significantly more pronounced  
453 perceptual audiovisual interaction effects than the less unpleasant ones (see LT-HT, rightmost  
454 data plot in **Fig. 6, A2**). In a one-way RM-ANOVA with the factor LT-HT, the effect of this factor  
455 on the visual pleasantness rating difference was significant ( $F(1,30) = 41.8, p < 0.001$ ) with an  
456 important effect size ( $\eta_p^2 = 0.58$ ).

457           A similar pattern was observed for the pupil reactions. The difference in pupil dilation  
458 was considered for low versus high unpleasantness traffic noise exposure (auditory and visual  
459 tasks pooled, n=61). The time course of differences in pupil reaction exhibited a significant  
460 relative increase in pupil size for highly-unpleasant traffic noise samples compared with less-  
461 unpleasant ones (**Fig. 6, B1**).

462 When the average pupil area change was separately computed within the auditory or  
463 visual task participant groups, a significantly greater pupil size change was evident after highly  
464 unpleasant traffic noise stimulation in both types of tasks (**Fig. 6, B2**). One-way RM-ANOVAs  
465 with the factor LT-HT confirmed the important effect size obtained for this factor in the auditory  
466 task ( $F(1,29) = 25.4, p < 0.001, \eta_p^2 = 0.47$ ) in comparison with the effect size in the visual task  
467 ( $F(1,30) = 10.1, p = 0.034, \eta_p^2 = 0.25$ ).

468

### 469 **3.4 Gaze fixations and saccade statistics**

470

471 Seventy-two epochs were extracted from the vertical and horizontal gaze position data  
472 ranging from the onset to the end of the 4-s presentation of the audiovisual content. Epochs  
473 were rejected if either less than 12% of data points per epoch were available or more than  
474 40% of samples were rejected because of blinks in the 20-s segment around the presentation  
475 onset. An instantaneous velocity threshold of 0.6 pixel (20°/s) was applied to identify  
476 saccades. The remaining episodes were labelled as fixations. The average position and  
477 duration were identified for each fixation episode. If the positions of consecutive fixations did  
478 not differ by more than 25 pixels (0.8°) we considered them to belong to the same fixation.  
479 The duration of such fixations was computed from the onset of the first to the end of the last  
480 episode belonging to it. For each epoch, the average fixation duration and the cumulative  
481 distance of the saccades, separating the fixations were computed. Then, the average scores  
482 were computed for each of the 4 conditions for each participant, except for the epochs  
483 excluded because of the noisiness of the pupil data. Following the same rationale as the one  
484 described in section 3.2, individual response differences were considered in the group-level  
485 summary statistics using the median-based bootstrap technique and RM-ANOVAs to analyze  
486 the auditory effect [B-T] (i.e., Bird song vs. Traffic noise) and the visual effect [V-nV] (i.e.,  
487 Vegetated vs. non-Vegetated) on fixation duration and cumulative saccade distance.

488 The analysis of eye-tracking data yielded a set of significant effects that depended on  
489 the audiovisual stimulation. Fixation duration was strongly affected by the image category of  
490 the visual scenes, being significantly longer for the vegetated scenes in both tasks (**Fig. 4, B**).  
491 The RM-ANOVA with the factors “sound” (i.e., Bird song vs. Traffic noise, [B-T]) and “image”  
492 (i.e., Vegetated vs. non-Vegetated, [V-nV]) also revealed the significant visual effect [V-nV] on  
493 fixation duration during the auditory task ( $F(1,29) = 14.4, p < 0.001, \eta_p^2 = 0.33$ ) and the visual  
494 task ( $F(1,30) = 19.0, p < 0.001, \eta_p^2 = 0.39$ ). Consistent with the longer fixation durations, the  
495 cumulative saccade distance was shorter for vegetated scenes (**Fig. 4, C**), though the  
496 bootstrapping technique confirmed this effect only during the visual task. This corresponded  
497 to the RM-ANOVA result, with a significant visual effect [V-nV] on the cumulative saccade  
498 distance ( $F(1,30) = 8.8, p = 0.006, \eta_p^2 = 0.23$ ). A significant result was observed for the auditory  
499 effect during the visual task: bird song significantly increased gaze travel distance ( $F(1,30) =$   
500  $4.3, p = 0.047, \eta_p^2 = 0.13$ ).

501

## 502 **4. Discussion**

503

504 The objective of the present laboratory study was to investigate audiovisual interactions  
505 in judgments of the pleasantness of urban environments with varying levels of nature in the  
506 visual landscapes or soundscapes. We hypothesized that these perceptual interactions would  
507 be associated with specific objective psychophysiological responses, namely *corrugator*  
508 *supercilii* electromyographic activity, heart rate, pupil reactions, and gaze behavior, with these  
509 reflecting changes in valence, arousal, or attention.

510

### 511 **4.1 Behavioral findings**

512

513 Significant perceptual audiovisual interactions were demonstrated in both auditory and  
514 visual judgment tasks. The presence of nature (bird song or vegetation) increased both the

515 auditory and visual pleasantness of the excerpts of urban environments presented in our  
516 study.

517 First, we confirmed a previously reported modification of auditory pleasantness by visual  
518 context (Viollon et al., 2002), with sound pleasantness being judged as greater when  
519 presented in the context of vegetated scenes as opposed to non-vegetated scenes. We further  
520 showed that visual pleasantness judgments were influenced by the auditory context. The  
521 visual pleasantness of the depicted urban scenes was judged to be greater when they were  
522 accompanied by bird song rather than road traffic noise. This result is in agreement with  
523 previous findings that assessment of landscapes was negatively affected by man-made  
524 sounds such as traffic noise in comparison with natural sounds such as bird song (Ren et al.,  
525 2018). Moreover, we found that in visual pleasantness judgments, the modulation by the  
526 auditory context varied depending on the degree of unpleasantness elicited by the road traffic  
527 noise samples. The depicted urban scenes were judged to be less visually pleasant when  
528 accompanied by more unpleasant (compared with less unpleasant) urban road vehicle pass-  
529 by noise.

530 A similar phenomenon was studied in the interaction of videos and music, and was  
531 termed the “affective congruency” effect. It refers to the enhancement of valence judgments  
532 in combined audiovisual exposures in comparison with auditory or visual stimuli of the same  
533 valence (either positive or negative) presented separately (Gao et al., 2017). This means that  
534 pleasant sounds combined with pleasant images produce a stronger impression of overall  
535 pleasantness. The same holds for negative valences (Gao et al., 2017). This was also shown  
536 by Cassina et al. (2018) in a study dealing with urban soundscapes. They highlighted the  
537 combined effect of negative visual elements and negative sound sources (e.g., road traffic) on  
538 the perceived tranquility of urban environments, with tranquility being known to be closely  
539 related to pleasantness (Li & Lau, 2020). However, the affective congruency effect highlighted  
540 by Gao et al. (2017) was shown for positive vs. negative valence stimuli only if they were of  
541 high arousal. There is evidence that the audiovisual integration of emotional stimuli yielding  
542 similar results to ours is associated with specific activity in the medial prefrontal cortex (Gao

543 et al., 2020). This might reflect integrative top-down cognitive processes during audiovisual  
544 integration. Another indication of the largely cognitive nature of this effect is the finding that  
545 the degree of matching between visual and sound features can alter this relationship. Unlike  
546 bird song or traffic noise, pleasantness judgments of human-generated sounds like speech or  
547 footsteps do not appear to be sensitive to the visual context (Viollon et al., 2002). This  
548 reservation might be explicitly tested in further studies.

549 We also showed that a number of physiological and gaze-behavior effects accompanied  
550 these modulations of pleasantness judgments: pupil size, EMG, heart rate, saccadic distance  
551 and fixation duration were all affected by the studied conditions. Physiological reactions and  
552 gaze behavior were typically significant in both the auditory and visual tasks, or were not  
553 significant in either one. On the other hand, the sound category (bird song or traffic noise) and  
554 the image category (vegetated or not) provoked significant effects in only some of the objective  
555 measures. In particular, the average fixation duration and cumulative saccade length were  
556 significantly affected by visual content but not significantly by the auditory content in either  
557 task (**Fig. 4, B-C**), whereas EMG and heart rate responded significantly to the auditory  
558 component but not to the visual one (**Fig. 5, B-C**). The pupillary response changed significantly  
559 as a function of both the visual and auditory content of urban environments (**Fig. 5, A**) and  
560 therefore constituted the most reliable physiological measure of the perceptual audiovisual  
561 interaction during pleasantness assessment.

562

#### 563 **4.2 Gaze behavior discriminated vegetated from non-vegetated urban scenes**

564

565 In our study, when participants observed urban scenes containing vegetation, their  
566 average fixation duration was longer and their saccadic distances were shorter in comparison  
567 with observation of urban scenes without vegetation. This is consistent with previous findings  
568 on gaze fixation during observation of natural scenes of high or low fascination (Berto et al.,  
569 2008). However, this difference should not be attributed exclusively to the presence of  
570 vegetation. It is known that even among different vegetated scenes, fixations are longest for

571 scenes evaluated as having the highest landscape quality (Cottet et al., 2018), which might  
572 closely correspond to the pleasantness ratings captured in our study. Therefore, longer  
573 fixations in our study may be associated with the potential of more-pleasant vegetated visual  
574 environments to gently attract effortless attention. According to Attention Restoration Theory,  
575 such changes improve wellbeing and facilitate recovery of attentional resources (Kaplan,  
576 1995).

577 At the same time, the more-pleasant natural sounds did not affect gaze behavior in the  
578 same way as the vegetated scenes. To the contrary, bird song facilitated saccades, which  
579 may be evidence for a redistribution of visual attention as a function of the auditory context,  
580 as has been reported by Ren & Kang (2015). Modification of the distribution of spatial visual  
581 attention by the auditory context requires further exploration.

582

### 583 **4.3 Corrugator supercilii EMG and heart rate changes significantly discriminated** 584 **between traffic noise and bird song**

585

586 As expected, both the activity of the corrugator supercilii muscle and heart rate were  
587 higher when participants listened to traffic noise rather than to bird song. These findings are  
588 likely due to the unpleasant feelings caused by hearing motorized vehicles passing close-by.  
589 This confirms earlier findings with other acoustic stimuli, in that sounds of negative valence  
590 provoke unintentional activation of *corrugator supercilii* and an acceleration of heart rate  
591 (Bradley & Lang, 2000; Park et al., 2018).

592 The corrugator supercilii EMG differed as a function of sound category, but was not  
593 modified by the image category. This may be explained by the much smaller difference in  
594 pleasantness across the image categories of the urban scenes presented (vegetated or not)  
595 in comparison with the sound categories (bird song or traffic noise).

596 Heart rate acceleration in response to road traffic noise was observed only during the  
597 visual task, thus reflecting implicit discomfort, elicited by the non-attended modality. However,  
598 because of the moderate statistical significance of the heart rate data in the present study

599 ( $p < 0.05$ ), this finding requires further confirmation. In at least one study, explicit pleasantness  
600 was shown to be more strongly associated with changes in functional magnetic resonance  
601 imaging-measured cerebral activity in the amygdala than it was with heart rate responses  
602 (Irwin et al., 2011). This suggests that heart rate responses may be a less sensitive indicator  
603 of pleasantness than *corrugator supercillii* EMG.

604

#### 605 **4.4 The pupil reacted with greater dilation to both unpleasant auditory and visual** 606 **stimulation**

607

608 Pupil size increased significantly in response to both traffic noise and non-vegetated  
609 images in comparison with their categorial counterparts, regardless of the task, be it visual or  
610 auditory (**Fig. 5, A**). Compared with the image categories, the sound categories produced  
611 larger pupillary response effects. However, it is conceivable that the pupillary response is  
612 primarily accounted for by the difference in arousal mediated by upregulation of sympathetic  
613 autonomic activity, rather than by the variation in valence (Bradley et al., 2008). Greater pupil  
614 size is known to be associated with both highly negative and positive complex sounds,  
615 indicating the role of arousal in regulation of this physiological variable (Oliva & Anikin, 2018).  
616 Thus, the sound category effect on pupil size is very likely explained by arousal, potentiated  
617 by the fact that the traffic noise samples had higher sound pressure levels than the bird song  
618 samples. The finding that the arousal picked up by the pupillary dilation was more evident in  
619 sound discrimination is supported by a previous study that found a relationship between  
620 subjective arousal and pupil diameter in response to sound clips, but not to visual scenes  
621 (Burley et al., 2017).

622 High-arousal images (erotic, aggression, or mutilation scenes) also provoke pupil  
623 dilation, whereas natural images are associated with the strongest pupil constriction (Bradley  
624 et al., 2017). Therefore, the difference in pupillary responses to non-vegetated and vegetated  
625 scenes may be explained by differences in arousal level.

626



627 **4.5 Pleasantness judgments of traffic noises and audiovisual interactions were**  
628 **reflected in pupillary activity**

629

630       Importantly, we found that pleasantness differences were associated with pupil  
631 responses not only when comparing the global categories of traffic noise and bird song, but  
632 also when contrasting samples of traffic noise differing in unpleasantness. Highly-unpleasant  
633 traffic noises reduced the pleasantness of the visual scenes to a greater extent than less-  
634 unpleasant traffic noises. In the same manner, greater pupil dilations were associated with the  
635 highly-unpleasant samples rather than the less-unpleasant traffic noise samples, irrespective  
636 of whether a visual or auditory scene was judged. Perceptual audiovisual interactions in  
637 pleasantness ratings were thus associated with corresponding pupillary reactions.

638       However, this greater audiovisual modulation of pupillary reactions by the subset of  
639 highly-unpleasant traffic noise samples (**Fig. 6, B1-2**) may also be explained by variations in  
640 loudness, specifically the intensity of the sounds. Indeed, pupillary dilation in response to  
641 auditory stimulation is positively correlated with both subjective salience and loudness (Liao  
642 et al., 2016).

643       As to the subcategories of the contrasting sounds presented in our study, the mean  
644 sound pressure level of the more-unpleasant traffic noise sounds was higher than that of the  
645 less-unpleasant ones (60.8 dB(A) vs. 51.7 dB(A) respectively), and the rank order correlation  
646 between the sound pressure levels of the road traffic noises and their corresponding average  
647 auditory unpleasantness ratings was highly significant ( $r=0.78$ ,  $p<0.001$ ,  $n=18$ ). However, for  
648 the road traffic pass-by noises used in our study the annoyance ratings previously reported  
649 when sound pressure level was equalized at 60 dB(A) (Gille et al., 2016) did not correlate  
650 significantly with the pleasantness ratings collected during this current study. This might be  
651 explained by the important role of loudness in both (un)pleasantness ratings and the  
652 physiological arousal related to the auditory salience of sounds as reflected in pupillary  
653 reactions (Boswijk et al., 2020).

654

## 655 **4.6 Integrative vision of behavioral and psychophysiological measures of audiovisual** 656 **interaction**

657

658 To summarize, we believe that the main driving mechanism for the lower pleasantness  
659 ratings produced by the stimuli from the less-pleasant category may be an increase in arousal  
660 level due to their salience, which is reflected by pupil dilation. Indeed, there is evidence that  
661 both the pleasantness and restorative potential of natural sounds correlate with lower arousal  
662 (Ratcliffe et al., 2020). In contrast, the emotional valence, which was reflected in the EMG  
663 activity, affected only the auditory modulation of pleasantness ratings. The longer fixation  
664 durations for vegetated scenes may be vision-specific manifestations of lower arousal, which  
665 is supported by an increase in parasympathetic heart rate variability in a number of studies  
666 (Mygind et al., 2021). One critical limitation of our study is that the crucial manipulation of the  
667 valence category — both in images and sounds — may have been partially confounded with  
668 low-level perceptual factors like the loudness of the sounds and local variations in the  
669 brightness of the images. However, since in real life these confounds appear to be tightly  
670 bound to the stimuli, the current results highlight the advantages of using eye-tracking  
671 technology to record pupil size and gaze behavior to better understand the mechanisms  
672 involved in the audiovisual interactions observed during the appraisal of our urban  
673 environment.

674

## 675 **Conclusions**

676

677 The current work aimed to contribute to a better understanding of the mechanisms  
678 involved in the perceptual audiovisual interaction phenomenon that is known to occur during  
679 visual and auditory perception of urban environments. In this investigation, we proposed a  
680 combined psychophysical and physiological methodology to assess both auditory and visual  
681 perceptions of urban environments, and interactions between these two modalities. In this  
682 methodology, different types of physiological measures (electromyography of the eyebrow

683 muscle, heart rate, pupil size, and gaze behavior) were considered to help us understand the  
684 mechanisms. Under controlled conditions, 61 participants, mainly students, were asked to  
685 assess the auditory or visual pleasantness of briefly presented excerpts from urban  
686 environments that varied in the degree to which natural features (visual or sound) were  
687 included. We showed that both auditory and visual pleasantness judgments are subject to  
688 perceptual audiovisual interactions that strongly reflect the 'naturalness' of the exposure. The  
689 current study highlighted several physiological indicators to be associated with the perceptual  
690 audiovisual interactions observed during the appraisal of urban environments. While  
691 electromyography and heart rate measures were primarily related to auditory pleasantness,  
692 the gaze behavior measures were linked to visual pleasantness. Compared with road traffic  
693 sounds, the natural sounds resulted in lower eyebrow electromyographic activity and heart  
694 rate, while natural images were associated with slower gaze behavior. To the contrary, pupil  
695 area reacted to both auditory and visual conditions, with pupil responses discriminating  
696 between pleasant and unpleasant sound and visual environments. The pupil was relatively  
697 constricted by all the natural stimuli, and was found to be sensitive to subtle variations in  
698 unpleasantness between different traffic noise samples and the modulation of visual  
699 pleasantness by these sounds.

700 The different physiological measures employed provide evidence that the complex  
701 mechanisms involved in perceptual audiovisual interactions are largely driven by arousal level  
702 due to the salience of the audiovisual stimulation. In particular, this was well reflected by pupil  
703 size: pupil size measures constituted the most reliable physiological measures of the  
704 perceptual audiovisual interaction during pleasantness assessment. The audiovisual  
705 integration of emotional elements from urban environments might reflect integrative top-down  
706 cognitive processes. Improvement in the auditory and visual presence of nature in the city can  
707 have a positive impact on the wellbeing and health of city dwellers by reducing arousal and  
708 stress.

709 Future perspectives to this work would be to consider participant groups with a higher  
710 mean age and standard deviation to have a more representative sample, and to investigate

711 the mechanisms involved in the audiovisual interactions observed during the appraisal of our  
712 urban environment with the use of eye-tracking technology to record pupil size and gaze  
713 behavior.

714

#### 715 **Acknowledgements**

716

717 This work was funded by the LABEX CELYA (ANR-10-LABX-0060) and the LABEX IMU  
718 (ANR-10-LABX-0088) of Université de Lyon, within the program "Investissements d'Avenir"  
719 operated by the French National Research Agency (ANR).

720

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881 **Figure captions**

882

883 **Figure 1.** Methods. (A1) Visual depictions of non-vegetated (top,  $n=18$ ) and vegetated  
884 (bottom,  $n=18$ ) urban scenes. (A2) Audiovisual combinations resulting in four  
885 experimental conditions. (A3) The laboratory setup showing the eye-tracking system,  
886 electrophysiological system, and loudspeakers. (B) The procedure and its timeline  
887 (B1-B4). Depending on the group, reminders for rating the pleasantness of either the  
888 auditory environment (Auditory task) or the visual environment (Visual task) were  
889 shown above the visual analogue scale (B3).

890

891 **Figure 2.** Mean pleasantness scores and standard errors. The mean scores are  
892 shown for the four combinations of sound (bird song (B), traffic noise (T)) and image  
893 (vegetated scenes (V), non-vegetated scenes (nV)) categories during the task of  
894 evaluation of auditory pleasantness (A1) or visual pleasantness (A2). The effects of  
895 the Sound category factor (2 levels: bird song (B) and traffic noise (T)), and the effects  
896 of the Image category factor (2 levels: vegetated scenes (V) and non-vegetated  
897 scenes (nV)) on pleasantness scores during the auditory (B1) and visual (B2) tasks.  
898 \*\*\*  $p<0.001$ . Significant perceptual audiovisual interactions are highlighted with red  
899 dotted contours.

900

901 **Figure 3.** Time course of physiological reaction changes due to variation in nature  
902 presence within sound or image category, i.e. bird song vs. traffic noise (Auditory effect  
903 [B-T]) or vegetated scenes vs. non-vegetated scenes (Visual effect [V-nV]). (A) Time  
904 course of median pupil area changes, contrasting the more hedonic with the less  
905 hedonic condition. (B) Time course of median corrugator supercillii (EMG) activity  
906 changes. (C) Time course of median heart rate changes (RR intervals). 95% CI:  
907 bootstrap 95%-confidence intervals.

908

909 **Figure 4.** Behavior and eye-tracking measure changes due to variation in nature  
910 presence within sound or image category, i.e. bird song vs. traffic noise (Auditory effect  
911 [B-T]) or vegetated scenes vs. non-vegetated scenes (Visual effect [V-nV]), during the  
912 auditory task (Aud. task) and the visual task (Vis. task).

913 (A) Pleasantness score difference in favor of the a-priori more hedonic category, i.e.  
914 bird song or vegetated scenes. (B) Fixation duration difference. (C) Cumulative  
915 saccade distance difference. Individual values (ind. vals.), median values, and  
916 bootstrap 95% CIs are shown. \*\*\*  $p<0.001$ , \*\*  $p<0.01$ , \*  $p<0.05$ . Significant perceptual  
917 audiovisual interactions are highlighted with red dotted contours.

918

919

920 **Figure 5.** Physiological measure changes due to variation in nature presence within  
921 sound or image category, i.e. bird song vs. traffic noise (Auditory effect [B-T]) or  
922 vegetated scenes vs. non-vegetated scenes (Visual effect [V-nV]), during the auditory  
923 task (Aud. task) and the visual task (Vis. task).

924 (A) Pupil area difference. (B) Corrugator supercillii EMG difference. (C) Heart rate  
925 difference. Individual values (ind. vals.), median values, and bootstrap 95% CIs are  
926 shown. \*\*\*  $p < 0.001$ , \*\*  $p < 0.01$ , \*  $p < 0.05$ . Significant perceptual audiovisual  
927 interactions are highlighted with red dotted contours.

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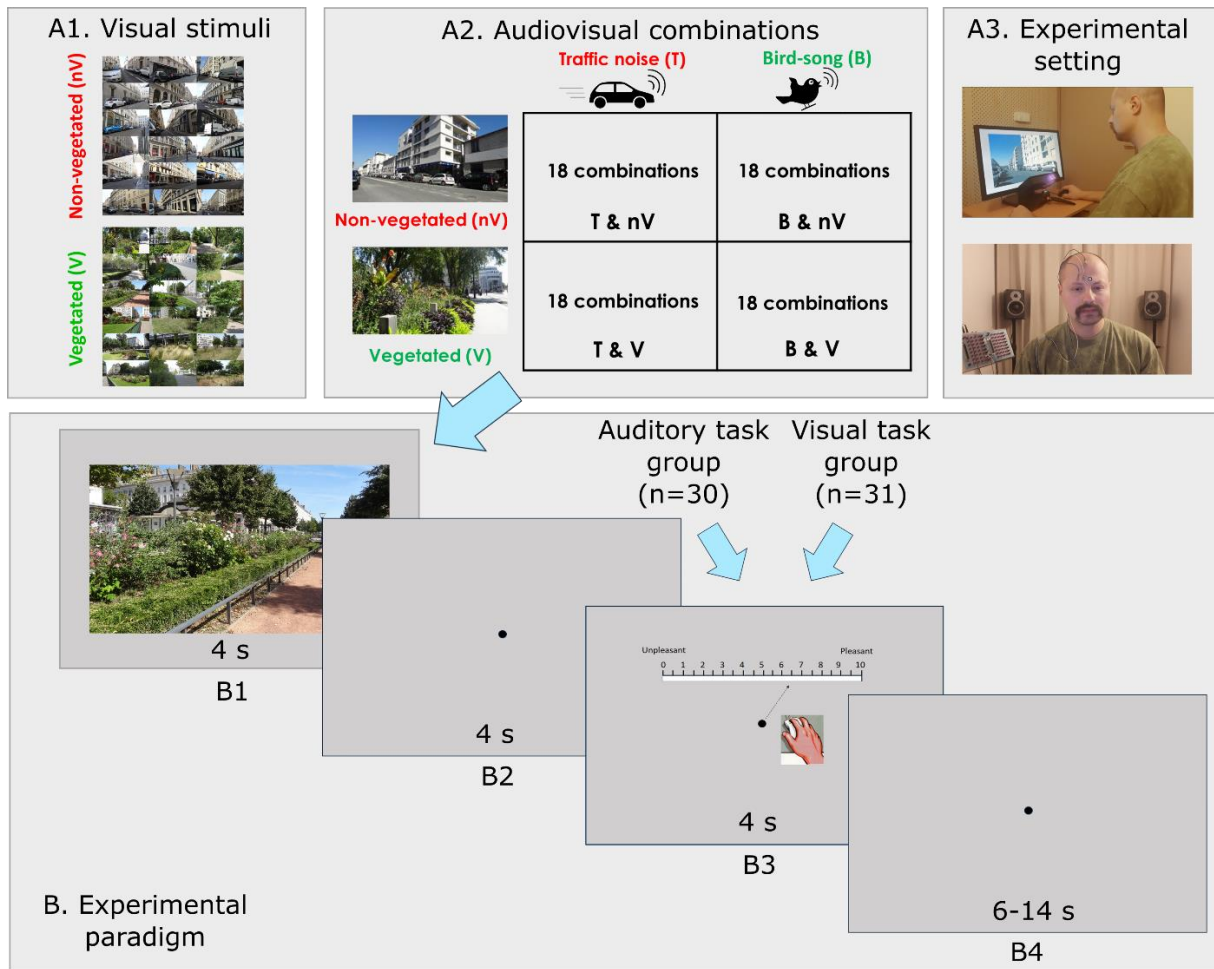
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930 **Figure 6.** Effects of the five most-unpleasant versus the five least-unpleasant traffic  
931 noise samples on perceptual audiovisual interaction and pupillary reactivity.

932 (A1) Highly- and Less-unpleasant urban road traffic noise (HT and LT, respectively) in  
933 terms of the median pleasantness rating differences relative to bird song in the auditory  
934 task (n=30). The 18 labels for traffic noise stimuli on the abscissa of A1 (XYZ) refer to  
935 previous studies employing these sounds (Gille et al., 2016; Morel et al., 2012): X  
936 stands for “vehicle type” (b: bus; d: motorcycle/moped; p: heavy vehicle; v: light  
937 vehicle), Y for “driving condition” (a = acceleration; d = deceleration; f = constant  
938 speed), Z for “road morphology” (o = open street; u = U-shaped street). (A2) Effects  
939 of Highly-unpleasant Traffic noise (HT) and Less-unpleasant Traffic noise (LT) on  
940 median visual pleasantness rating differences relative to bird song in the visual task  
941 (n=31). (B1) Difference in the time course of pupil dilation contrasting low- and highly-  
942 unpleasant traffic noise (i.e. traffic noise effect [LT-HT]), with both visual and auditory  
943 experiments pooled (n=61). (B2) Effects of variations in unpleasant traffic noise (i.e.  
944 traffic noise effect [LT-HT]) on pupil area difference during the auditory and the visual  
945 tasks. \*\*\*  $p < 0.001$ , \*\*  $p < 0.01$ , \*  $p < 0.05$ . Individual values (ind. vals.), median values,  
946 and bootstrap 95% CIs are shown. Significant perceptual audiovisual interactions are  
947 highlighted with red dotted contours.

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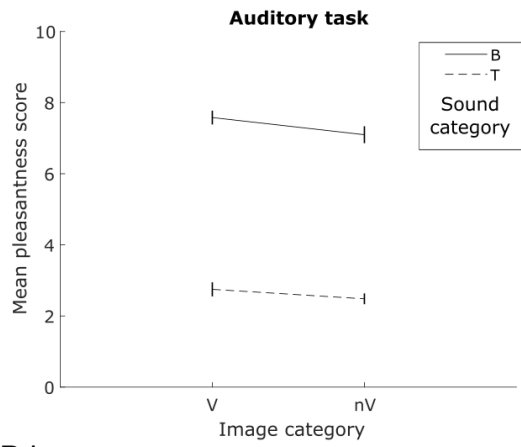
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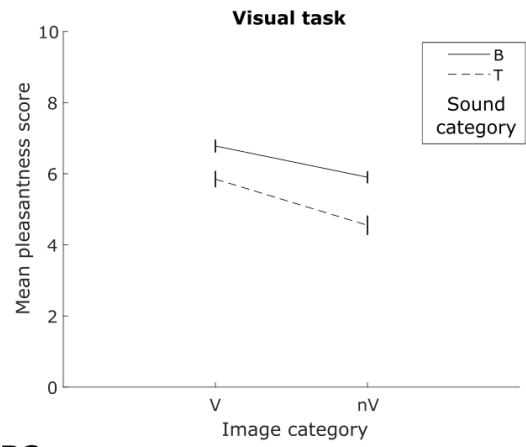
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951 **Figure 1**

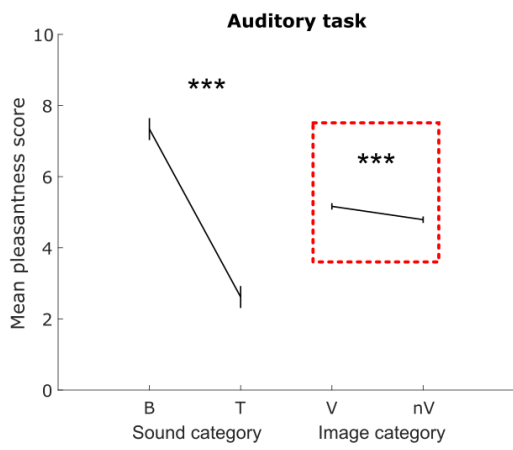
A1



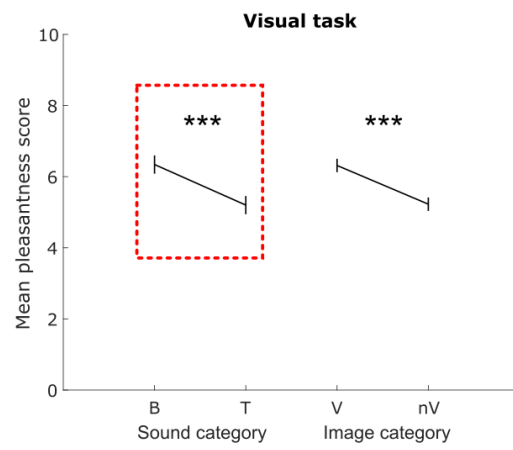
A2



B1

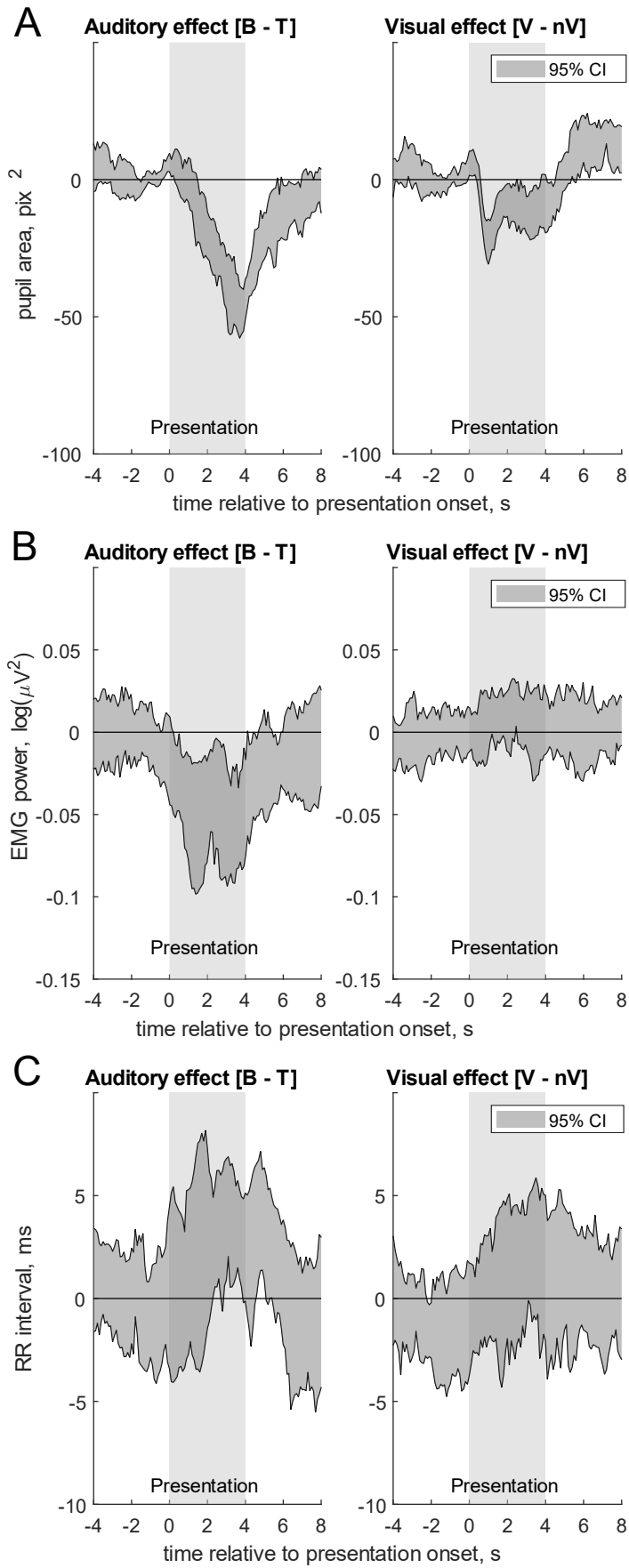


B2



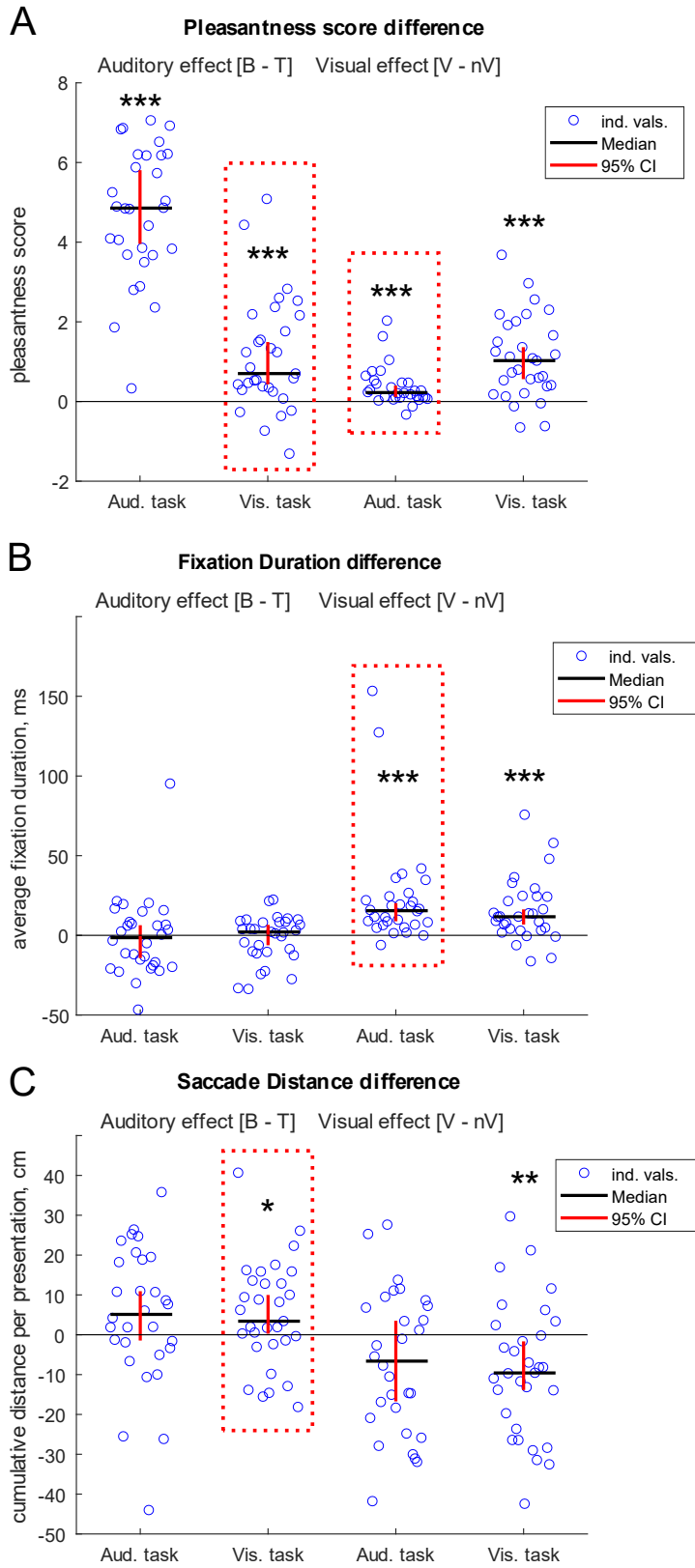
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**Figure 2**



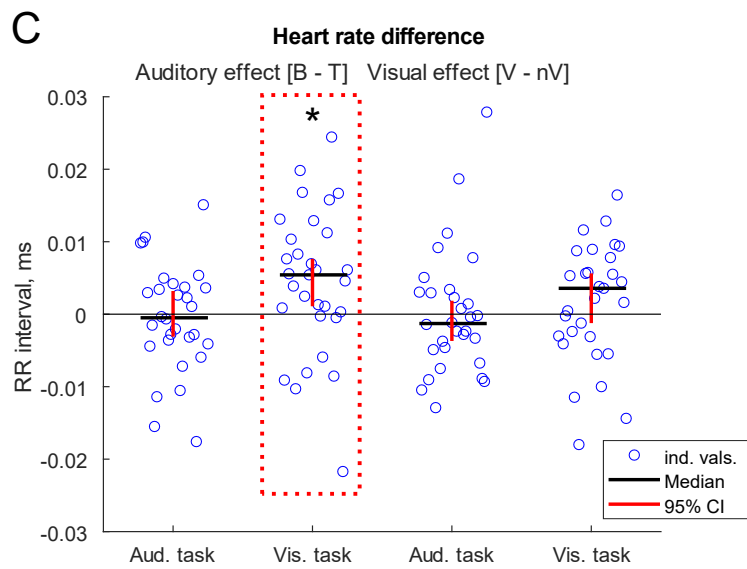
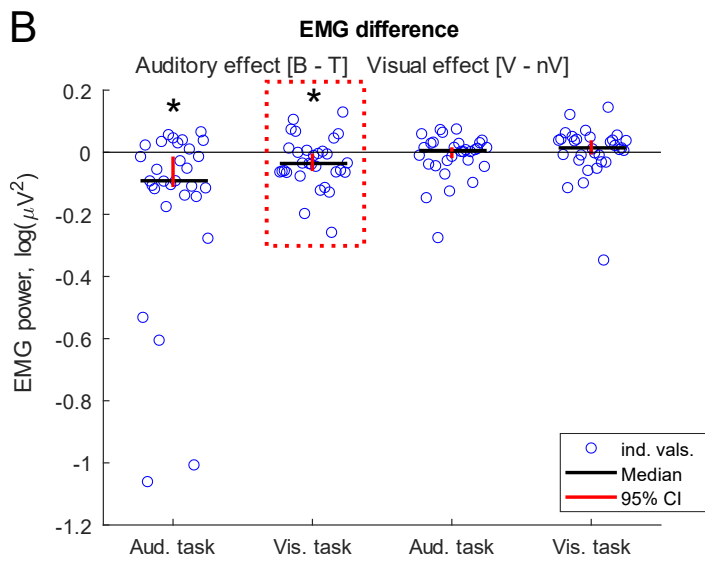
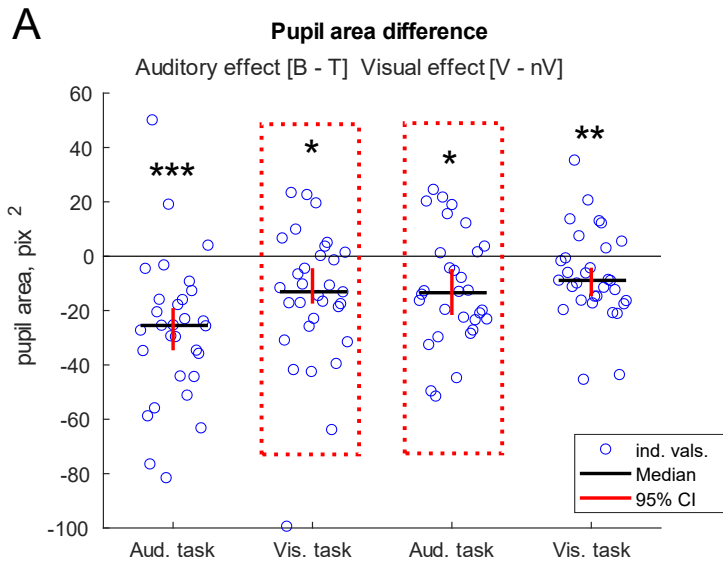
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**Figure 3**



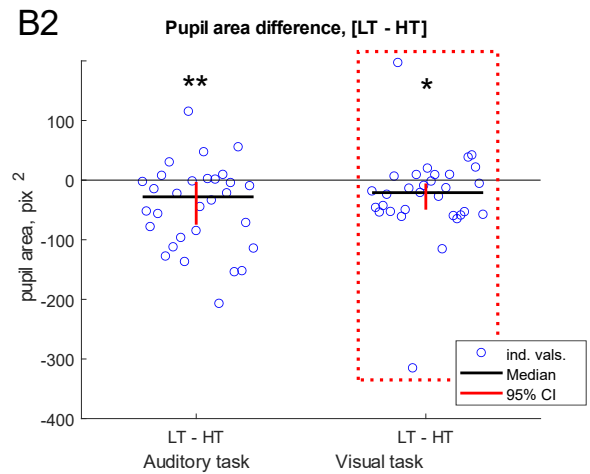
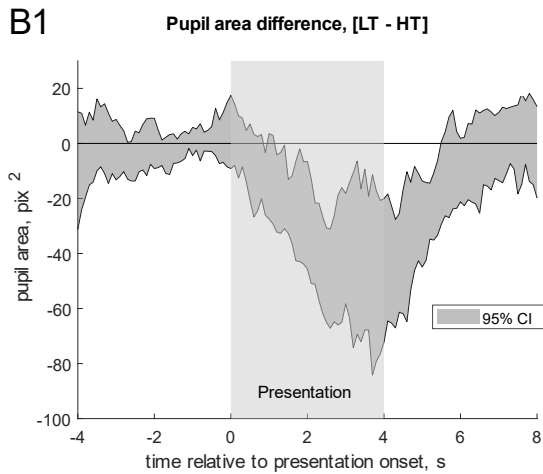
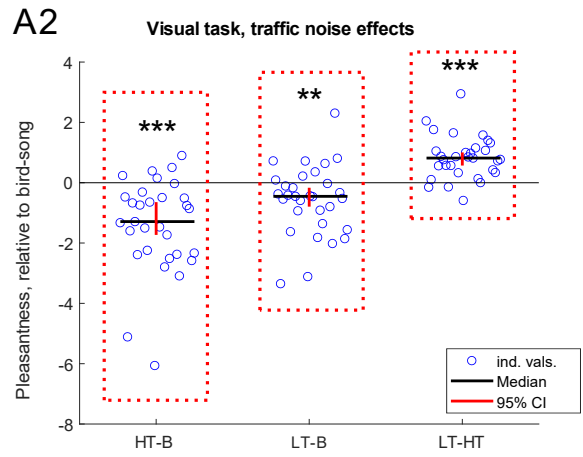
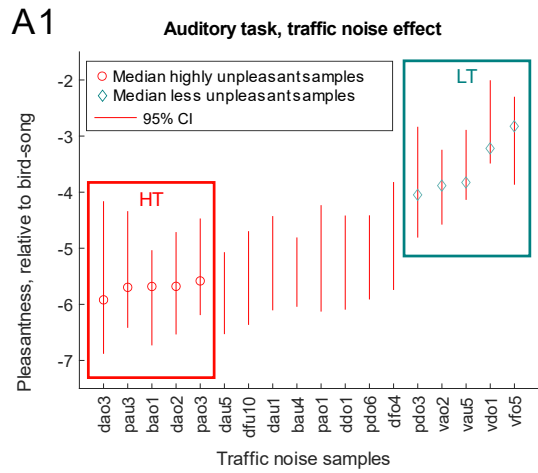
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958 **Figure 4**





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**Figure 5**



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**Figure 6**