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# Combined road traffic, railway and aircraft noise sources: total noise annoyance model appraisal from field data

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## Abstract

Appraisal of environmental noise effects on health considers single noise exposure. In large cities, noise exposure is frequently due to multiple sources. Their combination, interaction or successive presence is known to affect people's health. The prediction of their effects has been little studied and needs more investigation to address the problem. Studies dealing with annoyance due to combined noise sources proposed different total annoyance models. They were very rarely assessed using field annoyance data. The current work aims to assess them using data of annoyance due to different urban situations of two, and even three, combined transportation noise sources. The considered noises were from road, railway and aircraft traffic. Assessment of ten classical total annoyance models highlighted relevant existing models to account for combined transportation noise annoyance in cities. Perceptual total annoyance models, based on annoyance due to each transportation noise source, better performed total annoyance calculation than psychophysical total annoyance models based on the  $L_{den}$  index. As the dominant source effect mainly explained total annoyance responses from the residents, the strongest component model led to a good calculation of mean total annoyance ratings. But perceptual models with an interaction term, such as the vector summation and mixed models, better explained total annoyance judgments from residents as they account for the contribution of each combined noise source and their interaction. The perceptual linear regression model was also interesting as it accounted for the contribution of each combined noise source, and might be used for more than two combined noise sources. Those perceptual models accounted well for the resident feeling towards the different combined noise sources. These results might contribute to the endeavor aiming at filling the lack of consensus among the scientific community and the corresponding lack of regulations.

**Keywords:** Total noise annoyance; combined transportation noises

## 1. Introduction

Noise exposure is a great environmental and health concern in industrial countries. Noise levels increase (World Health Organization, 2018) due to urbanization and traffic growth. For environmental noise management, the European Directive 2002/49/EC (European commission, 2002a) makes it mandatory for European cities with more than

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45 100,000 inhabitants to produce strategic noise maps for each type of transportation  
46 noises. These maps characterize noise exposure using the day-evening-night level,  $L_{den}$   
47 index. They are used to estimate the number of Disability-Adjusted Life Years  
48 (DALYs) due to the impact of single environmental noise exposure on health (World  
49 Health Organization, 2011). Both environmental health impact assessment and urban  
50 planning only consider single noise exposure. But in large cities, combined noise  
51 exposure is a frequent situation and few data are available about the number of  
52 European citizens exposed to several noise sources (*cf.* Lercher *et al.*, 2017).  
53 Simultaneous noise sources may interact. For example, Öhrström and her colleagues  
54 (2007) reported a greater annoyance due to combined sound exposure from two equally  
55 noisy sources than annoyance due to the same total sound exposure involving one  
56 dominant source. It has also been highlighted that different noise sources successively  
57 perceived over time period affect people (*e.g.* Pierrette *et al.*, 2012a for annoyance due  
58 to road traffic noise combined with weak but permanent industrial noise; ENNAH,  
59 2013 for child learning impairment due to combined aircraft and road traffic noises).  
60 Thus, characterization and prediction of the effects of multiple noise source situations  
61 need endeavor (*e.g.* Lercher *et al.*, 2017, Lechner *et al.*, 2019 and Gille *et al.*, 2019).  
62

63 Annoyance due to combined noise exposures has been mainly studied for two  
64 environmental noise sources (*e.g.* Lam *et al.*, 2009 for combined road traffic and  
65 railway noises; Nguyen *et al.*, 2012 for combined aircraft and road traffic noises;  
66 Wothge *et al.* 2017 for combined aircraft and road traffic noises and combined aircraft  
67 and railway noises). Very few field studies investigated annoyance due to three  
68 combined transportation noise sources (*e.g.* Ragletti *et al.*, 2015 in Canada; Gille *et al.*,  
69 2016 in France; Lercher *et al.*, 2017 in the Alpine valley; Lechner *et al.*, 2019 in  
70 Innsbrück). Among field studies dealing with annoyance due to combined  
71 transportation noise sources, few of them investigated classical total annoyance models  
72 from the literature in order to highlight relevant ones (*e.g.* Nguyen *et al.*, 2012). The  
73 very limited number of studies dealing with total annoyance model appraisal using field  
74 data leads to a lack of consensus among the scientific community, and results in a  
75 corresponding lack of national regulations. Thus, more studies are needed to test total  
76 annoyance models, and to point out whether existing total annoyance models might be  
77 relevant for combined transportation noise exposure situations, when people are  
78 exposed to two, or even three noise sources. Close to large cities, such combined  
79 transportation noise exposure situations are frequent.  
80

81 In 2012, a French socio-acoustic survey (Ecotière *et al.*, 2014) was conducted for  
82 the Ministry of Ecology in order to study annoyance due to combined transportation  
83 noise sources in France. Different combinations of two transportation noise sources  
84 were considered (*i.e.* road traffic noise combined with railway noise, road traffic noise  
85 combined with aircraft noise, and railway noise combined with aircraft noise).  
86 Furthermore, a combination of three transportation noise sources was also under study  
87 (road traffic noise combined with railway and aircraft noises). These field data were  
88 analyzed using structural equation modeling to highlight various potentially influencing  
89 factors on total annoyance (Gille *et al.*, 2017). The analysis of transportation noise  
90 source contributions showed that aircraft noise has a higher influence on total  
91 annoyance than road traffic noise, and that in turn road traffic noise has a higher

92 influence on total annoyance than railway noise. These field data were used to test the  
93 exposure-effect relationships (Gille *et al.*, 2016) recommended by the European  
94 Commission (2002b) to predict annoyance due to single transportation noise exposure.  
95 They were also used to test Miedema's model (2004), which was proposed to predict  
96 annoyance due to combined transportation noise sources and was based on the  
97 previously mentioned exposure-effect relationships (*cf.* Gille *et al.*, 2016). The testing  
98 results showed that the different exposure-effect relationships and Miedema's model  
99 generally fail to provide a good prediction of both partial annoyance (*i.e.* annoyance  
100 due to a noise source heard in presence of another source) and total annoyance (*i.e.* due  
101 to combined noise sources), (*cf.* Gille *et al.*, 2016). Thus, assessment of more total  
102 annoyance models using field data has to be considered as a better characterization of  
103 total annoyance is needed.

104 The current work will focus on total annoyance due to combined transportation  
105 noise sources to point out 1) perceptual mechanisms which might govern total  
106 annoyance, and 2) relevant total annoyance models among the main ones proposed in  
107 the literature. Annoyance ratings gathered during the French socio-acoustic survey  
108 (Ecotièrre *et al.*, 2014) will be used for such purposes. Frequent combined transportation  
109 noise source situations in large cities will be considered: i) road traffic combined with  
110 aircraft noise, and ii) road traffic combined with railway noise. Furthermore, the less  
111 studied combined transportation noise exposure in the literature will be also under  
112 consideration in the current paper: road traffic noise combined with both railway and aircraft  
113 noise sources.

114

## 115 **2. The socio-acoustic survey**

116

117 The survey was conducted in 2012 by Ecotièrre *et al.* (2014) in 8 French cities  
118 exposed to various combined transportation noise sources (*i.e.* road traffic and railway;  
119 road traffic and aircraft; railway and aircraft; road traffic, railway and aircraft noises).  
120 The respondents were interviewed face-to-face through a questionnaire. In this section, the  
121 main characteristics of the survey are briefly summed up from published articles (Gille  
122 *et al.*, 2016 and Gille *et al.*, 2017).

123

### 124 *2.1 The questionnaire*

125 The 30-minute questionnaire in French (*cf.* Ecotièrre *et al.*, 2014) was organized with  
126 questions dealing with:

- 127 - housing description and assessment;
- 128 - neighborhood description and assessment
- 129 - global outdoor sound environment: description and assessment;
- 130 - noise from the different sources under study, considered separately: description and  
131 assessment of annoyance when the noise source is heard in presence of another  
132 transportation noise source depending on the city of residence (hereafter denoted  
133 by partial annoyance);
- 134 - overall noise resulting from the combined exposure under study (*i.e.* road traffic  
135 and railway; road traffic and aircraft; railway and aircraft; as well as road traffic,

136 rail and aircraft noise sources): description about the different noise sources within  
 137 the combination using items such as “road traffic noise alone would be bearable”;  
 138 - annoyance due to these combined noise sources (hereafter denoted by total  
 139 annoyance);  
 140 - non-acoustical factors related to the respondent (*e.g.* self-estimated noise  
 141 sensitivity).  
 142

143 The questions concerning partial and total noise annoyances complied with  
 144 ISO/TS 15666 technical specification recommendations for French language (*e.g.*  
 145 “Thinking about the last 12 months, when you are here at home, how much does noise  
 146 from road traffic annoy you?”; “Thinking about the last 12 months, when you are here  
 147 at home, how much do noise from road traffic and noise from railway together annoy  
 148 you?”). Respondents were asked to give an annoyance rating to the specified noise  
 149 source(s) on a continuous scale ranging from “0” to “10”, comprised of 11 evenly  
 150 spaced numerical labels and two verbal labels at both ends (“not at all” and  
 151 “extremely”). The self-estimated noise sensitivity in general was assessed on a  
 152 continuous scale from “0” to “10”, built on the same format (Ecotièrre *et al.*, 2014).  
 153

## 154 2.2 Study population

155 A total of 823 people were successfully interviewed face-to-face. The respondents  
 156 were aged between 18 and 80, and had been living permanently in their dwelling for at  
 157 least one year (*cf.* Gille *et al.*, 2017). Their socio-demographic characteristics are  
 158 presented in Table 1.  
 159

160 **Table 1.** Socio-demographic characteristics of the studied population (*cf.* Gille *et*  
 161 *al.*, 2017).

	N(%)	Mean ±SD(Min-Max)
Gender		
Male	48.5%	
Female	51.5%	
Age		46 ±16.9 (18-80)
Length of residence		13.4±14.1(1-77)
Occupation		
Working	55.9%	
Non-working	44.1%	
Retired	22.7%	
Student	4.9%	
Unemployed	7.4%	
Housewife	6.7%	
Disabled	1.2%	
Other	1.2%	

162 From the normally distributed noise sensitivity ratings, it appeared that about  
 163 70.5% of respondents reported themselves to be sensitive or highly sensitive to noise in  
 164 general.  
 165

## 166 2.3. Combined noise exposures under study

168 Noise exposure in terms of the  $L_{den}$  index was known thanks to strategic noise maps  
 169 available in 2012 for each city from the survey. The maps were drawn by technical services  
 170 under contract with the French government, using European Directive 2002/49/CE  
 171 guidelines. The noise maps were established for each single transportation noise exposure.

172 Table 2 gives the combined noise exposures for 6 cities studied during the socio-  
 173 acoustic survey, and studied in the current work. The corresponding combined transportation  
 174 noise exposures were respectively combined road traffic and railway noise sources,  
 175 combined road traffic and aircraft noise sources, and finally combined road traffic, railway  
 176 and aircraft noise sources. The combined railway and aircraft noise source situations (*i.e.*  
 177 without road traffic noise), studied during the socio-acoustic survey in two French cities, will  
 178 not be analyzed in the current work as it corresponds to a less common combined exposure  
 179 for inhabitants of cities. This type of exposure - not studied here - concerned 121  
 180 respondents from the socio-acoustic survey (*cf.* Gille *et al.*, 2017).

181 Table 2 summarizes for the combined exposures studied in the current paper, sample  
 182 size and noise exposure in terms of  $L_{den}$  range (*cf.* Gille *et al.*, 2017).

183  
 184 **Table 2.** Noise exposure expressed in  $L_{den}$  (dB(A)) per noise source and sample  
 185 size of areas in 6 cities of the survey (Ecotièrre *et al.*, 2014; Gille *et al.*, 2017).  
 186 Road: Road traffic; Rail: Railway; Air: Aircraft; <sup>1</sup>: city exposed to Orly airport  
 187 noise; <sup>2</sup>: city exposed to Roissy-Charles-de-Gaulle airport noise.  
 188

Exposure (Total sample size)	City (sample size)	Lden Road Traffic dB(A)	Lden Railway dB(A)	Lden Aircraft dB(A)
Road and Rail (301)	Bourg Les Valence (82) Caluire (79) Lyon 6 (140)	58.0 to 80.8 55.6 to 78.0 48.4 to 74.2	58.1 to 77.4 45.6 to 82.2 40.6 to 83.6	no exposure
Road and Air (212)	Paray-Vieille-Poste <sup>1</sup> (153) Saint Brice-sous-Forêt <sup>2</sup> (59)	49.9 to 77.9 53.7 to 67.5	no exposure	42.0 52.0 to 54.0
Road, Rail and Air (189)	Villeneuve-Saint-Georges <sup>1</sup> (189)	42.3 to 79.3	43.2 to 80.8	44.7 to 62.8

### 3. Perceptual mechanisms linked to total annoyance judgments

Annoyance ratings collected during the socio-acoustic survey were first analyzed to understand the main perceptual mechanisms which might govern total annoyance judgments.

For the different combined transportation noise exposures, the analysis was helped by means of the representation proposed by Vos (1992). For each combined noise exposure, the representation displays mean partial and total annoyance ratings versus  $L_{den}$  when only one noise within the combination varies in  $L_{den}$  values and the other(s) is(are) at a fixed  $L_{den}$  value. For each noise exposure,  $L_{den}$  values are displayed per 5 dB(A) interval as it is done for noise maps in European countries. The representation highlights the main perceptual mechanisms between mean partial annoyance ratings and mean total annoyance ratings. Then t-test analyses were carried out to confirm or not, from a statistical point of view, the significance of the observed differences between partial and total annoyance ratings. T-test analyses may highlight if total annoyance is greater than, equal to or lower than the maximum partial annoyance.

When total annoyance is equal to the maximum partial annoyance, total annoyance is governed by the most annoying noise source; such source is the strongest component within the combination. This was observed in different studies of combined noise sources (*e.g.* Berglund *et al.*, 1981; Morel *et al.*, 2012; Wothge *et al.*, 2017). This is explained by energy masking effects (*e.g.* Hellmann, 1982). The most annoying source is often the dominant source in global sound pressure level or in loudness (*e.g.* Berglund *et al.*, 1981). For that reason, the effect is denoted in the literature by the dominant source effect. But a non-dominant source in global sound pressure level can be the most annoying source within the combination (*e.g.* Wothge *et al.*, 2017). The phenomenon might be explained by partial energy masking between the noise sources (*e.g.* high energy masking at low frequencies as highlighted in Morel *et al.*, 2012).

When total annoyance is greater than the maximum partial annoyance, the phenomenon is called the synergistic effect. This effect has been explained by interactions between the combined noise sources and has been observed when annoyances due to each noise source within the combination are close (*cf.* Ohrström *et al.*, 2007; Ota *et al.*, 2008). When total annoyance is lower than the maximum partial annoyance, this is named the paradox effect. This latter is explained in the literature as a possible consequence of the method used to assess annoyance (*e.g.* Lercher, 2011), or explained in some noise situations by cognitive effects due to the presence of natural noises which are known to decrease annoyance (Alayrac *et al.*, 2011; Klein *et al.*, 2017) and sound unpleasantness (Guastavino, 2006).

The analysis is hereafter presented per exposure: road traffic noise combined with aircraft noise, road traffic noise combined with railway noise, and finally road traffic noise combined with both railway noise and aircraft noise.

#### 3.1 Road traffic noise combined with aircraft noise

The analysis carried out for the combined road traffic and aircraft noise sources showed that total annoyance ratings were not significantly different from the maximum partial annoyance ratings. The strongest component model from the literature (*cf.* section 4) should therefore allow a good calculation of total annoyance ratings.

As an example, figure 1 displays the representation proposed by Vos (1992), with mean annoyance ratings (for partial road traffic noise annoyance, partial aircraft noise annoyance and total annoyance) versus the variation of road traffic noise  $L_{den}$  per interval of 5 dB(A) when aircraft noise  $L_{den}$  is at a fixed value within the half-open interval [40; 45dB(A)].

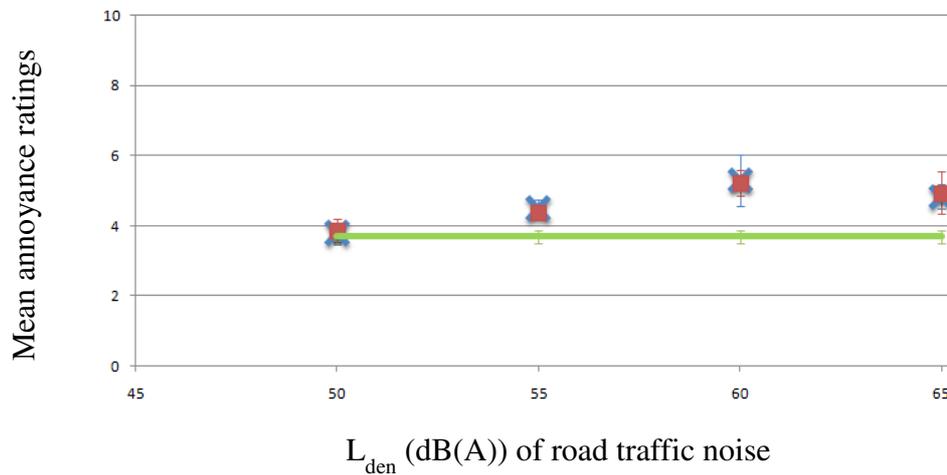


Figure 1: Mean annoyance ratings with standard errors versus the variation of  $L_{den}$  of road traffic noise per 5 dB(A) interval and when aircraft noise  $L_{den}$  is at a fixed value within the interval [40; 45 dB(A)].

■: partial road traffic noise annoyance; —: partial aircraft noise annoyance; ×: total annoyance due to combined road traffic and aircraft noises.

### 3.2 Road traffic noise combined with railway noise

When  $L_{den}$  of road traffic noise was identical to  $L_{den}$  of railway noise, no significant differences were observed between the two mean partial annoyance ratings. The results indicated thus no railway bonus.

For most of the studied situations of the combined road traffic and railway noise sources, total annoyance ratings were not significantly different from the maximum partial annoyance ratings. Among the different situations under study, only one case of synergistic effect was identified when road traffic noise ranged between 70 and 75 dB(A) and the railway noise level between 60 and 65 dB(A). Therefore, it can be expected that the strongest component model will allow in general a good calculation of total annoyance due to combined road traffic and railway noises.

### 3.3 Road traffic noise combined with both railway noise and aircraft noise

For this combination of three transportation noise sources, total annoyance was equal to the maximum partial annoyance. Actually, t-test analyses showed that total annoyance ratings were not significantly different from the maximum partial annoyance ratings. The strongest component model from the literature should thus allow a good calculation of total annoyance ratings.

## 4. Main total annoyance models from the literature

Total annoyance models are usually grouped into two categories: psychophysical models and perceptual models. Psychophysical models link total annoyance ratings to one or several noise metrics, and perceptual models link total annoyance ratings to perceptual data, such as partial annoyance ratings (Berglund and Nilsson, 1997).

265

#### 266 4.1 Presentation of total annoyance models from the literature

267 In the current study, 10 main total annoyance models from the literature (6 psychophysical ones and  
268 4 perceptual ones) are considered. They are briefly described below using the following notations:

269  $A_{Total}$ : total annoyance,

270  $A_i$ : partial annoyance due to noise source  $i$  heard within the combination or its specific annoyance when  
271 noise source  $i$  is heard in isolation (when the other noise sources of the combination do not emit any  
272 noise),

273  $L_{Total}$ : total noise level for the combined noises,

274  $L_i$ : noise level for noise source  $i$ .

275

#### 276 **Psychophysical models**

277 As these models are based on mean sound pressure levels, these variables have to explain a  
278 significant part of annoyance ratings in order to make the models meaningful. This is not always the  
279 case in socio-acoustic surveys dealing with noise annoyance assessment (e.g. Pierrette *et al.*, 2012a and  
280 2012b).

281

#### 282 **The energy summation model**

283 This model links total annoyance to total noise level:

$$284 A_{Total} = a L_{Total} + b \quad (1)$$

285 This equation leads to the same mathematical expression of annoyance due to each noise source,  
286 whatever the noise sources considered, *i.e.* different noise sources cause the same annoyance at the same  
287 noise level  $L$ . Such a result has not been validated in various field studies. For example, Miedema and  
288 Oudshoorn (2001) showed that, for the same  $L_{den}$ , annoyance ratings due to road traffic, aircraft and  
289 railway noises do not lead to the same relationships.

290

#### 291 **The independent effect model**

292 This model expresses total annoyance as a function of the sound pressure level of each combined  
293 noise source:

$$294 A_{Total} = \sum_{i=1}^n a_i L_i \quad (2)$$

295 Compared to the energy summation model, this model allows that changes due to one noise source  
296 could influence total annoyance ratings as this model allows different noise sources to have independent  
297 contributions to total annoyance. As no potential interaction effect between the combined noise sources  
298 is taken into account, phenomena such as the synergistic effect will be neglected by the model.

299

#### 300 **The energy difference model**

301 This model, established for two combined noise sources, expresses total annoyance as a function of  
302 the total sound pressure level and the difference in sound pressure levels of both noise sources.

303

$$304 A_{Total} = a L_{Total} + b/L_1 - L_2/+c \quad (3)$$

305 The application of this model is thus limited to combinations of two noise sources. This model  
306 proposed by Taylor (1982) corresponds to a modification of the energy summation model. The

307 difference between the two sound pressure levels has been introduced to take into account potential  
 308 interaction effects between the combined noise sources. But this model leads to the same relationships  
 309 between each noise source in isolation and their respective annoyance, which is not true (e.g. Miedema  
 310 and Oudshoorn, 2001 for transportation noise sources).

### 312 **The mixed model**

313 Morel *et al.* (2012) proposed a model of total annoyance as a function of the sound pressure level of  
 314 each source and the absolute value of the difference between these levels. The purpose is to take into  
 315 account potential interaction effects between combined noise sources.

$$316 \quad A_{Total} = a_1 L_1 + a_2 L_2 + b|L_1 - L_2| + c \quad (4)$$

317 As for the previous model, the application of this model is limited to two combined noise sources.  
 318 But contrary to the previous one, this model might lead to different relationships between each noise  
 319 source and the corresponding annoyance.

### 321 **The quantitative model**

322 This model was proposed by Vos (1992). Annoyance depends on an overall noise index  $L_t$ . This  
 323 index corresponds to the sum of a corrected sound pressure level from each source. The correction is  
 324 applied in such a way that the corrected sound pressure level leads to the same annoyance due to a  
 325 source of the combination chosen as a reference.

326 In the case of a combination of different noise sources, the annoyance  $A_i$  due to a source  $i$  is  
 327 calculated from its sound pressure level  $L_i$ :

$$328 \quad A_i = a_i L_i + b_i \quad (5)$$

329 The annoyance due to the reference source at a sound pressure level  $L_{ref}$  is denoted by  $A_{ref}$ , and  
 330 given by the following equation:

$$331 \quad A_{ref} = a_{ref} L_{ref} + b_{ref} \quad (6)$$

332 A penalty is added to the sound pressure level  $L_i$  of the source  $i$  to provide the sound pressure level  
 333 of the equally annoying reference noise source. This penalty  $P_i$ , obtained by equalizing the two previous  
 334 equations, is given by:

$$335 \quad P_i = \frac{b_i - b_{ref} + (a_i - a_{ref}) * L_i}{a_{ref}} \quad (7)$$

336 Such penalty  $P_i$  allows the noise from each source to be translated into the equally annoying sound  
 337 pressure level of the reference source; the overall noise index  $L_t$  is then obtained by summing all sound  
 338 pressure levels:

$$339 \quad L_t = k * \log \left( 10^{\frac{L_{ref}}{k}} + \sum_{i=1}^n 10^{\frac{L_i + P_i}{k}} \right) \quad (8)$$

340 where  $k$  is a parameter to be adjusted,  $n$  is the number of noise sources combined with the reference  
 341 source. Vos (1992) proposed to consider road traffic noise as the reference source, and found that a  $k$   
 342 value equal to 15 optimized the calculation.

### 344 **The annoyance equivalents model**

345

346 The annoyance equivalents model stemmed from Miedema's work (Miedema, 2004), which  
 347 includes the generalization of the quantitative model.

348 From multi-level regressions applied on data from different surveys dealing with noise annoyance  
 349 due to transportation noise sources, Miedema and Oudshoorn (2001) had proposed annoyance equations  
 350 for each transportation noise source. These equations link the sound pressure level  $L$  ( $L_{den}$ , or  $L_{dn}$  the  
 351 day-night level) of each noise source to each respondent's annoyance rating as follows:

$$352 \quad A_{ij} = \beta_0 + \beta_1 L + u_{0j} + \epsilon_{ij} \quad (9)$$

353 where  $i$  represents the respondent and  $j$  represents the survey. For survey  $j$ , the intercept is  $\beta_0 + u_{0j}$ . The  
 354 terms  $u_{0j}$  and  $\epsilon_{ij}$  are error terms which follow a normal distribution.

355 From these annoyance equations considered without the intercept term  $u_{0j}$ , Miedema (2004) set the  
 356 following equations, based on  $L_{den}$ , for road traffic, railway and aircraft noises as indicated by the  
 357 respective subscripts Road, Air and Rail:

$$358 \quad A_{Road} = -107,0 + 2,22 * L_{den,Road} \quad (10)$$

$$359 \quad A_{Air} = 2,17 * L_{den,Air} - 91,4 \quad (11)$$

$$360 \quad A_{Rail} = 2,10 * L_{den,Rail} - 110,1 \quad (12)$$

361 Miedema (2004) considered road traffic noise as a reference source and calculated a correction term  
 362 to be applied to the sound pressure level of the other sources.

363 The railway noise level and the aircraft noise level are then corrected to simulate the level of road  
 364 traffic noise that would generate the same annoyance rating:

$$365 \quad L'_{Rail} = \frac{(A_{Rail}+107,0)}{2,22} = \frac{(-3,1+2,10*L_{den,Rail})}{2,22} \quad (13)$$

$$366 \quad L'_{Air} = \frac{(A_{Air}+107,0)}{2,22} = \frac{(15,6+2,17*L_{den,Air})}{2,22} \quad (14)$$

367 The overall noise index of the annoyance equivalents model is then for road traffic noise combined  
 368 with aircraft noise:

$$369 \quad L'_{Road+Air} = 10 * \log(10^{\frac{L_{den,Road}}{10}} + 10^{\frac{L'_{Air}}{10}}), \quad (15)$$

370 for road traffic noise combined with railway noise:

$$371 \quad L'_{Road+Rail} = 10 * \log(10^{\frac{L_{den,Road}}{10}} + 10^{\frac{L'_{Rail}}{10}}), \quad (16)$$

372 and for road traffic noise combined both with aircraft noise and railway noise:

$$373 \quad L'_{Road+Air+Rail} = 10 * \log(10^{\frac{L_{den,Road}}{10}} + 10^{\frac{L'_{Air}}{10}} + 10^{\frac{L'_{Rail}}{10}}). \quad (17)$$

## 374 **Perceptual models**

### 375 **The strongest component model**

376 This model considers that total annoyance due to combined noise sources is equal to the most  
 377 annoying source within the combination of  $n$  noise sources (Berglund *et al.*, 1981):

$$378 \quad A_{Total} = \max_{i=1,n}(A_i) \quad (18)$$

379 This perceptual model is generally known to lead to a good calculation of total annoyance (*e.g.*  
 380 Botteldooren and Verkeyn, 2002; Pierrette *et al.* 2012a and 2012b). But some studies reported a weak

383 quality (cf. Gille *et al.* 2019; Lechner *et al.* 2019). Due to its mathematical formulation, it is not able to  
384 account for perceptual mechanisms such as synergistic effect.

385 Considering the perceptual mechanisms highlighted in the studied field data, we may expect a good  
386 correlation between annoyance calculated from this model and the measured total annoyance.

### 388 **The linear regression model**

389 The total annoyance is expressed as a weighted sum of the annoyance due to each combined noise  
390 source  $i$ :

$$391 A_{Total} = \sum_i w_i A_i \quad (19)$$

392 where  $w_i$  is the weighting applied to the annoyance due to each source  $i$ . This model is a perceptual form  
393 of the independent effect model previously presented. According to Berglund and Nilsson (2000), the  
394 weighting  $w_i$  can be explained by the time of appearance of the source. However, (Botteldooren and  
395 Verkeyn, 2002) pointed out that this explanation of the weighting by the duration of noise occurrence is  
396 not valid for all sources. Botteldooren and Verkeyn (2002) found that this model was a less effective  
397 predictor than the strongest component model.

398 However, the weighted coefficients of annoyance due to each noise source are interesting as the weights  
399 can highlight the relative influence of each noise source to total annoyance. This can not be pointed out  
400 by the strongest component model.

### 402 **The mixed model**

403 This model is limited to two combined noise source situations. It is based on the principle of the  
404 previous model and considers in addition an interaction term:

$$405 A_{Total} = a_1 A_1 + a_2 A_2 + b/A_1 - A_2/+c \quad (20)$$

406 This model is a perceptual form of the mixed model previously presented among the  
407 psychophysical models. This perceptual model assumes that people are able to separately identify and  
408 assess the different noise sources in their environment. Their assessment is adjusted according to which  
409 noise source appears to be more annoying. As the linear regression model, the mixed model may allow  
410 different contributions of annoyance due to each noise source to the total annoyance to be taken into  
411 account. The potential theoretical improvement compared to the linear regression and the strongest  
412 component models lies in the interaction term which may allow perceptual mechanisms to be accounted  
413 for. Pierrette *et al.* (2012a and 2012b) showed a significant interaction term in a combined road traffic  
414 and industrial noise exposure where mean total annoyance ratings were equal to mean road traffic noise  
415 annoyance ratings (average over all respondents). The significant interaction term was explained by the  
416 fact that nearly one third of the respondents judged the soft permanent industrial noise as annoying as  
417 the loud intermittent road traffic noise. Contrary to the perceptual mixed model, the strongest  
418 component model was not able to account for the point of view of one third of the respondents.

### 420 **The vector summation model**

421 As the previous one, this model is limited to the case of two combined noise sources. It is  
422 calculated using annoyance due to each noise source within the combination, and an interaction term,  
423 denoted by  $\alpha_{12}$ :

$$424 A_{Total} = \sqrt{A_1^2 + A_2^2 + 2 * A_1 * A_2 \cos(\alpha_{12})} \quad (21)$$

425 By iteration, Berglund *et al.* (1981) found that the model better predicted total annoyance when the  
426 term  $\alpha_{12}$  is  $90^\circ$ , i.e. when the interaction term is zero, despite a slight overestimation of annoyance by  
427 the model (*cf.* Botteldooren and Verkeyn, 2002).

428 In order to determine the angle  $\alpha_{12}$  which optimizes the calculation of total annoyance, Morel  
429 (2012) proposed to calculate a value of  $\alpha_o$  from each triplet of ratings of each respondent ( $A_1, A_2, A_{Total}$ ),  
430 and then to average all values of  $\alpha_o$  over the respondents. The formula for  $\alpha_o$  is as follows:

$$431 \quad \alpha_o = \cos^{-1}\left(\frac{A_{Total}^2 - (A_1^2 + A_2^2)}{2A_1A_2}\right) \quad (22)$$

432 Thus, the interaction term has to be determined for every new combined noise study, in order to  
433 improve the performance of this model. However, given the absence of weightings for annoyance due to  
434 each noise source, the model does not allow different contributions of each noise source to total  
435 annoyance to be taken into account.

#### 437 4.2 Relevance of total annoyance models

438 The relevance of the total noise annoyance models was investigated using data from the French  
439 survey.

440 Linear regression analyses were carried out by fitting each model to the survey data. The regression  
441 analyses used respondents' total annoyance ratings,  $L_{den}$  values defining their noise exposure or their  
442 partial annoyance ratings from the French survey. Results of the different regression analyses are  
443 displayed in the three following tables (Tables 3 to 5). In particular, results for the total noise annoyance  
444 models considered for the combination of road traffic noise and aircraft noise are displayed in Table 3,  
445 for the combination of road traffic noise combined with railway noise in Table 4, and for the  
446 combination of the three transportation noise sources (road traffic, railway and aircraft noises) in Table  
447 5.

448 The sample size of the survey data is not big enough to use the equations displayed in these tables  
449 in further studies. The purpose of showing them is rather to highlight the fact that some coefficients of  
450 the obtained regressions may be not statistically significant, and thus the corresponding variables appear  
451 to be not relevant to be considered in total annoyance models. Such information is useful for further  
452 research works.

453 In all three tables, significant regression coefficients ( $p < 0.05$ ) are indicated using a superscript. The  
454 adjusted coefficient of determination  $R^2_{adjusted}$  resulting from the fit of each model to the measured data  
455 is given. In addition, a correlation analysis between the total annoyance ratings calculated by each  
456 model and the measured total annoyance ratings is also given, with the correlation coefficient, and the  
457 intercept and slope of the corresponding regression line, for further indications on the model  
458 performances: a perfect calculation by a model would lead to values of the intercept, slope, correlation  
459 coefficient respectively equal to 0, 1 and 1, *i.e.* all the dots would be perfectly lined up on the bisector of  
460 the plan. For the quantitative and annoyance equivalents models, the fitting was applied between the  
461 overall noise index and the measured total annoyance ratings. This was carried out as an attempt of  
462 improving the goodness-of-fit of these two models. For the vector summation model, the angle is  
463 optimized according to the procedure described in (Morel, 2012). The obtained angle value is given in  
464 each of the three tables.

465 For the different combined transportation noise situations under study, perceptual total annoyance  
466 models lead to better results ( $R^2_{adjusted}$  greater than 0.7 for two combined noise exposures, and greater  
467 than 0.5 for the three combined transportation noise exposure) compared to psychophysical total  
468 annoyance models ( $R^2_{adjusted}$  generally below 0.1).

**Table 3.** Total annoyance models for combined road traffic and aircraft noises.  $A_{Road}$ : road traffic noise annoyance;  $A_{Air}$ : aircraft noise annoyance;  $A_{Total}$ : total annoyance.  $L_{den, Total}$ : total  $L_{den}$ ;  $L_{den, Road}$ :  $L_{den}$  for road traffic noise;  $L_{den, Air}$ :  $L_{den}$  for aircraft noise;  $R^2_{adjusted}$ : the adjusted determination coefficient; Intercept, slope and correlation coefficient linked to the regression between measured and calculated total annoyances;  $L_t$ : overall noise index for the quantitative and annoyance equivalents models;  $k$ : parameter in the quantitative model;  $\alpha$ : angle in the vector summation model;  $a$ :  $p < 0.05$ .

<i>Psychophysical model</i>	<i>Equation</i>	$R^2_{adjusted}$	<i>Intercept</i>	<i>Slope</i>	<i>correlation</i>
Energy summation	$A_{Total} = 0,097^a * L_{den, Total} - 0,883$	0,028 <sup>a</sup>	4,648 <sup>a</sup>	0,032 <sup>a</sup>	0,180 <sup>a</sup>
Independent effects	$A_{Total} = 0,047 * L_{den, Road} + 0,139^a * L_{den, Air} - 4,121$	0,085 <sup>a</sup>	4,404 <sup>a</sup>	0,094 <sup>a</sup>	0,307 <sup>a</sup>
Energy difference	$A_{Total} = 0,184^a * L_{den, Total} - 0,126^a *  L_{den, Road} - L_{den, Air}  - 4,260$	0,090 <sup>a</sup>	4,368 <sup>a</sup>	0,099 <sup>a</sup>	0,315 <sup>a</sup>
Mixed	$A_{Total} = 0,047 * L_{den, Road} + 0,139^a * L_{den, Air} - 4,121 + 0,001 *  L_{den, Road} - L_{den, Air} $	0,085 <sup>a</sup>	4,404 <sup>a</sup>	0,094 <sup>a</sup>	0,307 <sup>a</sup>
Quantitative	$A_{Road} = 0,111^a * L_{den, Road} - 2,012$ ; $R^2_{adjusted} = 0,043^a$	$A_{Air} = 0,209^a * L_{den, Air} - 5,098^a$ ; $R^2_{adjusted} = 0,152^a$			
	$k=15: A_{Total} = 0,117^a * L_t - 2,620$	0,095 <sup>a</sup>	4,318 <sup>a</sup>	0,099 <sup>a</sup>	0,315 <sup>a</sup>
	$k=10: A_{Total} = 0,113^a * L_t - 2,236$	0,097 <sup>a</sup>	4,320 <sup>a</sup>	0,101 <sup>a</sup>	0,318 <sup>a</sup>
Annoyance equivalents	$A_{Total} = 0,123^a * L_t - 2,475$	0,045 <sup>a</sup>	4,595 <sup>a</sup>	0,050 <sup>a</sup>	0,223 <sup>a</sup>
<i>Perceptual model</i>	<i>Equation</i>	$R^2_{adjusted}$	<i>Intercept</i>	<i>Slope</i>	<i>correlation</i>
Strongest component	$A_{Total} = 0.840^a * \max(A_{Road}; A_{Air}) + 1.194^a$	0,754 <sup>a</sup>	0,194 <sup>a</sup>	0,840 <sup>a</sup>	0,869 <sup>a</sup>
Linear regression	$A_{Total} = 0,521^a * A_{Road} + 0,482^a * A_{Air} + 0,412^a$	0,760 <sup>a</sup>	1,145 <sup>a</sup>	0,762 <sup>a</sup>	0,873 <sup>a</sup>
Mixed	$A_{Total} = 0,491^a * A_{Road} + 0,497^a * A_{Air} + 0,220^a *  A_{Road} - A_{Air}  + 0,105$	0,784 <sup>a</sup>	1,025 <sup>a</sup>	0,787 <sup>a</sup>	0,887 <sup>a</sup>
Vector summation	$A_{Total} = \sqrt{A_{Road}^2 + A_{Air}^2 + 2 * A_{Road} * A_{Air} \cos(\alpha)}$ $\alpha = 115,3^\circ$	0,775 <sup>a</sup>	1,091 <sup>a</sup>	0,835 <sup>a</sup>	0,881 <sup>a</sup>

**Table 4.** Total annoyance model for combined road traffic and railway noises.  $A_{Road}$ : road traffic noise annoyance;  $A_{Rail}$ : railway noise annoyance;  $A_{Total}$ : total annoyance.  $L_{den, Total}$ : total  $L_{den}$ ;  $L_{den, Road}$ :  $L_{den}$  for road traffic noise;  $L_{den, Rail}$ :  $L_{den}$  for railway noise;  $R^2_{adjusted}$ : the adjusted determination coefficient; Intercept, slope and correlation coefficient linked to the regression between measured and calculated total annoyances;  $L_t$ : overall noise index;  $k$ : parameter;  $\alpha$ : angle;  $a$ :  $p < 0.05$ .

<i>Psychophysical model</i>	<i>Equation</i>	$R^2_{adjusted}$	<i>Intercept</i>	<i>Slope</i>	<i>correlation</i>
Energy summation	$A_{Total} = 0,147^a * L_{den, Total} - 5,162^a$	0,062 <sup>a</sup>	5,005 <sup>a</sup>	0,065 <sup>a</sup>	0,256 <sup>a</sup>
Independent effects	$A_{Total} = 0,134^a * L_{den, Road} + 0,017 * L_{den, Rail} - 5,042^a$	0,065 <sup>a</sup>	4,979 <sup>a</sup>	0,071 <sup>a</sup>	0,267 <sup>a</sup>
Energy difference	$A_{Total} = 0,143^a * L_{den, Total} + 0,032 *  L_{den, Road} - L_{den, Rail}  - 5,123^a$	0,065 <sup>a</sup>	4,970 <sup>a</sup>	0,071 <sup>a</sup>	0,267 <sup>a</sup>
Mixed	$A_{Total} = 0,086^a * L_{den, Road} + 0,072^a * L_{den, Rail} + 0,082^a *  L_{den, Road} - L_{den, Rail}  - 5,881^a$	0,076 <sup>a</sup>	4,849 <sup>a</sup>	0,084 <sup>a</sup>	0,291 <sup>a</sup>
Quantitative	$A_{Road} = 0,155^a * L_{den, Road} - 5,933^a$ ; $R^2_{adjusted} = 0,088^a$	$A_{Rail} = 0,119^a * L_{den, Rail} - 3,455^a$ ; $R^2_{adjusted} = 0,089^a$			
	$k=15: A_{Total} = 0,199^a * L_t - 9,307^a$	0,105 <sup>a</sup>	4,788 <sup>a</sup>	0,108 <sup>a</sup>	0,329 <sup>a</sup>
	$k=10: A_{Total} = 0,198^a * L_t - 8,927^a$	0,105 <sup>a</sup>	4,803 <sup>a</sup>	0,108 <sup>a</sup>	0,328 <sup>a</sup>
Annoyance equivalents	$A_{Total} = 0,156^a * L_t - 5,598^a$	0,070 <sup>a</sup>	4,997 <sup>a</sup>	0,074 <sup>a</sup>	0,271 <sup>a</sup>
<i>Perceptual model</i>	<i>Equation</i>	$R^2_{adjusted}$	<i>Intercept</i>	<i>Slope</i>	<i>correlation</i>
Strongest component	$A_{Total} = 0,884^a * \max(A_{Road}; A_{Rail}) + 0,769^a$	0,843 <sup>a</sup>	0,769 <sup>a</sup>	0,885 <sup>a</sup>	0,918 <sup>a</sup>
Linear regression	$A_{Total} = 0,562^a * A_{Road} + 0,422^a * A_{Rail} + 0,923^a$	0,736 <sup>a</sup>	1,405 <sup>a</sup>	0,738 <sup>a</sup>	0,859 <sup>a</sup>
Mixed	$A_{Total} = 0,455^a * A_{Road} + 0,513^a * A_{Rail} + 0,436^a *  A_{Road} - A_{Rail}  + 0,152$	0,844 <sup>a</sup>	0,829 <sup>a</sup>	0,846 <sup>a</sup>	0,919 <sup>a</sup>
Vector summation	$A_{Total} = \sqrt{A_{Road}^2 + A_{Rail}^2 + 2 * A_{Road} * A_{Rail} * \cos(\alpha)}$ $\alpha = 112,8^\circ$	0,842 <sup>a</sup>	0,743 <sup>a</sup>	0,891 <sup>a</sup>	0,918 <sup>a</sup>

**Table 5.** Total annoyance model for combined road traffic, railway and aircraft noises.  $A_{Road}$ : road traffic noise annoyance;  $A_{Air}$ : aircraft noise annoyance;  $A_{Rail}$ : railway noise annoyance;  $A_{Total}$ : total annoyance.  $L_{den, Total}$ : total  $L_{den}$ ;  $L_{den, Road}$ :  $L_{den}$  for road traffic noise;  $L_{den, Air}$ :  $L_{den}$  for aircraft noise; ;  $L_{den, Rail}$ :  $L_{den}$  for railway noise ;  $R^2_{adjusted}$ : the adjusted determination coefficient; Intercept, slope and correlation coefficient linked to the regression between measured and the calculated total annoyances;  $L_t$ : overall noise index for the quantitative and annoyance equivalents models;  $k$ : parameter in the quantitative model;  $\alpha$ : angle in the vector summation model;  $a$ :  $p < 0.05$ .

<i>Psychophysical model</i>	<i>Equation</i>	$R^2_{adjusted}$	<i>Intercept</i>	<i>Slope</i>	<i>correlation</i>
Energy summation	$A_{Total} = 0,003 * L_{den, Total} + 6,389^a$	<0,001	6,581 <sup>a</sup>	<0,001	0,008
Independent effects	$A_{Total} = 0,017 * L_{den, Road} + 0,112^a * L_{den, Air} - 0,045 * L_{den, Rail} + 1,736$	0,085 <sup>a</sup>	5,878 <sup>a</sup>	0,100 <sup>a</sup>	0,315 <sup>a</sup>
Quantitative	$A_{Road} = 0,057^a * L_{den, Road} + 1,867$ ; $R^2_{adjusted} = 0,041^a$				
	$A_{Rail} = 0,067^a * L_{den, Rail} + 0,246$ ; $R^2_{adjusted} = 0,039^a$	$A_{Air} = 0,109^a * L_{den, Air} + 0,446$ ; $R^2_{adjusted} = 0,067^a$			
	$k=10: A_{Total} = 0,061 * L_t + 1,523$	<0,001	6,589 <sup>a</sup>	<0,001	0,021
	$k=15: A_{Total} = 0,062 * L_t + 1,396$	<0,001	6,584 <sup>a</sup>	<0,001	0,029
Annoyance equivalents	$A_{Total} = 0,056 * L_t + 2,876$	0,017	6,447 <sup>a</sup>	0,018	0,133
<i>Perceptual model</i>	<i>Equation</i>	$R^2_{adjusted}$	<i>Intercept</i>	<i>Slope</i>	<i>correlation</i>
Strongest component	$A_{Total} = 0,860^a * \max(A_{Road} ; A_{Air} ; A_{Rail}) + 0,487$	0,594 <sup>a</sup>	2,533 <sup>a</sup>	0,691 <sup>a</sup>	0,771 <sup>a</sup>
Linear regression	$A_{Total} = 0,594^a * A_{Air} + 0,275^a * A_{Road} - 0,006 * A_{Rail} + 1,241^a$	0,566 <sup>a</sup>	2,808 <sup>a</sup>	0,573 <sup>a</sup>	0,757 <sup>a</sup>

469 Looking into the details in each of these 3 tables, it appears that energy summation is  
470 the worst of the psychophysical models. The annoyance equivalents model has no  
471 significant coefficients to describe total annoyance due to three combined transportation  
472 noise exposure.

473 As expected from the analysis on perceptual mechanisms associated with total  
474 annoyance judgments (*cf.* section 3), the strongest component model provided a good  
475 calculation of total annoyance for all the studied combined transportation noise exposures.  
476 This model generally accounts well for total annoyance felt by people. This is in agreement  
477 with t-tests analyses carried out in section 3 between total annoyance ratings and the  
478 maximum partial annoyance ratings.

479 All the variables of the perceptual linear regression and mixed models were comprised  
480 between 0 and 10. Their associated coefficients thus allowed contributions of each variable  
481 to total annoyance to be considered. These two perceptual models gave interesting  
482 information on the contribution of each partial annoyance to total annoyance for the  
483 combined transportation noise exposures studied.

484 In the case of combined road traffic and aircraft noise exposure, partial road traffic  
485 noise annoyance and partial aircraft noise annoyance nearly equally contributed to total  
486 annoyance within the perceptual linear and mixed models. The mixed model indicated a  
487 significant interaction term between the two partial annoyances. This term moderately  
488 contributed to total annoyance compared to each partial annoyance. The relevance of this  
489 interaction term is also observed in the vector summation model with an optimized angle  
490 different from 90°. Thus the strongest component model highlighted the main trend: total  
491 annoyance equalized the maximum partial annoyance which might be road traffic noise  
492 annoyance or aircraft noise annoyance depending on the noise exposure level of the noise  
493 sources. The linear regression and mixed models highlighted in details contributions of each  
494 partial annoyance to total annoyance. The relative contributions of each partial annoyance  
495 and the interaction term might be explained by the fact that the 212 respondents exposed to  
496 aircraft and road traffic noises had different feelings regarding each noise source within the  
497 combined exposure: 55% of them quite agreed or agreed with the item “road traffic noise  
498 alone would be bearable” and 40% of them quite agreed or agreed with the item “aircraft  
499 noise alone would be bearable”. Thus with a good adjustment quality of model (*e.g.*  
500 adjusted determination coefficient values), the linear regression and the mixed models are  
501 able to give more information compared to the strongest component model.

502 In the case of the combined road traffic and railway noise exposure, the interaction term  
503 of the mixed model between partial road traffic noise annoyance and partial railway noise  
504 annoyance was significant and nearly equally contributed to total annoyance in comparison  
505 with partial annoyances. The relevance of the interaction term was also observed within the  
506 vector summation model with an optimized angle different from 90°. These close  
507 contributions of variables indicated by the linear regression and mixed models might be  
508 explained by the fact that among the 301 respondents 43% of them quite agreed or agreed  
509 with the item “road traffic noise alone would be bearable” and 53% of them quite agreed or  
510 agreed with the item “railway noise alone would be bearable”.

511 In the case of the exposure to the three combined transportation noises under study,  
512 partial railway noise annoyance did not contribute to total annoyance within the perceptual  
513 linear regression model as its coefficient was non-significant. Partial aircraft noise  
514 annoyance appeared to contribute more than partial road traffic noise annoyance to total  
515 annoyance. These respective contributions of partial annoyances to total annoyance might  
516 be explained by feelings expressed by the 189 respondents: 63% of them quite agreed or  
517 agreed with the item “railway noise alone would be bearable”, 60% of them quite agreed or  
518 agreed with the item “road traffic noise alone would be bearable”, and only 22% of them  
519 quite agreed or agreed with the item “aircraft noise alone would be bearable”.

## 520 5. Discussion

521  
522 The analysis of potential perceptual mechanisms related to total annoyance judgments  
523 revealed that total annoyance ratings did not in general differ from the maximum partial  
524 annoyance ratings. This was mainly observed for the different combined transportation  
525 noise source situations under study during the French socio-acoustic survey. This result is in  
526 agreement with literature findings dealing with combined transportation noise sources (*e.g.*  
527 Wothge *et al.*, 2017). Due to this effect, the strongest component model led to a good  
528 calculation of total annoyance.

529 For all the studied combined transportation noise exposures in the current work, the  
530 studied psychophysical total annoyance models based on  $L_{den}$  led to poor adjustment quality  
531 of total annoyance. The perceptual total annoyance models led to a better calculation of total  
532 annoyance. Such results agreed with literature findings on psychophysical total annoyance  
533 model assessment, for example Nguyen *et al.* (2012) for combined road traffic and aircraft  
534 noise exposure in Ho Chi Minh City and Hanoi, and Pierrette *et al.* (2012a and 2012b) for  
535 combined road traffic and industrial noise exposure in Lyon suburbs. Their respective  
536 findings showed that the strongest component model better calculated total annoyance.  
537 Lechner *et al.* (2019) obtained comparable results between 55 and 65 dB in the Alpine  
538 valleys. This range corresponded to the highest category of sound pressure level for the  
539 three combined transportation noise source situations they studied in Innsbrück. By  
540 considering the whole range of noise exposure in Innsbrück (from 35 up to 65dB), they  
541 highlighted an annoyance equivalents model, based on quadratic functions rather than linear  
542 regressions, with better results than the strongest component model. These different results  
543 highlighted the difficulty of defining a unique total annoyance model, and the need for more  
544 studies dealing with various combined noise situations and comparisons of existing total  
545 annoyance models.

546 In the current study, the other perceptual models, such as the linear regression, mixed  
547 and vector summation models, which consider partial annoyances and even potential  
548 interaction term as variables, gave an equally good or better calculation of total annoyance  
549 than the strongest component model. Specifically, the perceptual mixed model gave good  
550 results with interesting information on the relative contributions of partial annoyances and  
551 interaction term to total annoyance. The highlighted contributions were explained by  
552 feelings expressed by respondents about each noise source within the combination. This is

553 in agreement with Pierrette *et al.* (2012a and 2012b) dealing with road traffic noise  
554 combined with a permanent industrial noise. They pointed out the good quality of the  
555 strongest component model to account for the dominant source effect due to road traffic  
556 noise.

557 Moreover, the perceptual mixed model enables a good calculation of total annoyance  
558 and highlights contributions of each partial annoyance and of the interaction term. This term  
559 accounts for the fact that one third of respondents found the soft industrial noise as annoying  
560 as the dominant road traffic noise because the permanent industrial noise was still present  
561 when the road traffic was low.

562 A specific attention to the combined road traffic and railway noise source situations  
563 highlighted no significant differences between the two partial annoyance ratings when the  
564 two transportation noise exposures were at identical  $L_{den}$  values. This result thus indicated  
565 no railway bonus, such as the bonus of 5 dB which has been applied to railway noise in  
566 various European Union countries (*e.g.* France, Germany, Switzerland). This result  
567 contradicts the railway bonus identified in previous studies (*e.g.* Miedema and Oudshoorn,  
568 2001), and corroborates more recent findings from the literature showing no rail bonus in  
569 some European countries and Asian countries (*e.g.* Öhrström *et al.*, 2007; Lam *et al.*, 2009;  
570 Lechner *et al.*, 2019; Brink *et al.*, 2019). For example in a Swiss survey, Brink *et al.* (2019)  
571 highlighted no railway bonus effect on the percentage of highly annoyed (%HA) Swiss  
572 people when  $L_{den}$  from railway traffic was above 45 dB(A) despite the well-known railway-  
573 friendliness in Switzerland.

574 For the situation where all three combined transportation noise sources were studied,  
575 people expressed more negative feelings towards aircraft noise exposure close to Orly  
576 airport than towards higher sound pressure levels from railway and road traffic noises. Total  
577 annoyance was better calculated by perceptual models, the strongest component model and  
578 linear model. This latter highlighted a stronger contribution of aircraft noise annoyance to  
579 total annoyance than road traffic noise annoyance, and no contribution of railway noise  
580 annoyance. Such results for combined transportation noise sources were also observed in the  
581 vicinity of the Frankfurt airport by Wothge *et al.* (2017) who noticed the main contribution  
582 of aircraft noise and a minor contribution of the second transportation noise source (road  
583 traffic or railway noise) within the combination.

584 The current study has shown that perceptual total annoyance models better performed  
585 than psychophysical ones to estimate total annoyance. In particular, the linear regression  
586 model and the mixed model fitted well to the feelings expressed by people towards each  
587 noise source within the combination. Such results were obtained for the different combined  
588 transportation noise source situations in French cities (combined road traffic and aircraft  
589 noises, combined road traffic and railway noises, road traffic noise combined with both  
590 aircraft and railway noises). Klein *et al.* (2017), from laboratory data of combined road  
591 traffic and tramway noises, and also Gille and Marquis-Favre (2019), from field data of  
592 combined aircraft and road traffic noises, have shown that applying such perceptual models  
593 on predicted partial annoyances rather than measured partial annoyances allowed total  
594 annoyance to be better predicted in comparison with psychophysical models based on  $L_{den}$ .  
595 This constitutes highly interesting perspectives.

596 Furthermore, the current study highlighted that 70% of the survey respondents declared  
597 themselves to be sensitive or very sensitive to noise. This was in agreement with Lechner  
598 and Schnaiter's results obtained from a sample of 545 inhabitants of the Alpine valleys  
599 (Lechner and Schnaiter, 2019). This was also in agreement with the structural equation  
600 analysis carried out on the data of this French survey; the analysis highlighted the great  
601 contribution of noise sensitivity to annoyance models (e.g. Gille *et al.*, 2017).

602 Relevant perspectives would be to consider the benefit of taking into account noise  
603 sensitivity both in predicted partial annoyance models, and in predicted perceptual total  
604 annoyance models using predicted partial annoyance values as variables (cf. Gille and  
605 Marquis-Favre, 2019). Actually, it would be interesting in further works to test, for different  
606 population samples and combined noise situations, perceptual total annoyance models based  
607 on partial annoyance values predicted from models using noise sensitivity. If such testing  
608 confirms enhancement of total annoyance prediction for different combined noise situations,  
609 it might have interesting perspectives for regulatory applications.

## 610 **6. Conclusion**

611 Total annoyance prediction is still a complex scientific problem to be addressed. As a  
612 consequence, there is a lack of national regulations. More endeavors on this topic are thus  
613 needed. Although different total annoyance models exist in the literature, they were very  
614 rarely assessed using field annoyance data. The current work aims to compare them using  
615 data of annoyance due to different French urban situations of two, or three, combined  
616 transportation noise sources. The noises under consideration were road traffic, railway and  
617 aircraft noises. Appraisal of main total annoyance models highlighted those able to account  
618 for combined transportation noise annoyance in cities. Perceptual total annoyance models,  
619 based on annoyance due to each transportation noise source, better performed total  
620 annoyance estimation than psychophysical total annoyance models based on the  $L_{den}$  index.  
621 The dominant source effect mainly explained total annoyance judgments from French  
622 people exposed to combined noises. For that reason, the strongest component model led to a  
623 good calculation of mean total annoyance ratings. But perceptual models, such as the linear  
624 regression and mixed models, better explained total annoyance judgments from residents as  
625 they account well for the feeling expressed by people towards each combined noise source.  
626 More investigations are needed, in particular to assess whether applying such perceptual  
627 models on predicted partial annoyances rather than measured partial annoyances might be  
628 successful, as it has been highlighted in the literature for some combined noise situations.

629

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