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► To cite this version:

Alex Limin Wang, Sanjeev Bista, Arnaud Can, Basile Chaix. Personal noise exposure during daily commutes and subjectively reported stress: A trip stage level analysis of MobiliSense data. *Journal of Transport and Health*, 2023, 30, pp.101612. 10.1016/j.jth.2023.101612 . hal-04278668

HAL Id: hal-04278668

<https://hal.sorbonne-universite.fr/hal-04278668v1>

Submitted on 10 Nov 2023

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Personal noise exposure during daily commutes and subjectively reported stress: a trip stage level analysis of MobiliSense data

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Abstract

Background: The auditory and non-auditory health effects of noise have long been established in the literature but previous studies have mainly been in the context of occupational risk. Recent research suggests that daily noise exposures occurring during social activities and commute may be associated with higher psychological stress. Our aim was to explore the association between modes of transportation and noise on the one hand and noise exposures and reported stress on the other hand. Although existing literature shows that noise exposure is especially high during commutes, studies on the topic have been sparse due to cost and logistic constraints; furthermore, sample sizes have been small.

Methods: The present study uses data collected on the daily commutes of 253 participants of the Mobilisense cohort study between 2018 and 2020. Personal dosimeters were used to measure noise exposure by frequency bands over a period of 4 days, resulting in a sample of 7800 trip stage windows. Participants reported trip stress levels during an *a posteriori* phone mobility survey on a scale from 1 (no stress) to 7 (significantly stressful conditions). Modes of transportation (metro, car, walking, etc.) were collected from the same mobility survey based on Global Positioning System (GPS) receivers.

Results: While all transport modes resulted in higher exposure to low frequency noise compared to walking, all modes but tramway and driving or being the passenger of a car were associated with an increased exposure to high frequency noise. The LAeq noise indicator (overall noise) was associated with reported stress: for every 10 dB(A) increase in LAeq, individuals reported experiencing 1.118 times (95% confidence interval: 1.067, 1.172) higher levels of stress. Multiple noise indicator models did not show evidence that specific frequency components were associated with stress beyond overall noise.

Conclusion: Our findings suggest that noise exposure during commutes vary according to modes of transportation. Given that noise exposure resulted in higher reported levels of stress, future research should examine transportation noise effects on physiological variables.

Key Words: Noise exposure, transport, stress

1 **Introduction**

2 Noise is a pervasive component of day-to-day life and is associated with both auditory and non-
3 auditory health effects like cardiovascular diseases, diabetes, anxiety and depression (1–5).
4 Existing studies on the causal relationship between noise exposure, noise perception and health
5 have yielded inconsistent findings which may be attributed to conceptual and methodological
6 issues (6). Only a small number of studies have attempted to examine how momentary perceived
7 noise can influence people’s subjective perceptions. Bild et al. postulates that a sound is
8 determined to be a “noise” if it interferes with an individual’s daily activities and social
9 interactions (7). Other factors, like the time of day when the noise occurs, as well as the duration
10 of the occurrence can also affect noise perception (8,9). Existing studies in the literature also
11 tend to focus on individuals’ chronic noise exposure to one specific type of noise from a specific
12 source (e.g. road traffic, railway, or aircraft) usually at one particular geographic location (e.g.
13 school, home, or workplace) (4,10–12). It has also been emphasized that studies tend to focus on
14 noise in residential areas and ignore exposure in public urban areas (16). Indeed, as participants
15 are dynamic in their daily movements (e.g. running errands, buying groceries), they are exposed
16 to multiple sources of noise over various geographic locations for varying amounts of time
17 (13,14). Neglecting the dynamics of individuals’ daily movements can lead to a substantial
18 misclassification of the overall exposure (15). Therefore, taking dynamic spatiotemporal data of
19 how individuals interact with their environment helps to establish a more accurate assessment of
20 the relationship between environmental noise exposure and stress (6,17–19).

21
22 This study therefore proposes a novel mobility survey strategy based on Global Positioning
23 System (GPS) receivers which decomposes trips into trip stages, and utilizes location

24 information and participants' confirmation to identify the modes of transportation taken. It also
25 incorporates noise exposure for each trip stage. Based on this novel methodology, the empirical
26 aim of this study was to utilize the accuracy gains offered by this mobility survey to assess (i)
27 how personal exposure to noise (overall and low- and high-frequency noise) varied according to
28 activity patterns and during personal transport activities (i.e. by transportation mode); and (ii)
29 whether personal exposure to noise during trips was associated with the reported stress levels of
30 participants.

31

32 **Methods**

33 *Population*

34 Participants included adults of both genders from the Mobilisense cohort which was recruited
35 using a two-stage stratified sampling design. In the first stage, neighbourhood sampling took
36 place through the random selection of local neighbourhoods in the Metropolitan Area of Paris
37 (Grand Paris). Neighbourhoods were stratified by quartiles of area-level household income as
38 well as by quartiles of road traffic density (using the traffic model from the Ministry of
39 Infrastructure). Within each income area stratum, 30 neighbourhoods were randomly selected in
40 each of the two extreme quartiles of traffic density, resulting in 60 neighbourhoods in each area
41 income quartile and 240 neighbourhoods overall. In the second stage, census information
42 collected by the French National Institute of Statistics and Economic Studies (Insee) was used to
43 sample dwelling units in each of the selected neighbourhoods. This sampling design was useful
44 to maximize disparities in exposure to air pollutants and noise, while allowing us to document
45 deviations from representativity to the background population of the Grand Paris. Overall,
46 33,501 dwellings were selected from the 240 previously identified neighbourhoods based on the

47 2013-2014 censuses. Demographic and sociodemographic information on these dwellings was
48 also obtained from the census. Each dwelling was contacted twice by postal mail. Finally, 282
49 eligible participants aged from 30 to 64 years old were included between May 2018 and March
50 2020. This age range was selected to reflect a segment of the general adult population in Grand
51 Paris that is both likely to be integrated in professional life (as we wanted to look at trip-level
52 exposure during commutes) and is potentially affected by the onset of chronic diseases. We
53 applied the following inclusion criteria: speaking French, being free of cardiovascular,
54 cerebrovascular or specific contagious pulmonary diseases and glaucoma, not wearing an
55 implanted device, not wearing an auditive device and not having audition problems, not being
56 pregnant and not breastfeeding a child, not being a smoker and not living in a smoking
57 household (for the proper functioning of air pollution sensors), not intending to move outside the
58 Grand Paris area during the 2-year duration of the study, not being a night worker, not working
59 outside the region 4 days or more per week, and not being cognitively impaired.

60
61 The participants were recruited at their home after signing an informed consent letter. Prior to
62 sensor-based assessment, participants were guided through pre-study computerized
63 questionnaires which collected information pertaining to dimensions including but not limited to:
64 socioeconomic status, occupational history over 2 years, health-related behaviour (e.g., physical
65 activity, past smoking, etc.), resources for transport (e.g., driving license, public transport pass,
66 etc.), perceptions related to air pollution and noise, etc. Participants carried sensors over a 6 day
67 period and then underwent a GPS-based mobility survey along with a post-questionnaire during
68 a follow-up phone survey. The GPS-based mobility survey targeted the period where the GPS
69 receiver and other sensors were worn. The sampling and data collection protocol of

70 MobiliSense was approved by the National Council for Statistical Information, the French Data
71 Protection Authority, and the Ethical Committee of Inserm.

72

73 *Sensor based protocol and mobility survey*

74 Participants wore a Class I equivalent dosimeter SV 104A on their belt with the microphone
75 secured near the ear and on top of clothing for 4 days during their commutes and were instructed
76 to recharge it overnight. Noise dosimeters had three filters available to provide three distinct
77 measurement profiles for sound (20). The three filters (or weightings) A, C, and Z are as follows:
78 A approximates the range of sounds heard by the human ear; C is a standard weighting of the
79 audible frequencies but focuses more on the effect of low-frequency sounds as well as peak
80 sounds resulting from sudden or brief noises (i.e. crashes or bangs) (21) ; Z represents the actual
81 noise that is made with no weighting (Z stands for zero) and ranges from 8Hz to 20kHz. .

82

83 Personal dosimeters recorded noise level measurements between 20Hz and 10kHz per second
84 and were calibrated before and after use by each participant following the manufacturer's
85 instructions. In order to account for the natural scope of human hearing which ranges from 20Hz
86 to 20kHz with reduced sensitivity to low and high frequency sounds (below 1kHz and above
87 4kHz) (22), sound level measurements were "weighted" using A- and C-weightings to produce
88 one second intervals of A- and C-weighted measurements (noted as LAeq,1s and LCEq,1s
89 respectively). In order to take into account noise level fluctuations over a period of time, the
90 "average energy" or Leq value is calculated to produce an energetic mean. The Leq is not a
91 simple arithmetic average as decibels are measured in logarithmic values. It reflects the constant

92 noise level that would have been produced with the same energy rather than the noise actually
93 perceived during the given period.

94

95 For each trip stage window, several acoustic indicators were computed. First, the equivalent
96 continuous sound level (L_{eq}) with A- and C-weightings was calculated. Second, we determined
97 so-called spectral indicators for bands of low frequency (20Hz to 125Hz), medium frequency
98 (160Hz to 2kHz) and high frequency (2.5kHz to 20kHz). For each frequency interval, based on
99 the one second A-weighted equivalent continuous sound levels, an energetic mean was
100 calculated for each trip stage to produce $L_{Aeq}[20Hz-125Hz]_T$, $L_{Aeq}[160Hz-2kHz]_T$ and
101 $L_{Aeq}[2.5kHz-20kHz]_T$. These are henceforth referred to as low frequency, medium frequency,
102 and high frequency noises; in this case, the subscript “T” refers to the time period during which
103 the measurement was taken. Third, we calculated $L_{Ceq,1s}$ - $L_{Aeq,1s}$ noted $CA,1s$. This difference
104 accounts for low frequency sounds below 1kHz. The average of such difference at the second
105 level was calculated for each trip stage.

106

107 Participants also wore a GPS receiver and were asked to complete a travel diary on the places
108 visited and modes of transportation taken as supporting information for the mobility survey,
109 which was carried out a few days after the end of data collection. In order to assess participants’
110 transportation modes and stress reports per trip, GPS tagged commutes were uploaded to
111 Tripbuilder Web, an online application which integrates Google Maps and which automatically
112 generates trip stages from location data and identifies the mode of transportation taken for each
113 trip stage. According to Heshner and Button, trips often involve different modes of transportation
114 (e.g. walking and public transportation), while trip stages refer to the unimodal portions of trips

115 (segments of trips which are based on a unique mode of transportation (23). A purely unimodal
116 trip occurs only if the same mode of transportation is taken from the departure place to the
117 destination without the use of any other modes (including walking).

118

119 Once data collection was completed, research assistants used the GPS data and identified trips
120 and transportation modes displayed in the Tripbuilder web mapping application to conduct, with
121 minimal delays after the GPS follow-up, a telephone interview with the participants (mobility
122 survey). Only research assistants had access to the application screen while participants were
123 sent detailed paper screenshots of their GPS trips via postal mail. In addition, the research
124 assistants considered the paper travel diary as supportive information during the telephone
125 mobility survey. Participants were walked through the different days and through each trip stage
126 taken to help facilitate recall. Research assistants confirmed or if necessary, manually edited the
127 type of transportation taken at each trip stage. Participants were also successively asked to report
128 *a posteriori* the level of stress experienced for each trip stage and whether any particular trip
129 stage over that day was more stressful than the others. The data collection steps as well as the
130 type of data collected in each stage are detailed in Figure 1. Stress level was coded on a scale of
131 1 to 7 for each trip stage. The stress scale corresponds to the following: 1 - Conditions are
132 perfect, no stress; 2/3/4 - Objectively stressful conditions were present, which however did not
133 bother the participant, with a gradation of 2 (mild), 3 (intermediate), and 4 (significant); 5/6/7 -
134 Objectively stressful conditions which stressed the participants slightly (=5), intermediately (=6),
135 and significantly (=7).

136

137 It was specified that the sources of discomfort and stress must be linked either to the transport
138 conditions themselves (e.g. traffic jam, cancelled train, crowded metros, etc.) or to the
139 circumstances of the trip (e.g. the person was late, he fell, etc.). A summary sentence was then
140 used to identify stressful trip stages and to pinpoint whether the travel conditions themselves
141 were really the source of stress, such as: “That day, when you took the metro in the morning to
142 go to X, or in the afternoon to go to Y or in the evening to go to Z, were the travel conditions
143 particularly stressful? For example, was the metro crowded? Were there any delays or were you
144 running late?” By the responses given by the participants, research assistants placed the
145 conditions on the stress scale.

146

147 *Classification of trips*

148 Based on the travel modes indicated in each trip stage, we discerned the following categories:
149 walking only; other active modes (biking, rollerblading, skateboarding, etc.); personal motorized
150 transport (driver); personal motorized transport (passenger); RER/TER/SNCF; bus; metro; tram;
151 and other. RER/TER/SNCF incorporates the RER (higher speed trains travelling to and from the
152 suburbs), TER (trains from Paris towards suburbs or adjacent regions), and SNCF standard
153 suburban trains. Personal motorized vehicles (as a passenger or driver) include both four-
154 wheeled motorized vehicles (including taxis) and two-wheeled motor vehicles. The “other”
155 category incorporates miscellaneous modes like other long-distance trains, plane trips, boats, etc.

156

157 *Sociodemographic and time-related covariates*

158 Age was coded in 3 categories. Education was coded into 4 categories: no education/primary
159 education/lower secondary education; higher secondary and lower tertiary; intermediate tertiary;

160 and upper tertiary education. Employment status was classified into 4 categories: stable job;
161 unstable or temporary job; unemployed; and other (e.g. retired). Household income levels were
162 calculated by standardizing average household income by family size (one unit per member ≥ 14
163 years, 0.5 unit otherwise) and then divided into quartiles.

164

165 With regards to time, our analysis distinguished weekends from weekdays, as well as time of the
166 day (morning: 1:00 am – 9:59 am; day: 10:00 am – 6:59 pm; evening: 7:00 pm 0:59 am).

167

168 *Statistical analysis*

169 The dataset consisted in the trip stage windows for each participant with corresponding
170 information on the mode of transportation, amount of stress experienced, and the appropriate
171 acoustic indicators.

172

173 Objective 1 involved assessing the relationship between transportation modes and noise
174 indicators, using linear mixed effect models. Noise exposure was measured according to the
175 various indicators. Both individual random effect and temporal autocorrelation [AR(1) structure]
176 were included in the linear model. All analyses were performed in R version 1.2.5042 (24).

177 Mixed models were estimated using the nlme package version 2.1-2.131, while plots were made
178 using the ggplot2 package version 2.2.1.

179

180 Objective 2 was the assessment of the relationship between noise and stress. A quasi-Poisson
181 model was used to assess the relationship between noise exposure and stress. The quasi-Poisson
182 model was chosen over a Poisson model as there was evidence of overdispersion of the outcome.

183 The stress variable was transformed into “stress-minus-1” in order to obtain a count variable
184 ranging from 0 to 6 rather than from 1 to 7. Since the outcome was log transformed, the
185 regression coefficients were exponentiated back. This can then be interpreted as multipliers of
186 the stress level for a particular variable. In order to take repeated measurements into account,
187 individual random intercepts were incorporated in the model. Temporal autocorrelation between
188 the repeated measurements within each participant was taken into account by using an
189 autoregressive AR(1) function which assigns a covariance structure with correlation that
190 decreases with increases in time intervals separating the measures for a participant (25,26).
191 Quasi-Poisson models were run using the GLMMadaptive package version 0.6-8 and the MASS
192 package version 7.3-51.4. Root mean square error (RMSE) values were used to compare the fit
193 of models.

194

195 **Results**

196 *Descriptive information on the sample*

197 Among our 282 participants, the noise data collection failed for 17 participants, and another 12
198 participants lacked noise frequency band data. These participants were excluded, leaving 253
199 participants for the present analysis. Of the 12994 stages of trips identified for these participants,
200 4264 were made on days where the protocol did not include a noise data collection. We further
201 excluded 916 trip stages for which noise data were missing, and 14 trip stages for which there
202 was less than 50% of the noise data. We analysed data on 7800 trip stages from 253 participants.
203 Among this final sample, 58% were women; 73% had a permanent job, 13% were retired, and
204 4% unemployed; and 50% had three or more years of university education.

205

206 Overall, 6522 (83.6%) trip stages were reported as being “1” on the stress scale while only 24
207 (0.31%) were reported as “6” and 14 (0.18%) as “7”. In the distribution of trip stages, 59.3%
208 were entirely walked trips; 5.1% using bikes/roller-skates/skateboards; 2.6% were with
209 buses/coaches, 7.5% with metros, 4.1% with suburban trains, and 1.2% with tramways; and
210 16.8% and 3.2% involved personal motorized vehicles as the driver or passenger, respectively.
211 The mean duration of trip stages was 12.1 minutes, with the median duration being 6.5 minutes
212 (standard deviation 20.1). The range of the duration of trip stages was 0.05 minutes to 567
213 minutes.

214

215 *Modes of transportation and noise exposure*

216 As shown in Figure 2, the median LAeqT exposure was highest for trips involving the metro
217 [median 74.7 dB(A), interdecile range: 65.1, 80.2 dB(A)] while it was lowest for entirely walked
218 trips [median 68.7 dB(A), interdecile range: 54.0, 76.9 dB(A)]. Personal motorized vehicle trip
219 stages taken as the passenger showed the largest range in terms of LAeqT exposure [median 68.9
220 dB(A), minimum 25.7, maximum 96.9 dB(A)].

221

222 As shown in Table 1, mixed effects models were generated for each noise indicator as the
223 outcome, and included participant random effect and temporal autocorrelation, as well as
224 sociodemographic variables as a way of correcting for the sociodemographic distortions in the
225 sample.

226

227 Regarding LAeq, individuals in the study experience on average a 5.5 dB(A) (95% CI 4.7, 6.3)
228 increase in noise exposure when taking the metro compared to walking as well as a 4.0 dB(A)

229 (95% CI 3.0, 5.1) increase when taking suburban trains (RER/TER/SNCF) compared to walked
230 trips. Although to a lower extent, there were also indications of a higher LAeq noise exposure in
231 the bus, in the tram, when driving a car, and with other active modes compared to walking.
232 Furthermore, when compared to walking, all transport modes were associated with a higher
233 exposure to low frequency noise, especially those involving taking the bus and driving a car. All
234 transport modes except for taking the tram or driving a car were related to a higher exposure to
235 high frequency noise when compared to walking, and this is especially true for using the metro.

236

237 *Relationship between noise exposure and stress*

238 Table 2 reports how the potential confounders were related to the reported stress in trips in quasi-
239 Poisson models. Sociodemographic covariates showed no association. Weekend trips were
240 associated with a lower reported stress while morning trips were related to a higher stress.

241 Certain modes of transportation resulted in higher reported levels of stress. Compared to walked
242 trips, taking the bus/coach led to 1.859 times (95% CI 1.518, 2.277) higher stress levels; metro
243 1.862 times (95% CI 1.639, 2.114); and RER/TER/SNCF 2.022 times (95% CI 1.724, 2.370)
244 higher stress levels. Using a car as a driver or passenger was also associated with higher levels of
245 stress than walking. However, it is for the other active modes that the reported stress level was
246 the highest, with a ratio of 2.796 (95% CI 2.338, 3.343).

247

248 Table 3 presents the associations between noise exposure (6 different indicators) and subjective
249 stress, adjusted for the variables reported in Table 2. In order to test whether noise indicators
250 were nonlinearly associated with stress, quadratic terms were also added into the model.

251 However, as there was no evidence of quadratic patterns, the squared noise indicator terms were

252 dropped from the models. In 1-indicator models, for every 10 dB(A) increase in LAeqT, the level
253 of reported stress was shown to increase by 1.118 times (95% CI 1.067, 1.172). Similar trends
254 were observed for the remaining acoustic indicators (except for CA), possibly due to the high
255 correlation between noise indicators (see Figure 3). As a result, r-squared values and the root
256 mean square error (RMSE) indicators among the different models were relatively similar.

257

258 We then estimated models for the trip-level stress outcome including the LAeq and each time
259 one additional indicator (bottom of Table 3). In these models, only LAeq remained associated
260 with stress, while all of the other indicators lost their association with the outcome.

261

262 **Discussion**

263 *Summary of findings and interpretation*

264 This study analysed the association between several noise indicators and stress in daily
265 commutes within a real-life setting. We documented disparities in noise exposure across
266 transportation modes. We controlled for sociodemographic factors due to the related distortions
267 in our sample: people from different social and demographic backgrounds typically use different
268 transportation modes and participants included in our small sample may not be representative of
269 their sociodemographic groups in terms of place of residence and transportation modes used.
270 Thus, it was necessary to control for these variables to avoid sample distortions which would
271 affect the transportation modes' effects on exposure and stress. We also controlled for the day of
272 the week and the time of day. Previous studies have indeed found that the subjectivity of noise
273 perception is influenced by the time of day during which the noise occurs (8) and that noise is

274 less likely to be perceived as being “normal” when it occurs at night (between 10:00 p.m. and
275 8:00 a.m.) compared to when it occurs during the day (9).

276

277 A higher overall level of noise exposure was documented in metros and in suburban trains, and
278 to a lower extent in other modes compared to walking. However, our study which assessed
279 personal exposure to low and high noise frequencies brought novel information by showing that
280 exposure to particular noise frequencies also varied by transportation modes. For instance, while
281 taking the bus and driving were associated with particularly higher exposure to low frequency
282 noise compared to walking, using the metro is especially associated with higher exposure to high
283 frequency noise. Contrary to the metro, taking the tram or driving a car were associated with a
284 lower exposure to high frequency noise than walking. The noise at these high frequencies
285 (>2.5kHz) heard in the tram or in a car comes mainly from the outside of the vehicle, which
286 filters out some of the noise. This is different to the metros, which produce a lot more of high
287 frequency, squealing/screeching noises.

288

289 In our innovative approach assessing the stress effects of noise by frequency bands, all indicators
290 of noise exposure showed a positive association with trip-level self-reported stress. We
291 controlled for transportation modes and sociodemographic characteristics because the two likely
292 causally influence the noise exposure in trips and also influence stress through other pathways
293 than noise. We did not find evidence that any of our refined noise indicators accounting for
294 frequency bands were associated with stress beyond overall noise. This is in opposition with our
295 a priori expectation that high frequency noise may be particularly stressful.

296

297 *Strengths and limitations*

298 Regarding strengths, the present study uses newly developed methodologies for the joint
299 collection and processing of GPS, mobility survey, and personal noise exposure data to present
300 an accurate assessment of noise exposure in daily commutes.

301
302 In a previous study of ours where we ranked acoustic indicators on the basis of their predictive
303 ability (27), C-weighted acoustic indicators tended to outperform their A-weighted counterparts,
304 despite the fact that A-weighted indicators are the most commonly used for summarizing sound
305 exposure. However, this previous study did not measure sounds by frequency bands, in contrast
306 to the present work. Thus, the present use of both A- and C-weighted indicators as well as CA,
307 and low-, medium-, and high-frequency noise indicators allowed for a more comprehensive
308 examination of the relationship between specific frequencies of sound and resulting stress levels,
309 although it led to a negative finding.

310
311 Compared to most previous studies which focused on individuals' chronic exposures to specific
312 sources of noise at static locations (1), the present study considers individuals' personal
313 exposures to different sources of noise at multiple geographic locations and during travel
314 between these locations. The main strength of this study lies in the particular GPS-based
315 mobility survey methodology which enabled the identification of transportation modes and start
316 and end times of trip stages. This detailed information was used in conjunction with the time-
317 stamped noise data. A related strength lies in the large number of observations collected which
318 translated to 7800 trip stages. This is considerably more than previous studies looking at personal
319 noise exposure and stress. Our GPS-based mobility survey also allowed us to innovatively

320 collect information on stress during trips at the trip stage level. Overall, the use of wearable
321 sensors and innovative survey methodologies for trip conditions allowed for the accurate and
322 continuous measurement of personal exposure over time as well as its effects on stress. This
323 enabled the investigation of the noise – stress association in a “real-life” context while moving
324 away from previously-used laboratory environments.

325

326 Regarding limitations, although participants were instructed to wear the noise dosimeters over 4
327 full days with the exception of sleep, dosimeter data contain missing periods. An additional
328 challenge lies in the fact that we had to align two separately collected sources of data for the
329 same trips (GPS / mobility survey data and noise data). This was addressed through the use of
330 timestamps indicating the start and end points of each trip, as well as points of change when it
331 came to modes of transportation. Although the start and end times of trip stages were derived
332 from an algorithmic processing of GPS data and were confirmed during the phone mobility
333 survey with the participants, challenges to this approach lie in the fact that the accuracy of the
334 starts and ends of trips as well as the changes in mode of transportation during trips can be
335 reduced for a number of reasons. For example, accuracy is reduced when GPS data is lacking
336 and approximated timestamps must be assigned manually during the mobility survey.

337 Furthermore, “transfers” between trip stages can occur in an underground environment in the
338 Paris region, especially for public transportation. As a result, geolocation data is often not
339 available for these transfer episodes, although they do have associated start and end times. Also,
340 certain modes of transportation (i.e., tram) consisted of a small number of measurements (only
341 91 out of 7800 trip stages), which made the corresponding associations less reliable than others.

342

343 Regarding noise, due to the considerable amount of data collected, automated processes were
344 required for the filtering of data. These processing steps leading up to the calculation of the noise
345 parameters could potentially be a source of measurement bias. It was also noted that 100 trip
346 stages out of 7800 (1.3%) had an average LAeq below 30 dB(A), which might involve
347 measurement error, as these levels are abnormally low.

348

349 In addition, most previously conducted studies use self-reported recall questionnaires and
350 retrospective assessments to examine participants' stress (28,29). Similarly, our study assessed
351 stress in trips *a posteriori* during the mobility survey, with a delay between the end of data
352 collection and the survey. Although attempts were made to perform the mobility survey with as
353 minimal of a delay as possible, this approach is susceptible to bias as psychological stress is
354 highly dynamic and *a posteriori* reinterpretation is possible. Therefore, we cannot exclude
355 measurement error and recall bias related to specific participants or specific trips. These issues
356 indicate the need for an integrated assessment approach which incorporates ecological
357 momentary assessment (EMA), i.e., in situ surveys of stress using smartphones, with GPS
358 receivers and wearable noise sensors to produce accurate assessments of short-term effects of
359 noise on stress (30).

360

361 An additional limitation is whether the study participants are representative of a larger
362 population. Originally, a sample of around 49000 individuals were selected from the census as
363 being eligible for participation in the study. Participants' interest in engaging in the study was
364 gauged through postal mail. Therefore, although the final group of participants was not a
365 convenience sample, it is also not a "representative sample" given the small final sample size.

366 However, individual and contextual determinants of participation in the study have been
367 investigated, and it should allow us to address potential selection biases.

368

369 Another limitation is related to the fact that this study mainly focuses on the relationship between
370 measured noise over the short term and acute rather than chronic psychological stress. It is
371 important to note, however, that the impacts of noise on individuals' psychological stress may
372 stem from a cumulative exposure over time and may only become apparent after a certain period
373 (time-lagged and accumulated effect). The long-term portion of the Mobilisense study will
374 compare participants' health outcomes after a one or two-year follow-up period, permitting for
375 the investigation of the relationship on a longer temporal scale.

376

377 *Conclusion*

378 Our future research will evaluate the interactions between mobility contexts and sound levels in
379 their association with psychological stress. Furthermore, our future work will have to take into
380 account the subjectivity of noise perception which can be affected by non-acoustic factors like
381 the personal sensitivity to noise, levels of mental arousal, the meaning of and the predictability of
382 sound levels, as well as perceived control over the sound source. Moreover, future studies should
383 give more consideration to the behavioural consequences of noise, for example in terms of
384 physical activity, as research suggests noise affects whether people choose to exercise or not
385 (31). Some of these aspects could be incorporated into future research through the use of an
386 enhanced version of the mobility survey. Future work should also take into account potentially
387 unmeasured confounders which may also affect stress, such as air pollution, vibration, etc. as
388 studies have shown that it is difficult to separate these effects from those of noise (31). These
389 stressors can be accounted for through the use of additional sensors such as the air pollution
390 monitors that were used in the MobiliSense study.

391

392 The combination of GPS and noise dosimeter data collection along with the use of a GPS-based
393 mobility survey allowed us to better explore the relationship between noise exposure and stress
394 at an unprecedented level of accuracy: at the level of trip stages for which exact transportation
395 modes were identified. The associations that were found between noise indicators and
396 subjectively reported stress indicated that overall noise levels rather than particular noise
397 frequencies contributed to stress. Although perhaps only applicable to cities with a similar urban
398 and transport infrastructure, our results suggest that noise exposure varies depending on the
399 modes of transportation taken. We are also able to conclude that noise at levels typically

400 encountered in transport poses a threat to human wellbeing by increasing stress. These findings
401 suggest that noise is an important concern in the daily lives of urban residents which urgently
402 needs to be addressed through engineering and adequate urban planning transformations related
403 to transportation systems.

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Figure 1: Flow chart showing study stages and the data collected from each stage

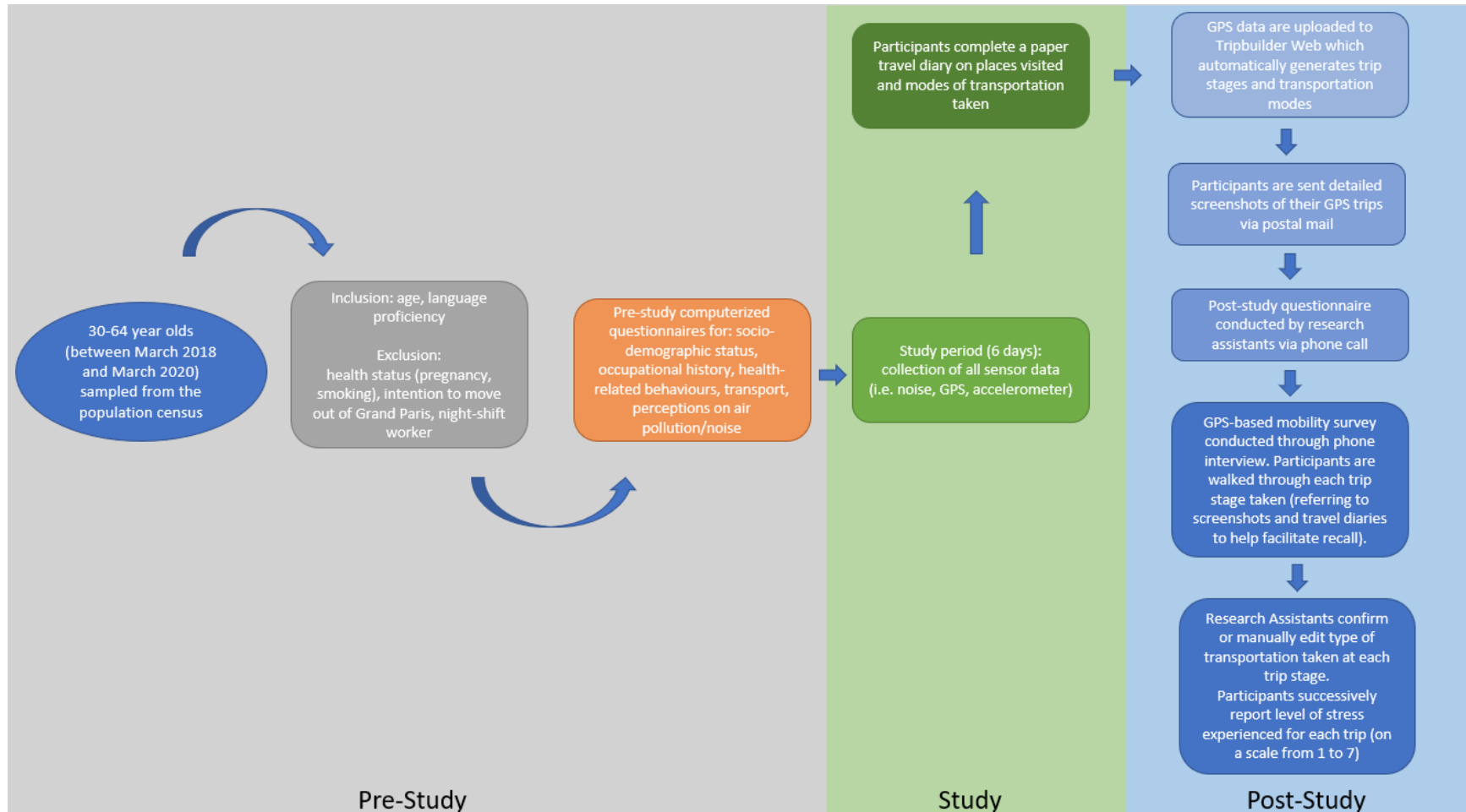


Figure 2: Distribution of LAeqT by Transportation Mode

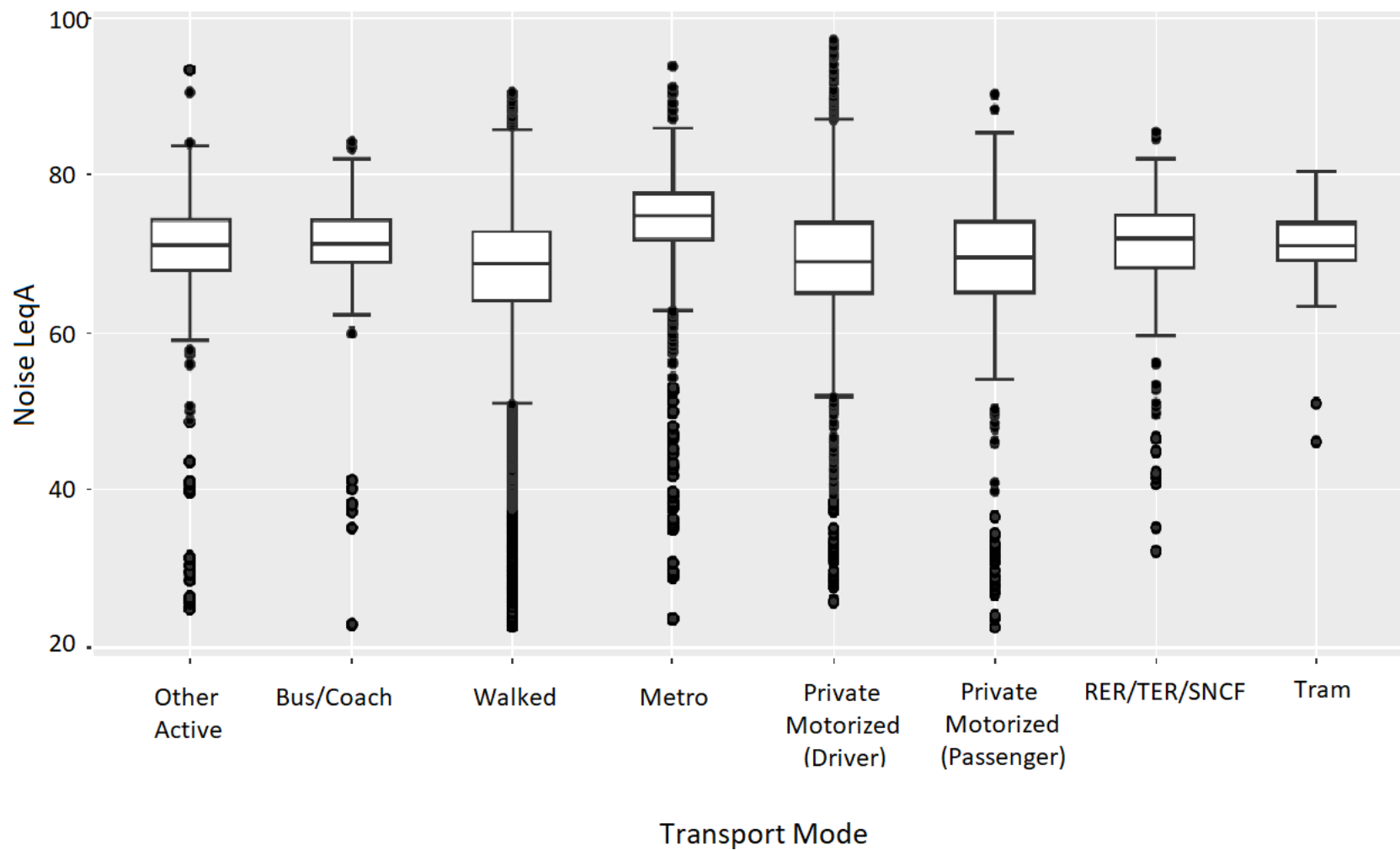


Figure 3: Correlation Matrix of Noise Indicators

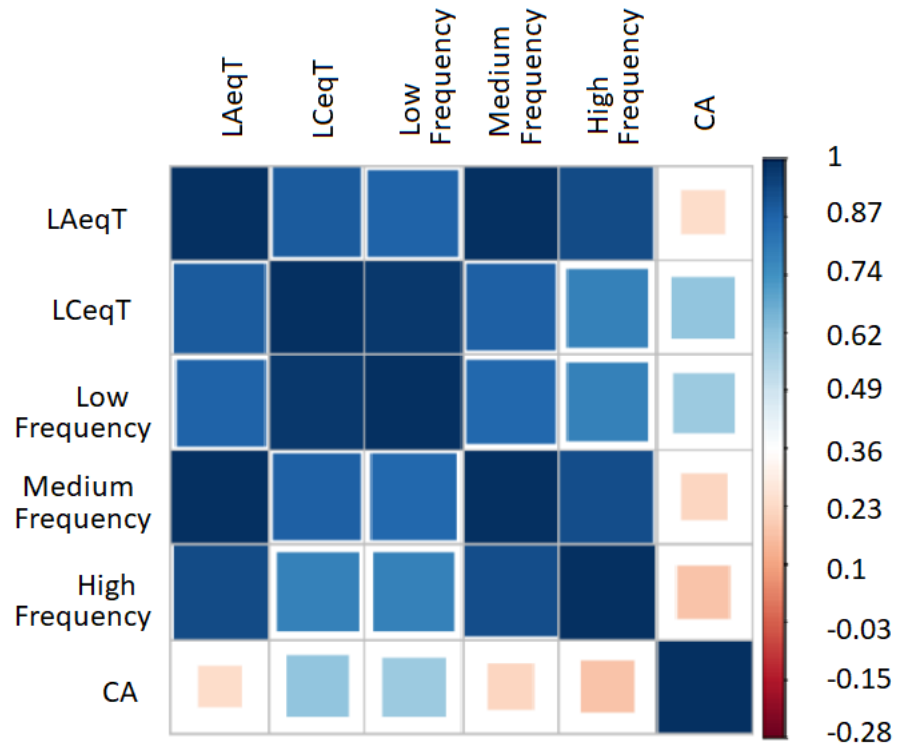


Table 1: Associations between mode of transportation and indicators of noise exposures from random effect linear models controlling for time autocorrelation and sociodemographic variables, the Mobilisense Study

	L _A eqT	L _C eqT	CA	Low Freq	Medium Freq	High Freq
Transportation mode						
Walking	Ref.	Ref.		Ref.	Ref.	Ref.
Other active	3.514 (2.411, 4.617)	4.921 (3.816, 6.026)	1.399 (0.815, 1.983)	5.718 (4.572, 6.865)	3.475 (2.324, 4.625)	3.606 (2.598, 4.613)
Bus/Coach	2.728 (1.433, 4.022)	10.360 (9.063, 11.658)	7.655 (6.955, 8.355)	8.690 (7.345, 10.035)	2.574 (1.224, 3.923)	2.188 (1.005, 3.371)
Metro	5.475 (4.695, 6.256)	6.079 (5.296, 6.862)	0.580 (0.158, 1.002)	5.973 (5.161, 6.784)	5.661 (4.847, 6.476)	4.055 (3.341, 4.768)
RER/TER/SNCF	4.033 (2.989, 5.077)	5.083 (4.037, 6.129)	1.046 (0.482, 1.610)	5.494 (4.409, 6.578)	4.308 (3.219, 5.397)	1.407 (0.453, 2.361)
Tram	2.307 (0.414, 4.199)	5.264 (3.367, 7.160)	2.914 (1.891, 3.938)	5.393 (3.426, 7.359)	2.513 (0.539, 4.486)	-1.810 (-3.539, -0.080)
Personal motorized (driver)	2.201 (1.576, 2.826)	10.491 (9.865, 11.117)	8.360 (8.026, 8.693)	9.576 (8.927, 10.226)	1.786 (1.135, 2.438)	-0.577 (-1.148, -0.007)
Personal motorized (passenger)	-0.300 (-1.469, 0.869)	7.049 (5.877, 8.220)	7.333 (6.703, 7.964)	6.407 (5.193, 7.622)	-0.745 (-1.964, 0.474)	-3.254 (-4.322, -2.185)
Education level						
Primary, lower secondary	Ref.	Ref.		Ref.	Ref.	Ref.
Higher secondary	-3.805 (-7.666, 0.056)	-2.421 (-6.255, 1.413)	1.398 (0.007, 2.789)	-2.615 (-6.666, 1.437)	-4.100 (-8.137, -0.062)	-4.354 (-7.812, -0.895)
Intermediate tertiary	-4.693 (-8.662, 0.723)	-4.268 (-8.209, -0.326)	0.457 (-0.972, 1.886)	-4.353 (-8.518, -0.188)	-4.999 (-9.150, -0.849)	-4.736 (-8.292, -1.181)
Upper tertiary	-2.084 (-5.902, 1.734)	-1.629 (-5.421, 2.162)	0.466 (-0.908, 1.840)	-1.550 (-5.556, 2.457)	-2.297 (-6.289, 1.695)	-2.306 (-5.726, 1.114)
Employment						
Unstable job	Ref.	Ref.		Ref.	Ref.	Ref.
Stable job	-0.595 (-4.769, 3.580)	-0.778 (-4.921, 3.365)	-0.201 (-1.676, 1.275)	-1.252 (-5.633, 3.129)	-0.539 (-4.903, 3.826)	-1.140 (-4.877, 2.596)
Unemployed	-0.052 (-5.987, 5.883)	-0.893 (-6.785, 4.999)	-0.894 (-3.007, 1.219)	-2.564 (-8.793, 3.666)	-0.085 (-6.291, 6.121)	-0.392 (-5.706, 4.922)
Retired	-1.739 (-6.777, 3.300)	-1.042 (-6.044, 3.960)	0.700 (-1.095, 2.494)	-1.610 (-6.898, 3.678)	-1.865 (-7.134, 3.404)	-1.930 (-6.441, 2.582)
Other	-0.198 (-5.016, 4.620)	-0.795 (-5.578, 3.987)	-0.638 (-2.349, 1.073)	-1.324 (-6.380, 3.733)	-0.160 (-5.198, 4.878)	-0.413 (-4.726, 3.900)
Relationship (couple vs. not)	-1.407 (-3.638, 0.825)	-2.129 (-4.345, 0.087)	-0.740 (-1.544, 0.063)	-1.214 (-3.556, 1.127)	-1.346 (-3.679, 0.987)	-1.034 (-3.033, 0.965)
Household income						
NA	-2.547 (-8.373, 3.279)	-1.378 (-7.165, 4.410)	1.141 (-1.024, 3.307)	-1.209 (-7.319, 4.901)	-2.474 (-8.565, 3.616)	-1.626 (-6.850, 3.598)
1 st tertile	Ref.	Ref.		Ref.	Ref.	Ref.
2 nd tertile	-0.762 (-3.013, 1.489)	-1.629 (-3.864, 0.605)	-0.801 (-1.606, 0.004)	-1.255 (-3.618, 1.107)	-0.732 (-3.086, 1.621)	0.050 (-1.966, 2.065)
3 rd tertile	-1.598 (-4.092, 0.896)	-0.695 (-3.288, 1.897)	-0.012 (-0.906, 0.883)	-1.254 (-3.871, 1.363)	-1.624 (-4.231, 0.984)	-1.254 (-3.487, 0.980)
Female (vs. male)	0.021 (-1.694, 1.736)	-0.048 (-1.751, 1.654)	-0.055 (-0.671, 0.560)	0.629 (-1.171, 2.429)	0.025 (-1.768, 1.818)	-0.366 (-1.902, 1.170)
Age group						
30-44	Ref.	Ref.		Ref.	Ref.	Ref.
45-60	0.469 (-1.583, 2.522)	0.509 (-1.529, 2.547)	0.073 (-0.661, 0.808)	0.580 (-1.574, 2.734)	0.472 (-1.675, 2.618)	0.599 (-1.239, 2.438)
≥60	0.386 (-2.515, 3.286)	-0.300 (-3.180, 2.580)	-0.629 (-1.669, 0.410)	-0.475 (-3.519, 2.569)	0.441 (-2.592, 3.474)	0.100 (-2.498, 2.698)
Weekend vs. weekdays	1.271 (0.656, 1.887)	0.784 (0.167, 1.401)	-0.440 (-0.768, -0.112)	1.486 (0.846, 2.126)	1.317 (0.674, 1.959)	1.282 (0.719, 1.844)
Time						
Morning	0.276 (-0.251, 0.804)	0.853 (0.324, 1.381)	0.577 (0.292, 0.862)	0.155 (-0.395, 0.705)	-1.556 (-2.406, -0.705)	0.956 (0.474, 1.438)
Day	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.
Evening	-0.470 (-0.962, 0.021)	-0.215 (-0.707, 0.278)	0.270 (0.004, 0.535)	-0.572 (-1.084, 0.059)	-5.500 (-6.295, -4.704)	-0.337 (-0.786, 0.112)

Table 2: Quasi-Poisson models for the relationship between noise exposure and stress, adjusted for sociodemographic variables and adjusted or not for transportation modes: ratios (95% confidence intervals)

	Adjusted for sociodemographics	Adjusted for sociodemographics and transportation modes
Weekend vs. weekdays	1.392 (1.221, 1.587)	1.349 (1.188, 1.532)
Time		
Morning	1.259 (1.254, 1.264)	1.151 (1.052, 1.260)
Day	Ref.	Ref.
Evening	1.058 (1.052, 1.064)	1.032 (0.942, 1.131)
Education Level		
Primary, lower secondary	Ref.	Ref.
Higher secondary	1.498 (0.299, 7.499)	1.289 (0.302, 5.504)
Intermediate tertiary	1.094 (0.208, 5.761)	0.912 (0.204, 4.079)
Upper tertiary	2.231 (0.456, 10.924)	1.889 (0.451, 7.907)
Employment		
Unstable job	Ref.	Ref.
Stable job	1.602 (0.306, 8.397)	1.528 (0.346, 6.738)
Unemployed	0.825 (0.074, 9.185)	0.823 (0.094, 7.197)
Retired	1.286 (0.174, 9.480)	1.688 (0.280, 10.170)
Other	1.242 (0.183, 8.422)	1.319 (0.237, 7.341)
Relationship (couple vs. not)	0.769 (0.315, 1.874)	0.858 (0.384, 1.915)
Income		
NA	0.142 (0.007, 2.771)	0.133 (0.008, 2.161)
1 st tertile	Ref.	Ref.
2 nd tertile	0.827 (0.342, 2.001)	0.838 (0.379, 1.856)
3 rd tertile	0.483 (0.182, 1.287)	0.458 (0.190, 1.107)
Age Group		
30-44	Ref.	Ref.
45-60	0.978 (0.433, 2.206)	0.921 (0.444, 1.914)
≥60	0.876 (0.272, 2.817)	0.572 (0.197, 1.659)
Female (vs. male)	0.740 (0.373, 1.470)	0.672 (0.362, 1.246)
Transportation Mode		
Walking		Ref.
Other Active		2.796 (2.338, 3.343)
Bus/Coach		1.859 (1.518, 2.277)
Metro		1.862 (1.639, 2.114)
RER/TER/SNCF		2.022 (1.724, 2.370)
Tram		0.962 (0.600, 1.544)
Personal Transport Driver		1.813 (1.617, 2.031)
Personal Transport Passenger		1.262 (1.042, 1.529)

Table 3: Associations between noise indicators and stress analyzed at the trip stage level, after adjustment for sociodemographic variables, day of week, time of day, and transportation mode from Quasi-Poisson models: null, 1-indicator, and 2-indicator models

	LAeqT u: 10 dB(A)	LCeqT u: 10 dB(A)	CA u: 1 dB(A)	Low Frequency u: 10 dB(A)	Medium Frequency u: 10 dB(A)	High Frequency u: 10 dB(A)	R ²	RMSE
<i>Null</i>							0.6372	2.9442
<i>1-indicator</i>								
LAeqT	1.118 (1.067, 1.172)						0.6402	2.9408
LCeqT		1.091 (1.041, 1.142)					0.6393	2.9314
CA			0.993 (0.985, 1.001)				0.6375	2.9477
Low frequency				1.079 (1.032, 1.128)			0.6392	2.9288
Medium frequency					1.110 (1.061, 1.161)		0.6399	2.9417
High frequency						1.097 (1.045, 1.152)	0.6396	2.9383
<i>2-indicator</i>								
LAeqT + LCeqT	1.132 (1.043, 1.229)	0.985 (0.908, 1.070)					0.6403	2.9423
LAeqT + CA	1.115 (1.062, 1.171)		0.999 (0.990, 1.007)				0.6403	2.9423
LAeqT + Low frequency	1.132 (1.052, 1.218)			0.985 (0.918, 1.056)			0.6402	2.9433
LAeqT + Medium frequency	1.472 (0.843, 2.570)				0.769 (0.452, 1.307)		0.6408	2.9380
LAeqT + High frequency	1.146 (1.049, 1.253)					0.970 (0.883, 1.065)	0.6400	2.9407

Supplementary Material

Table 1: Counts and percentages for the number of days of delay between the end of the study period and the mobility survey

Number of Days of Delay	Count	Percentage
0	1	0.403
1	9	3.629
2	35	14.113
3	40	16.129
4	52	20.968
5	38	15.323
6	28	11.290
7	16	6.452
8	5	2.016
9	5	2.016
10	7	2.823
11	2	0.806
12	1	0.403
14	2	0.806
15	1	0.403
16	1	0.403
22	1	0.403
23	1	0.403
28	1	0.403