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Effectively hearing natural sounds is a robust contributor to positive outdoor sound perception in the everyday living environment

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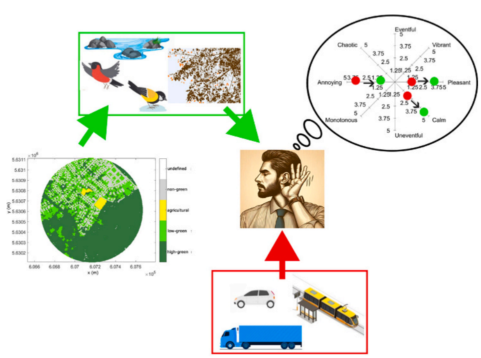
HIGHLIGHTS

- Large-scale soundwalks (n = 4465) conducted in residential environments
- Natural sounds boost pleasantness and calmness, and reduce annoyance.
- Natural sounds improve soundscapes even with prominent traffic noise.
- Greenery in wider area helps people effectively hear natural sounds.

GRAPHICAL ABSTRACT



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ABSTRACT

Natural sounds are known for their positive affective and restorative effects on people, as well as their ability to enhance soundscapes dominated by technical sounds. While small-scale experiments have demonstrated these benefits, their real-world applicability remains less explored. This study, part of a large-scale citizen science project called "De Oorzaak", analyzed data from 4665 participants who completed soundwalks, revealing that effectively hearing natural sounds strongly predicts positive soundscape experiences. The impact of natural sounds on pleasantness, calmness, and annoyance is limited when hearing traffic noise is very high or low, but becomes strong at intermediate levels, common in dense urban areas. Land use also plays a key role: green infrastructure identified by the Flemish Green Maps —including treedense areas, low-greenery zones, and farmland—greatly increases the likelihood of perceiving natural sounds. Notably, green features within a 500 m radius matter more than those immediately nearby. This larger area may serve as a more significant source of natural sounds capable of reaching the listener and being noticed. The provision of natural sounds can therefore be considered as an important and robust ecosystem service of green infrastructure.

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1. Introduction

Natural sounds are in general positively perceived by people and induce relaxation. Alvarsson et al. (2010) showed that exposure to (pleasantly rated) nature sounds led to faster physiological recovery from psychological stress compared to exposure to technical sounds. Krzywicka and Byrka (2017) found that their participants assigned stronger restorative qualities to top natural sounds compared to highly rated urban sounds. Jo et al. (2019) demonstrated that forest-derived auditory stimulation induced physiological and psychological relaxation effects in people. Ratcliffe (2021) concluded that nature sound, even when isolated from other sensory modalities, are most often positively affectively appraised and perceived as restorative. Buxton et al. (2021) affirmed that natural sounds improve health, increase positive affect, and lower stress and annoyance as a conclusion from their national park study. Uebel et al. (2021) found that park soundscapes are able to offer perceived restoration. Chen and Kang (2023) showed that natural sounds encourage social interactions in urban parks. Liu et al. (2024) showed that natural sounds can positively influence stress recovery, as evidenced by changes in EEG patterns. Korpilo et al. (2024) pointed at a robust connection between stress recovery and especially soundscape experiences in neighborhood nature. Van Renterghem (2019) provided explaining mechanisms why natural sounds work for people, embedded in the overarching framework of positive human-nature interactions.

Vegetative features of sufficient size can serve as sources of natural sounds. They generate sounds inherent to their structure, such as the rustling of leaves. Vegetation further attracts or provides habitats for sound-producing organisms such as birds and insects. Also water-related sounds—such as rain, raindrops on leaves, and flowing or falling water— contribute significantly to creating natural soundscapes. These sounds, commonly categorized as either biophony and geophony (Pijanowski et al., 2011), are typically highly valued by people, depending on the context. Bird songs often score best (Yang and Kang, 2005; Hong and Jeon, 2013; Krzywicka and Byrka, 2017; Van Renterghem et al., 2020; Uebel et al., 2021), but in the work of Guastavino (2006), natural sounds related to wind appeared to be top rated. Following the analysis by Buxton et al. (2021), water feature sounds had the largest effect size for health and positive affective outcomes.

In everyday environments, natural sounds rarely exist in isolation but blend with anthropophony, where technical sounds—especially traffic noise—are a dominant and a much less appreciated component of the soundscape. Controlled listening tests, both in laboratory and real-life settings, have demonstrated that adding natural sounds enhances such soundscapes, thereby improving overall perceived environmental quality. This effect has been observed for water feature sounds (Nilsson et al., 2010; Jeon et al., 2010; You et al., 2010; Hong et al., 2021; Aletta et al., 2023; Van Renterghem, 2024; Calarco and Galbrun, 2024; Ooi et al., 2024) and bird songs (Jeon et al., 2010; Cerwen, 2016; Van Renterghem et al., 2020; Hong et al., 2021; Aletta et al., 2023; Ooi et al., 2024) augmenting road traffic dominated sonic environments.

While the positive effects of natural sounds in combination with road traffic noise have been well demonstrated, previous studies typically involve test panels of only a few dozen to a few hundred respondents. Moreover, such research is often conducted in well controlled settings, such as specific pre-selected areas in urban parks or squares, or even in virtual environments with full control over the audio-visual exposure. In contrast, the current study examines the impact of natural sounds in real-life living environments with full ecological validity, drawing on a large population-based survey of over 4500 respondents across the entire region of Flanders, Belgium.

This study investigates the impact of effectively hearing natural sounds on the sonic environment. Effectively hearing is the endpoint of three key factors: the presence of natural sound sources, their ability to propagate to the listener, and the listener's capacity to notice them. Since natural sounds typically arise from natural features, this research further investigates which types of green infrastructure enhance their effectively hearing.

The focus on natural sounds as a (potentially) positive component of the sonic environment aligns well with the soundscape paradigm (Schafer, 1977), that received quite some attention during the last decades (Raimbault and Dubois, 2005; Yang and Kang, 2005; Axelsson et al., 2010; Brown et al., 2011; Aletta et al., 2016; Kang et al., 2016). The data gathering will be inspired by such studies, but the current work should not be considered as a soundscape study per se given the focus on human perception relevant for environmental noise policy and urban (green) planning.

2. Research questions

In this work, following research questions are posed:

- To what extent does hearing natural sounds improve the soundscape quality in real life outdoor environments?
- Does the type of green infrastructure influence effectively hearing natural sounds?
- Does hearing natural sounds depend primarily on close by or on more distant green infrastructure?
- How does hearing natural sounds interact with abundant road traffic in real-life densely built environments?

3. Methodology

3.1. Soundwalk survey

The soundwalk survey was a preliminary initiative of the citizen science project "De Oorzaak" (Vuye et al., 2024). Leveraging the media campaign by the Flemish newspaper "De Morgen", along with the communication channels of the project and the University of Antwerp, the survey reached a wide audience. Participants were recruited through convenience sampling, as the survey was open to anyone in Belgium aged 18 or older who agreed with the informed consent. This study was approved by the Ethics Committee for the Social Sciences and Humanities of the University of Antwerp on September 18th, 2023 (Ref No: SHW_2023_215_1).

The questionnaire was implemented using Qualtrics® via an online tool. The landing page instructed participants to go outdoors for 2–5 min, actively listen and observe their surroundings while walking or standing, and immediately answer the subsequent questions. Although no particular location was suggested, performing the soundwalk in the direct vicinity of the residence is most likely. Nevertheless, the participants were also encouraged to answer the survey at different places, potentially multiple times. The questions were largely inspired by ISO (2018). The complete version translated into English is provided in Appendix A.

The questionnaire specifically asked which types of sounds were effectively heard, using a 5-point Likert scale with textual indication of all scores, ranging from "not at all" to "dominates completely". Although more sound sources were queried, in this paper, there is specific interest in hearing natural sounds and traffic sounds. Perceived affective quality is mainly assessed by the scores on the eight soundscape dimensions (as used in ISO, 2018), using a 5-point Likert scale with textual indication at all scores, ranging from "totally disagree" to "totally agree".

To allow identifying the geographical coordinates of the location of the soundwalk, the closest street and house number or, alternatively, the name of a location (e.g., a park or square), along with the postal code and municipality, were asked. In view of limited personal data gathering, only gender and birth year were asked.

3.2. Green features maps

The publicly available "Groenkaarten" (Green Maps) of Flanders (further indicated as FGM) will be used to link green features near respondents to hearing natural sounds. The FGM were derived from high-resolution orthophotos taken during aerial surveys in the summer months in the year 2021. These images, captured under optimal conditions when vegetation is fully developed, were processed and analyzed to classify different types of surfaces. The orthophotos were combined with an urban and agricultural zoning map. A "rest" zone is defined not belonging to either the urban or agricultural mask. In each of the three zones, Normalized Difference Vegetation Index (NVDI) and Near Infrared (NIR) photographs were used to distinguish between vegetated and non-vegetated surfaces. The FGM provides 5 different classes. High green (>3 m) means trees in agricultural, urban and "rest" zones. Low green contains vegetation up to 3 m in height, except in agricultural zones. The agricultural category contains both non-green areas (such as farmyard, barns and bare land) and low green areas aiming primarily at agricultural production (such as crops and meadows for grazing). Bluespace is not specifically categorized and would end up in the non-green class. The FGM have a high spatial resolution of 1 m. For more details on its production, the interested reader is referred to following reference (ANB, 2022).

The FGM were used to calculate the fraction of the non-green, low-green, high-green and agricultural pixels in circles with radii of 125 m, 250 m and 500 m around each address point provided by the respondents. This geographical data will form the basis for subsequent analysis linking green features to human hearing of natural sounds.

3.3. Data analysis and statistics

A first set of analyses deals with the impact of hearing natural sounds, in combination with hearing road traffic noise, on the overall appreciation of the outdoor sonic environment. The means of the scores (over all participants) on each soundscape dimension were calculated for each of the 5 natural hearing and road traffic hearing scores, and presented as spider plots using 4 axes (more precisely "Eventful-Uneventful", "Vibrant-Monotonous", "Calm-Chaotic", and "Annoying-Pleasant"). The (geometrical) centre of gravity of these spider plots allows for a single point representation in this multidimensional soundscape space. Given the large number of data points and to allow a direct link to the questionnaire, the perceptual attributes are directly represented without the transformations as e.g. proposed by Mitchell et al. (2022). Paired *t*-tests were conducted to examine whether the mean scores on a soundscape dimension differed significantly between two conditions (e.g. low and high score on hearing natural sounds). Although the 5-point Likert scale is inherently discrete, it was treated as a continuous variable, which is justified especially given the large sample size (Norman, 2010). Similarly, the t-test's robustness to non-normality in large datasets negated the need for further normality checks. All observations were treated as independent, without clustering by participant or location, despite possible repeated surveys by some participants or multiple assessments of certain places. Anonymity prevented such analysis.

The large number of data points enabled to further subset and analyze combinations of the natural sound hearing and road traffic hearing scores. Some extreme classes inevitably have fewer data points. Those with <20 data points were not further analyzed and depicted.

When studying the influence of natural sounds on the soundscape perception, focus was on pleasantness, calmness and annoyance. Pleasantness and calmness are soundscape dimensions that position in the (generally considered) positive right half plane. Pleasantness can be considered as a reasonable proxy for overall soundscape quality (Aletta et al., 2023). Calmness might be the dimension mostly strongly linked to mental restoration; ensuring restorative environments is key in modern spatial planning in the face of mounting pressures in modern society (Yang et al., 2025). Annoyance, and its mitigation, are often key concepts in environmental noise policies.

Multiple logistic regression was used with binary outcomes "at least moderately" (scoring minimum 3 out of 5, further indicated as *moderately*) or as "at least highly" (scoring minimum 4 out of 5, further indicated *highly*) pleasant, calm or annoying. Road traffic hearing was used as a confounder in this analysis given its abundance in the current region. The large number of data points, combined with the pooling of outcomes and the use of a subjective yet coarse 5-point hearing scale, ensures stable analyses. To complement the analysis, binary-input binary-output logistic regression is conducted to examine the effect of hearing at least a moderate (scoring minimum 3 out of 5) or high (scoring minimum 4 out of 5) level of natural sounds on experiencing at least moderate or high levels of pleasantness, calmness, and annoyance. Logistic regression curves are visualized and odds ratios and their 95 % confidence intervals are provided.

A second set of analyses looked at which green features near the respondent influence human hearing of natural sounds. Multiple logistic regression was used to predict either "at least moderately hearing" natural sounds (scoring minimum 3 out of 5, further indicated as *moderately hearing natural sounds*) and hearing "at least at lot" of natural sounds (scoring minimum 4 out of 5, further indicated as *hearing a lot of natural sounds*). Given the large number of datapoints together with pooling the outcomes should ensure stable analyses. Multiple logistic regression was used to account for hearing road traffic as a confounder, and to learn about the relative importance of the various green features. Separate analyses and models were made for green fractions within 500 m, 250 m and 125 m from the respondent.

Multicollinearity between predictors (hearing traffic, hearing natural sounds, green fractions) in the regression modelling is checked by calculating both the Pearson and Spearman correlation coefficients and the variability inflation factors (VIF). To limit the influence of outliers, a fixed cut off based on the 98th percentile of the natural features were set before processing, as a few datapoints with high fractions of some green features might steer the regression curves.

All statistical analyses were made with Matlab version 9.14.0.2239454 (R2023a). Focus in this work is on standard parametric inferential statistical models, allowing direct and clear interpretations.

4. Results

4.1. Soundwalk survey

Data collection took place between October 2023 and April 2024, yielding 4665 valid responses. Most answers were recorded shortly after the survey's release, with approximately 98 % of the total sample obtained by the end of November 2023. Given the survey's language was Dutch, most answers came from the Flemish region, with 35 % from the three largest cities namely Antwerp, Ghent, and Leuven.

Fig. 1 illustrates the geographical spread of the respondents. The map also delineates the boundaries of Belgian municipalities, colour-coded according to five population density classes. Following the Department of Environment (2018), categories 1 and 2 are considered rural, and categories 3 to 5 urban. Appendix B presents similar maps with dots colour-coded based on the extent to which traffic noise and natural sounds were heard, as well as the extent to which the soundscapes were rated pleasant, calm and annoying.

The sample included 55.1 % women and 43.6 % men, with a mean age of 51.9 years (SD = 13.8), skewed toward older individuals (25th percentile was 41 years). Compared to the Flemish population (mean age = 43 years; 50.5 % women, following Statistics of Flanders, 2024), the sample overrepresents women and older age groups. Participants from urban areas accounted for 67.3 %, while rural areas comprised 32.6 % of the sample. The distribution of the samples over the hour of the day is found in Appendix C, with most soundwalks (80.5 %) during the daytime (7:00–18:59).

4.2. Green features maps

The original FGM were subsampled to a 2-m resolution to limit

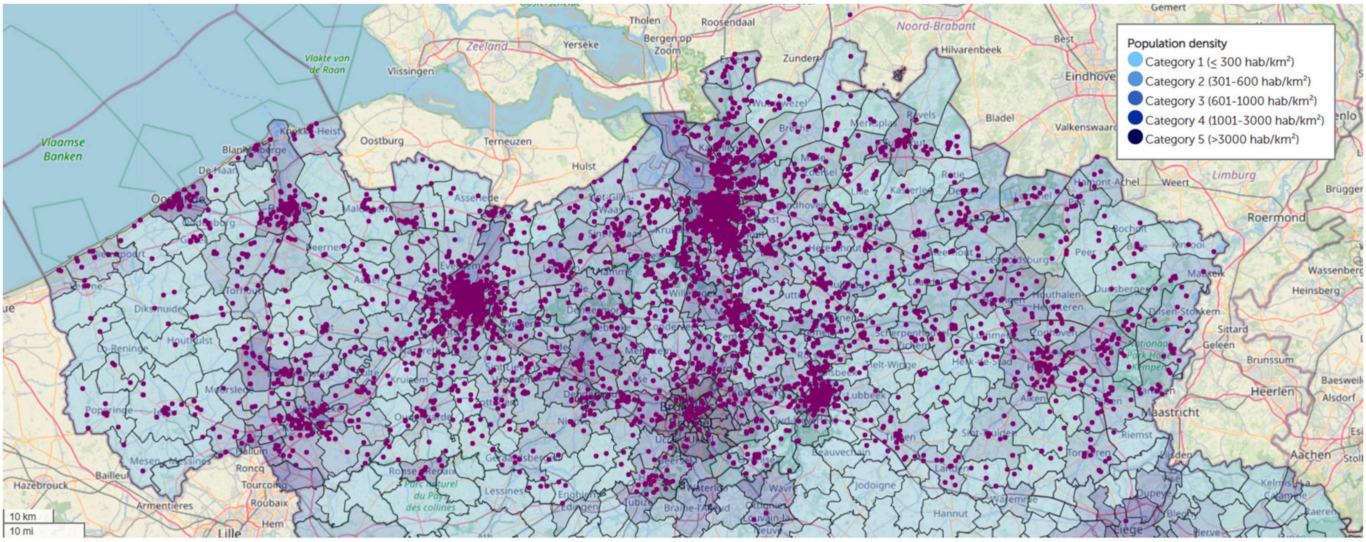

Fig. 1. Mapping the respondents' locations in the surveyed zone ($N = 4665$).

processing cost, and provide the fraction of the non-green, low-green, high-green and agricultural surface (by counting the number of pixels) in a circle around each address point, with radii of 125 m, 250 m and 500 m. Circles around respondents (with a radius of 500 m) outside the FGM borders or those at the interface between separate raster files were disregarded when analyzing the link between hearing natural sounds and land use. In total, this concerned 261 locations (5.6 %) of the 4665 valid answers.

For the 4404 remaining datapoints, 99.79 % of the 500 m radius circles end up in one of the four (non-green, low-green, high-green and agricultural) classes; the undefined/rest class is thus nearly absent. Averaged over all data points, 19.23 % of the surfaces categorize as low-green, 18.99 % as high-green, 13.27 % as agricultural, and 48.30 % as non-green. In Fig. 2, four example 500-m radius zones are depicted.

4.3. Overall soundscape analysis

In Fig. 3, the mean evaluations over all respondents can be found for

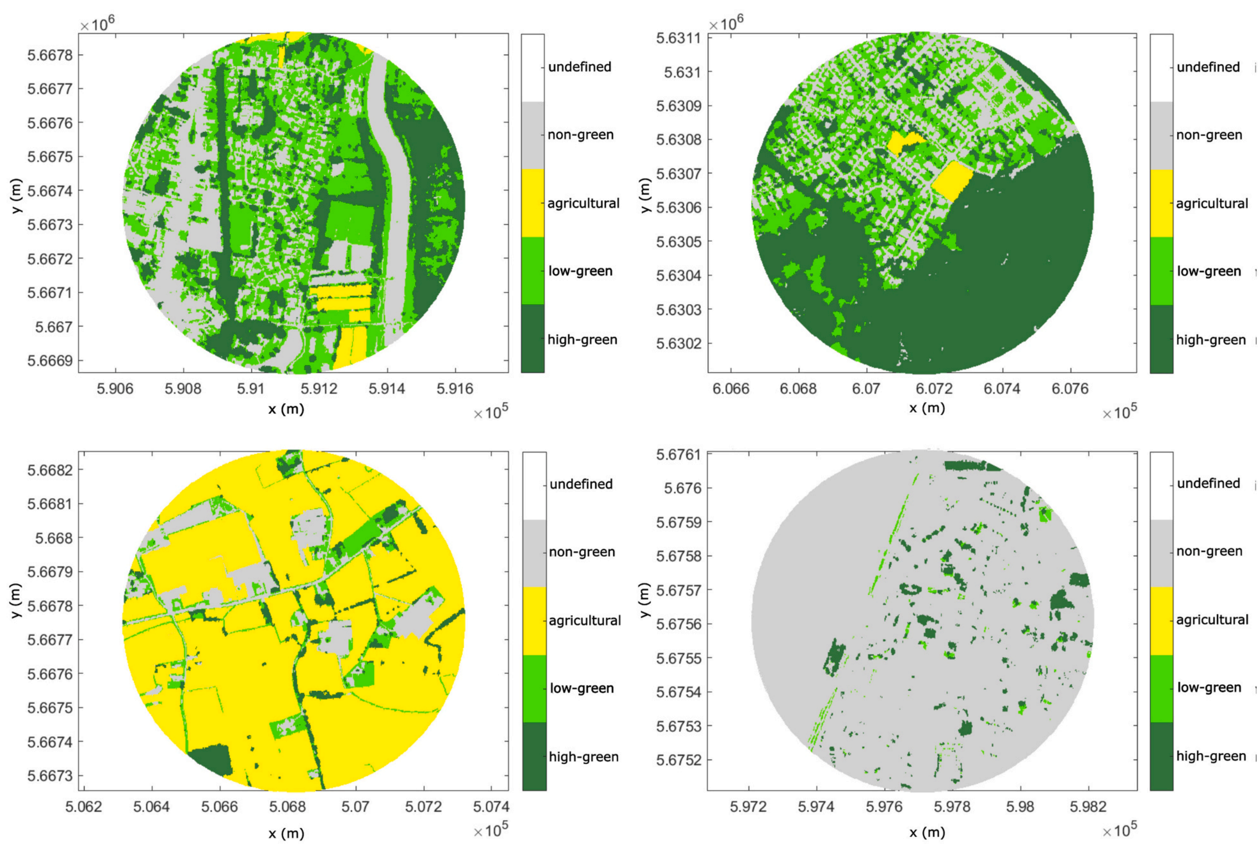

Fig. 2. Examples of local land use derived from the FGM (Flemish Green Maps) in circles with radii of 500 m centered around a few address points, with either a high share of low greenery (top left), high greenery (top right), agricultural land (bottom left) and non-green surfaces (bottom right).

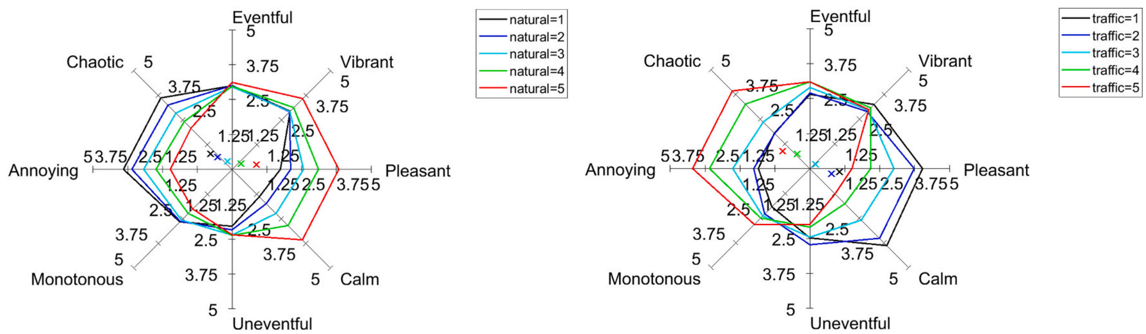

Fig. 3. Spider plots showing the mean evaluations on the soundscape dimensions (with 1 meaning "not at all" and 5 "fully agree") for the five scores on human hearing of natural sounds (with "1" meaning not heard at all, and "5" dominates), and the 5 scores for human hearing of traffic (with "1" meaning not heard at all, and "5" dominates). The crosses represent the centroids of the spider plots without the transformations as e.g. proposed by Mitchell et al. (2022).

each soundscape dimension, grouped per hearing natural sound scores (5 ratings), and grouped per traffic hearing scores (5 ratings), respectively. The mean scores and the standard values in numerical format are provided in Appendix D. When natural sounds are increasingly being heard, the centroids move from the chaotic axis toward the pleasant axis, passing along the origin. Note that in this evaluation, abstraction is made of the degree to which road traffic is heard.

Significant differences in the mean ratings (see Appendix D, with *p*-values at maximum 2.8E−3) between all of the natural sound hearing scores are found for the pleasant, annoying, calm and chaotic dimensions. The eventful dimension, in contrast, does not lead to any significant differences at the 5 % significance level. The monotonous, vibrant and uneventful dimensions lead to some significant differences.

The (geometrical) center of gravity of the spider plots grouped per road traffic hearing follows a reverse path compared to the grouping per natural hearing score, and now move away from the pleasantness axis toward the chaotic axis. Along the calm dimension, all traffic hearing scores separate well. For pleasant, annoying and chaotic, significant differences (see Appendix D) are found except when comparing the averages of the low traffic hearing scores 1 and 2.

In Fig. 4, the soundscape scores are now combined for each of the natural sounds hearing scores, at fixed road traffic hearing ratings. At traffic scores 2, 3 and 4, hearing more natural sounds seem to consistently improve the soundscape, meaning less annoying, more pleasant and calmer. At traffic hearing score 2, hearing natural scores 4 and 5 both give high ratings on these dimensions, but seem to have reached a maximum average score. For traffic hearing 3 and 4, scoring 5 on hearing natural sounds still gives a benefit relative to score 4, although, overall, values on these positive soundscape dimensions are somewhat lower.

4.4. Hearing natural sounds and pleasantness

The logistic regression analyses in Figs. 5 and 6 demonstrate a

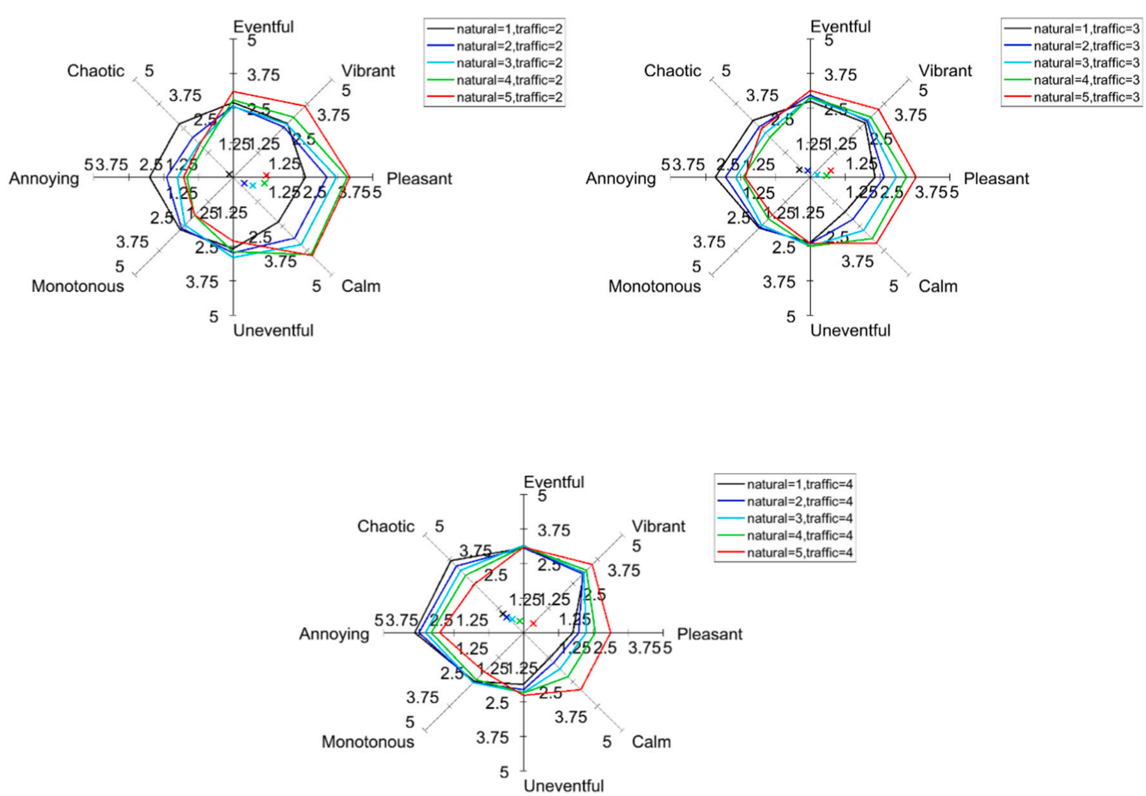

Fig. 4. Spider plots showing the mean evaluations on the soundscape dimensions for the 5 scores on human hearing of natural sounds, grouped per traffic hearing scores 2, 3 and 4. The crosses represent the centroids of the spider plots without the transformations as e.g. proposed by Mitchell et al. (2022).

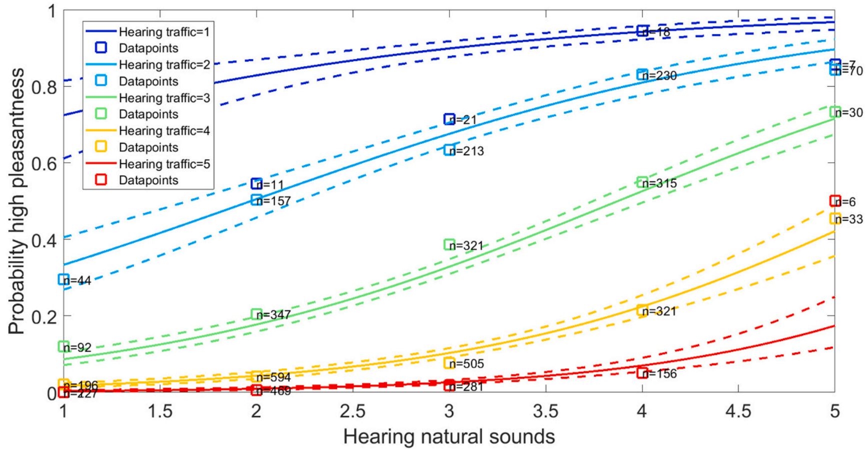

Fig. 5. Probability of "at least high" pleasantness in function of hearing natural sounds (with 1 "hearing not at all", and 5 "dominates") during the soundwalk (MODEL3). The full lines indicate the logistic regression models for each traffic hearing score, and the dashed lines the corresponding 95 % confidence intervals on these predictions. The open square markers show the classified data, with the number of points in each class.

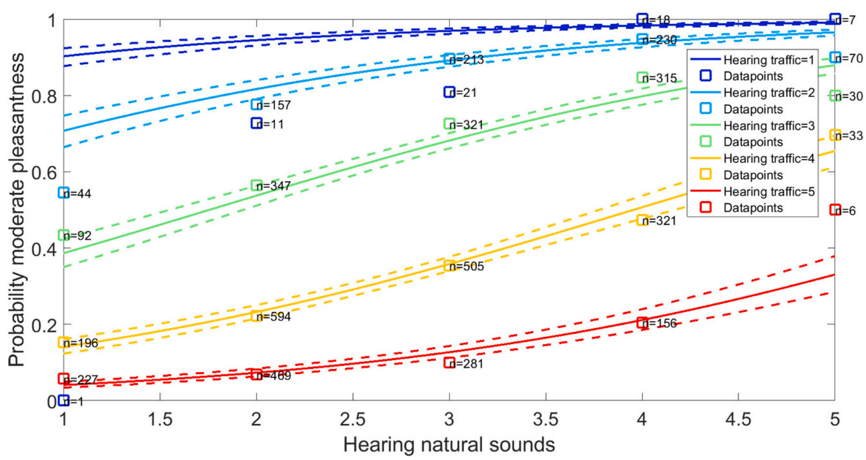

Fig. 6. See caption of Fig. 5, but now for "at least moderate" pleasantness and MODEL2.

significant and stable association between self-reported hearing natural sounds and the likelihood of experiencing moderate (scoring at least 3 out of 5) and high (scoring at least 4 out of 5) soundscape pleasantness. When predicting high pleasantness, including hearing traffic sounds (i.e. MODEL2) and including interactions between hearing natural and traffic sounds (i.e. MODEL3) are both statistical significant model improvements following a likelihood ratio test (MODEL2 relative to MODEL1, $\chi^2(1) = 1138.5$, $p \approx 0$; MODEL3 relative to MODEL2, $\chi^2(1) = 3.9$, $p = 0.047$). When modelling moderate pleasantness, including the interaction terms is not a statistical significant model improvement at the 5 % significance level (MODEL2 relative to MODEL1, $\chi^2(1) = 1339.1$, $p \approx 0$; MODEL3 relative to MODEL2, $\chi^2(1) = 2.8$, $p = 0.096$) and Fig. 6 consequently visualizes MODEL2.

The unadjusted odds ratio of 2.52 (95 % CI: 2.33–2.72; see Table 1, MODEL 1) suggests that people who hear natural sounds are about 2.5 times more likely to report high pleasantness than those who do not. After adjusting for hearing traffic noise (MODEL2), this ratio slightly decreases to 2.28 (95 % CI: 2.08–2.49) indicating a robust effect of hearing natural sounds. When adding the other sound sources that were rated by the respondents (construction noise, music, other people etc., see Appendix A), the odds ratio stays very close to those of MODEL 2 (2.25, with 95 % CI: 2.05–2.48), indicating that traffic noise is the dominant confounder. The other sound sources were consequently not considered in further analyses.

When interactions between hearing natural sounds and traffic noise are included (MODEL3), the effect of natural sounds on pleasantness depends on the level of self-reported traffic noise. As traffic noise increases, natural sounds become more crucial for achieving higher pleasantness. However, when traffic noise is dominant, the likelihood of high pleasantness remains low (below 20 %). In contrast, when traffic noise is minimal, very high pleasantness ratings are common (above 70 %), and the additional effect of natural sounds is limited.

At intermediate levels of traffic noise (score = 3), hearing natural sounds has the strongest impact, increasing the likelihood of high pleasantness from 10 % to 70 %. However, some categories have fewer observations, which should be considered when interpreting these results.

Similar findings can be reported for moderate pleasantness, although this soundscape quality level is more easily reached. Odds ratios for hearing natural sounds are consequently somewhat lower than when looking at high pleasantness. Adjusted for hearing road traffic, values for the OR are now just below 2. For moderate pleasantness, the interaction term (MODEL3) only reaches the 10 % statistical significance level ($p = 0.10$).

To further summarize by dichotomizing hearing natural sounds as a predictor, hearing a lot ($\geq$4/5) of natural sounds gives an (unadjusted) odds ratio of 5.03 (95 % CI: 4.34 to 5.82) for high pleasantness ($\geq$4/5); corrected for hearing traffic noise, this odds ratio reduces to 4.35 (95 % CI: 3.64 to 5.20). Also moderately hearing natural sounds ($\geq$3/5) is an important predictor of high soundscape pleasantness ($\geq$4/5); the OR

Table 1
Odds ratios, and 95 % confidence intervals on the odds ratios, following logistic regression analysis to predict either high or moderate soundscape pleasantness using hearing natural sounds (MODEL1), hearing natural sounds adjusted for hearing road traffic (MODEL2), and including interactions between natural and road traffic hearing (MODEL3). For moderate pleasantness, MODEL 3 is not shown as the interaction term is not statistically significant.

OUTCOME: high pleasantness	OR	95 % CI lower limit	95 % CI upper limit
MODEL1	2.52	2.33	2.72
MODEL2	2.28	2.08	2.49
MODEL3, hearingroadtraffic = 1	1.84	1.46	2.31
MODEL3, hearingroadtraffic = 2	2.04	1.77	2.35
MODEL3, hearingroadtraffic = 3	2.27	2.07	2.48
MODEL3, hearingroadtraffic = 4	2.52	2.20	2.89
MODEL3, hearingroadtraffic = 5	2.80	2.23	3.51

OUTCOME: moderate pleasantness	OR	95 % CI lower limit	95 % CI upper limit
MODEL1	2.06	1.94	2.20
MODEL2	1.84	1.71	1.99

(adjusted for hearing traffic noise) is now 4.07 (95 % CI: 3.37 to 4.92). Moderately hearing natural sounds (≥3/5) gives an OR (adjusted for hearing traffic noise) of 2.92 (95 % CI: 2.53 to 3.38) for moderate pleasantness (≥3/5). Hearing a lot of natural sounds (≥4/5) gives an OR (adjusted for hearing traffic noise) of 3.06 (95 % CI: 2.59 to 3.61) for moderate pleasantness (≥3/5).

In MODEL2 and MODEL3, collinearity between hearing natural sounds and hearing traffic sounds can be rejected. Pearson's ($r = -0.27$, $p \approx 0$) and Spearman's ($r = -0.26$, $p \approx 0$) correlation coefficients indicate a weak negative relationship, suggesting that more natural sounds correspond to less traffic noise but without collinearity issues. The Variable Inflation Factor (VIF) of 1.08 confirms both predictors contribute independently, ensuring reliable regression estimates.

4.5. Hearing natural sounds and calmness

The logistic regression analyses (Figs. 7 and 8) show a strong and stable link between hearing natural sounds and experiencing moderate (≥3/5) or high (≥4/5) soundscape calmness. For high calmness, including hearing traffic noise and its interaction with natural sounds (MODEL3) significantly improves the model (MODEL2 vs. MODEL1: $\chi^2(1) = 935.5$, $p \approx 0$; MODEL3 vs. MODEL2: $\chi^2(1) = 5.3$, $p = 0.022$). For moderate calmness, the interaction term does not improve the model at the 5 % significance level (MODEL3 vs. MODEL2: $\chi^2(1) = 2.99$, $p = 0.084$).

The unadjusted odds ratio (OR) of 2.61 (95 % CI: 2.40–2.83, see Table 2) suggests that hearing natural sounds makes individuals 2.6 times more likely to report high calmness. After adjusting for traffic noise (MODEL2), the OR drops slightly to 2.31 (95 % CI: 2.10–2.54) indicating again a robust effect of hearing natural sounds. When accounting for interactions (MODEL3), the effect of natural sounds becomes more pronounced as traffic noise increases. However, when traffic noise dominates, the chance of high calmness remains low (~20 %), whereas in low-traffic settings, high calmness is common (>80 %) with little added benefit from natural sounds. The strongest impact of natural sounds occurs at intermediate traffic noise levels, where calmness probability ranges from 30 % to 80 %.

For moderate calmness, similar trends appear, leading to slightly lower ORs. The interaction term in MODEL3 reaches only marginal significance ($p = 0.08$).

When hearing natural sounds is categorized as well, the data analysis can be further condensed. Those who report hearing a lot of natural sounds (≥4/5) have an unadjusted odds ratio of 5.24 (95 % CI: 4.50–6.10) for experiencing high calmness (≥4/5), which decreases to 4.38 (95 % CI: 3.66–5.24) after adjusting for traffic noise. Hearing at least moderate natural sounds (≥3/5) also remains a strong predictor, with an adjusted odds ratio of 4.33 (95 % CI: 3.54–5.29) for high calmness (≥4/5) and 3.93 (95 % CI: 3.33–4.63) for moderate (≥3/5) calmness. Additionally, hearing a lot of natural sounds (≥4/5) is associated with an adjusted odds ratio of 3.88 (95 % CI: 3.28–4.59) for moderate calmness (≥3/5). Overall, these findings align closely with those for soundscape pleasantness.

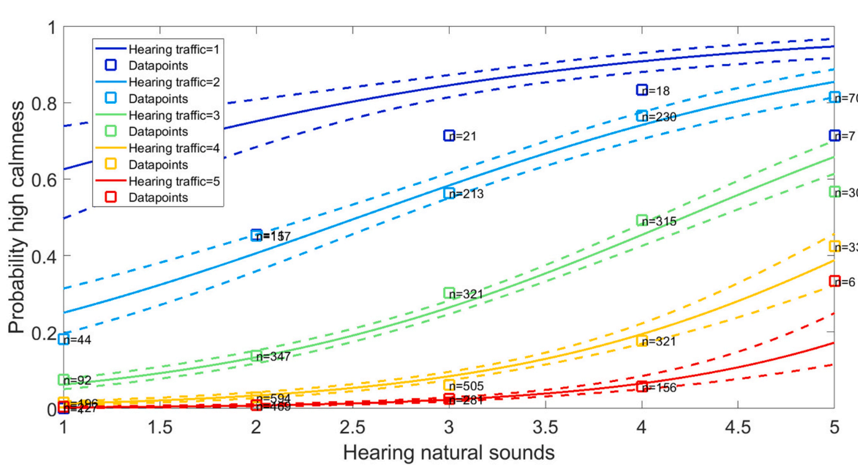

Fig. 7. Probability of "at least high" calmness in function of hearing natural sounds (with 1 "hearing not at all", and 5 "dominates") during the soundwalk (MODEL3). The full lines indicate the logistic regression models for each traffic hearing score, and the dashed lines the corresponding 95 % confidence intervals on these predictions. The open square markers show the classified data, with the number of points in each class.

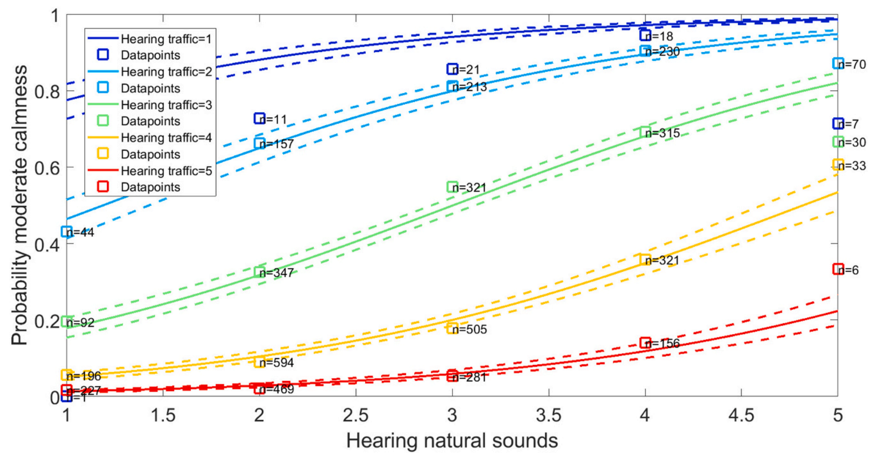

Fig. 8. See caption of Fig. 7, but now for “at least moderate” calmness and MODEL2.

Table 2
Odds ratios, and 95 % confidence intervals on the odds ratios, following logistic regression analysis to predict either high or moderate soundscape calmness using hearing natural sounds (MODEL1), hearing natural sounds adjusted for hearing road traffic (MODEL2), and including interactions between these two independent variables as well (MODEL3). For moderate calmness, MODEL 3 is not shown as the interaction term is not statistically significant.

OUTCOME: high calmness	OR	95 % CI lower limit	95 % CI upper limit
MODEL1	2.61	2.40	2.83
MODEL2	2.31	2.10	2.54
MODEL3, hearingroadtraffic = 1	1.81	1.44	2.27
MODEL3, hearingroadtraffic = 2	2.05	1.79	2.35
MODEL3, hearingroadtraffic = 3	2.32	2.11	2.55
MODEL3, hearingroadtraffic = 4	2.62	2.26	3.04
MODEL3, hearingroadtraffic = 5	2.97	2.34	3.78

OUTCOME: moderate calmness	OR	95 % CI lower limit	95 % CI upper limit
MODEL1	2.34	2.18	2.51
MODEL2	2.14	1.97	2.33

4.6. Hearing natural sounds and annoyance

The logistic regression analysis (see Figs. 9 and 10) shows a significant negative association between hearing natural sounds and reporting high (≥4/5) or moderate (≥3/5) annoyance when being outdoors. The odds ratio of 0.59 (95 % CI: 0.56–0.63, see Table 3) suggests that individuals who hear natural sounds are about 1.7 times less likely to report high annoyance. After adjusting for traffic noise, the odds ratio rises slightly to 0.70 (95 % CI: 0.66–0.75), indicating a persistent but slightly weaker effect. Compared to pleasantness and calmness, the impact of natural sounds on reducing annoyance is somewhat less pronounced.

Including interactions between hearing natural and traffic sounds (MODEL3) shows that as traffic noise increases, the impact of natural sounds on reducing annoyance weakens. When traffic noise is very high (score 5), the odds ratio is 0.84, with the upper confidence limit still below 1, indicating a minimal effect. Conversely, when traffic noise is lower, the odds ratio drops to 0.5, meaning that natural sounds play a stronger role in reducing annoyance. At a moderate traffic noise level (score 3), the likelihood of experiencing high annoyance ranges from 20 % to 50 %, depending on the natural sound exposure.

For moderate annoyance, the effects of natural sounds are slightly stronger. Interactions between hearing natural and traffic sounds are statistically significant for both high (MODEL2 relative to MODEL1, $\chi^2(1) = 983.7$, $p \approx 0$; MODEL3 relative to MODEL2, $\chi^2(1) = 12.3$, $p =$ 4.5E−4) and moderate annoyance (MODEL2 relative to MODEL1, $\chi^2(1) = 917.5$, $p \approx 0$; MODEL3 relative to MODEL2, $\chi^2(1) = 5.6$, $p = 0.018$).

When categorizing natural sound exposure, hearing a lot of natural sounds (≥4/5) is associated with an unadjusted odds ratio of 0.37 (95 % CI: 0.32–0.42) for high annoyance (≥4/5), increasing to 0.51 (95 % CI: 0.44–0.60) after adjusting for traffic noise. Hearing at least moderate natural sounds (≥3/5) is also a strong predictor of reduced annoyance, with adjusted odds ratios of 0.53 (95 % CI: 0.46–0.61) for high (≥4/5) annoyance and 0.43 (95 % CI: 0.37–0.50) for moderate (≥3/5) annoyance. The odds ratio remains similar for those hearing a lot (≥4/5) of natural sounds, with 0.43 (95 % CI: 0.37–0.51) for moderate (≥3/5) annoyance.

4.7. Green features and hearing natural sounds

The effect of green land use on hearing natural sounds was analyzed using logistic regression. MODEL1 used FGM fractions as the sole predictor, while MODEL2 adjusts for road traffic hearing. MODEL4 included both hearing traffic and all green fractions. The non-green fraction was excluded from MODEL4 due to its strong correlation with the green land types (Spearman correlation up to 0.84, VIF over 2). Correlations between green features were low (VIF up to 1.05) and no correlation was found with hearing traffic (VIF up to 1.03). Adding interaction terms between greenery and hearing traffic (MODEL3) did not improve the model, with p-values over 0.05. Therefore, MODEL3 was disregarded. No further interaction terms were explored in MODEL4 to avoid complexity and hindering drawing sound conclusions.

In Table 4, odds ratios for MODEL1, MODEL2 and MODEL4 are shown, for each of the four FGM classes considered, with outcome hearing at least a lot of natural sounds or hearing natural sounds to at least a moderate degree. High statistical significance (see Appendix E, *p*

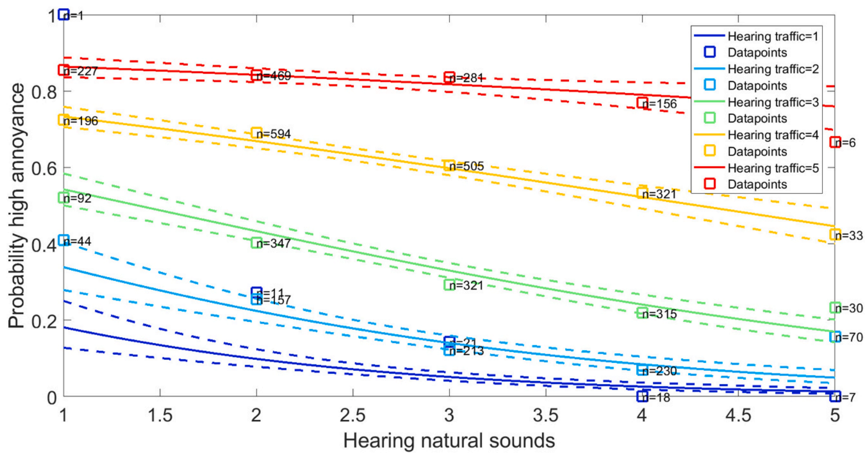

Fig. 9. Probability of "at least high" annoyance in function of hearing natural sounds (with 1 "hearing not at all", and 5 "dominates") during the soundwalk (MODEL3). The full lines indicate the logistic regression models for each traffic hearing score, and the dashed lines the corresponding 95 % confidence intervals on these predictions. The open square markers show the classified data, with the number of points in each class.

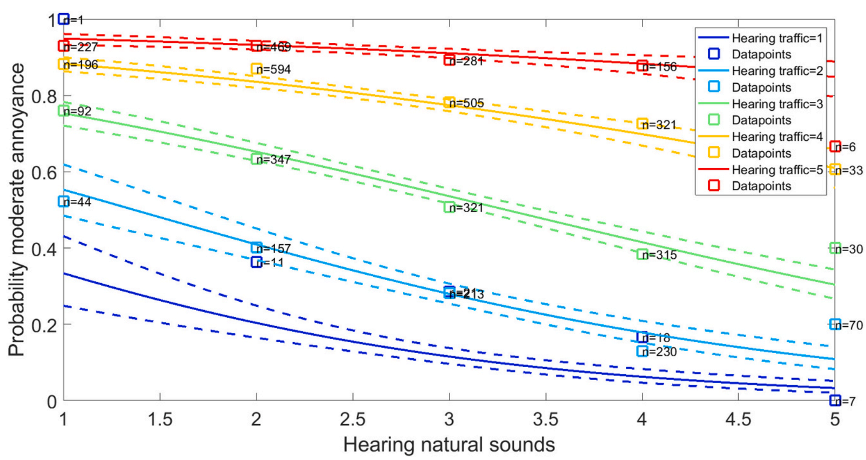

Fig. 10. See caption of Fig. 9, but now for "at least moderate" annoyance.

values at maximum 9.1E−9) is found for all green fractions and hearing road traffic. Separate analysis is made for the fractions of the natural geo-features within 500 m, 250 m and 125 m around the respondent's location. The logistic regression curves from MODEL1 are visualized in Figs. 11 and 12, which are the unadjusted models. For brevity, only the fractions within 500 m distance from the assessment point are presented.

With increasing fraction of any green features, the probability of at least moderately hearing natural sounds increases. The chance of hearing a lot of natural sounds is logically lower overall, but findings are similar. Logically, with increasing the fraction of non-green land use, these probabilities decrease. When the non-green fraction goes to 1, the chance of hearing a lot of natural sounds goes to zero.

Both low-green, high-green and agricultural land use contribute to hearing natural sounds. Within the region of study, maximum fractions (taking into account a cutoff of 98 % at the high end of these indicators, see Methodology) of low greenery and high greenery lead to probabilities of up to 70 % for at least moderately hearing natural sounds. When a respondent is surrounded to a large extent by agricultural land, this chance reaches even 80 %. When aiming at hearing a lot of natural sounds, these probabilities range to 40 % for low and high greenery, and 60 % for agricultural land use.

Odds ratios generally decrease as the radius of influence shrinks, suggesting that increasing greenery in a larger area around the listener is somewhat more effective for hearing natural sounds than focusing only on the immediate surroundings. MODEL4's odds ratios, adjusted for hearing traffic and other green features, show that increasing low greenery is slightly more effective than high greenery for hearing moderately natural sounds. However, for hearing a lot of natural sounds, high greenery is more effective. Agricultural land also plays a role but with slightly lower odds ratios. Although the confidence intervals are large, the key finding here is that all green features significantly contribute to hearing natural sounds.

5. Discussion

5.1. Natural sounds improve the soundscape quality

By means of individual soundwalks in the direct neighborhood of the dwelling, a large number (n = 4665) of evaluations of outdoor soundscapes in real-life living environments were collected. The dataset covered the full range of both high and low traffic and natural sound scores, with most score combinations having sufficient data points as well. This population based sampling logically led to more respondents in more densely populated areas. Consequently, road traffic hearing scores were typically high, scoring 4 out of 5 was the most prominent category. Notwithstanding such challenging sonic environments, increasingly hearing natural sounds showed to be a strong and robust predictor of better soundscape quality. In the current work, focus was on the pleasantness and calmness dimensions, of high interest in living

Table 3
Odds ratios, and 95 % confidence intervals on the odds ratios, following logistic regression analysis to predict either high or moderate annoyance using hearing natural sounds (MODEL1), hearing natural sounds adjusted for hearing road traffic (MODEL2), and including interactions between these two independent variables as well (MODEL3).

OUTCOME: high annoyance	OR	95 % CI lower limit	95 % CI upper limit
MODEL1	0.594	0.559	0.630
MODEL2	0.704	0.658	0.753
MODEL3, hearingroadtraffic = 1	0.494	0.400	0.611
MODEL3, hearingroadtraffic = 2	0.564	0.490	0.651
MODEL3, hearingroadtraffic = 3	0.644	0.592	0.701
MODEL3, hearingroadtraffic = 4	0.736	0.685	0.790
MODEL3, hearingroadtraffic = 5	0.840	0.746	0.946

OUTCOME: moderate annoyance	OR	95 % CI lower limit	95 % CI upper limit
MODEL1	0.538	0.504	0.574
MODEL2	0.635	0.591	0.683
MODEL3, hearingroadtraffic = 1	0.511	0.419	0.622
MODEL3, hearingroadtraffic = 2	0.560	0.493	0.637
MODEL3, hearingroadtraffic = 3	0.615	0.569	0.665
MODEL3, hearingroadtraffic = 4	0.675	0.618	0.737
MODEL3, hearingroadtraffic = 5	0.741	0.641	0.857

environments. Odds ratios around 2 were found, with narrow 95 % confidence intervals. This means that for each unit increase in hearing (more) natural sounds (on a 5-point scale), the likelihood of experiencing higher soundscape quality (in terms of pleasantness and calmness) is doubled.

Increasingly hearing natural sounds also leads to a decrease in perceiving the sonic environment as annoying at fixed traffic hearing scores. Effects are robust and strongly statistically significant, but somewhat more modest compared to looking at pleasantness and calmness. Note that characterizing the sonic environment as annoying during the walk might deviate from the standardized yearly-integrated noise annoyance question (ISO, 2021). To some extent, what is assessed here could be described as "short-term annoyance". Whether this is a different concept than the common policy-relevant self-reported long-term annoyance, and the extent to which both are correlated, is still unclear and under debate (Guski et al., 1999; Bartels et al., 2015; Schreckenberg et al., 2022). In addition, contextual and personal factors (Job, 1988; Fields, 1993; Miedema and Vos, 1999; Guski et al., 1999) could play a pivotal role when predicting noise annoyance.

Increased presence of natural sounds or reduced exposure to traffic

Table 4
Odds ratios, and 95 % confidence intervals on the odds ratios, following logistic regression analysis to predict either "at least hearing a lot" or "at least moderately hearing" natural sounds, using the fractions of (separate) green features (MODEL1), (separate) green features in combination with hearing road traffic (MODEL2), and all green features (except for the non-greenery fraction) together as predictors (MODEL4).

OUTCOME: hearing a lot of natural sounds	500 m			250 m			125 m		
	OR	95 % CI lower limit	95 % CI upper limit	OR	95 % CI lower limit	95 % CI upper limit	OR	95 % CI lower limit	95 % CI upper limit
MODEL1 low_green	21.0	9.4	47.3	14.7	7.5	28.8	10.1	5.8	17.8
MODEL2 low_green	17.6	7.7	40.3	11.4	5.8	22.6	7.6	4.3	13.5
MODEL4 low_green	19.2	7.8	47.6	17.8	8.5	37.3	16.1	8.6	30.0
MODEL1 high_green	6.4	3.4	12.0	5.7	3.2	10.1	5.7	3.5	9.4
MODEL2 high_green	7.3	3.8	13.9	6.3	3.5	11.3	6.0	3.6	10.0
MODEL4 high_green	25.1	14.3	44.0	17.3	10.5	28.4	11.7	7.6	18.1
MODEL1 agricultural	12.4	8.5	18.1	13.9	9.3	20.9	9.6	6.3	14.4
MODEL2 agricultural	9.4	6.4	13.9	10.7	7.1	16.3	7.8	5.1	11.9
MODEL4 agricultural	14.7	10.2	21.3	13.0	9.0	18.9	9.8	6.8	14.0
MODEL1 non_green	0.046	0.033	0.064	0.056	0.041	0.077	0.073	0.055	0.099
MODEL2 non_green	0.061	0.043	0.085	0.072	0.052	0.099	0.091	0.068	0.123

OUTCOME: hearing moderately natural sounds	500 m			250 m			125 m		
	OR	95 % CI lower limit	95 % CI upper limit	OR	95 % CI lower limit	95 % CI upper limit	OR	95 % CI lower limit	95 % CI upper limit
MODEL1 low_green	77.0	37.8	156.9	44.0	24.3	79.9	23.6	14.1	39.2
MODEL2 low_green	72.0	34.7	149.1	38.0	20.7	69.9	19.6	11.6	33.0
MODEL4 low_green	30.7	14.4	65.8	27.8	14.8	52.0	23.8	14.0	40.7
MODEL1 high_green	8.1	4.5	14.5	7.5	4.4	12.9	5.2	3.2	8.3
MODEL2 high_green	10.0	5.5	18.3	9.2	5.2	16.1	5.7	3.5	9.3
MODEL4 high_green	17.2	9.9	29.9	13.9	8.4	22.9	9.4	6.1	14.4
MODEL1 agricultural	17.2	11.5	25.7	21.0	13.3	33.2	16.9	10.4	27.5
MODEL2 agricultural	13.5	9.0	20.3	16.6	10.4	26.5	14.1	8.6	23.1
MODEL4 agricultural	13.6	9.4	19.6	13.7	9.3	20.2	12.4	8.3	18.3
MODEL1 non_green	0.052	0.039	0.069	0.055	0.042	0.073	0.066	0.050	0.087
MODEL2 non_green	0.063	0.047	0.085	0.066	0.049	0.088	0.078	0.059	0.103

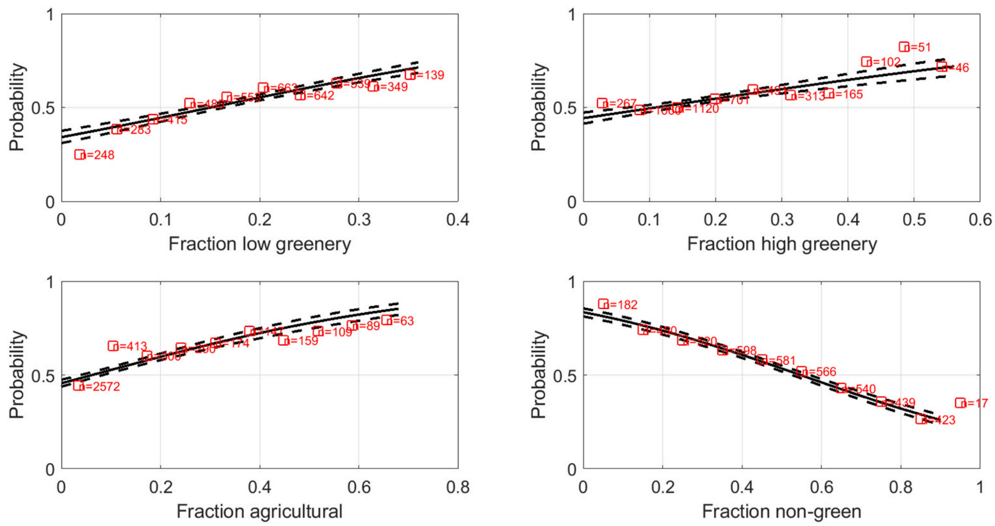

Fig. 11. Probability of "at least hearing natural sounds to a moderate degree", in function of the fraction of low greenery, high greenery, agricultural and non-green land use, within 500 m from the respondent (MODEL1). The full black lines show the logistic regression curves, the black dashed lines indicate the 95 % confidence intervals on the logistic regressions. The red squares show the actual data, with the number of datapoints falling within 10 classes uniformly distributed over the range of green feature fractions. Note that this classification is only performed to visualize the data in these plots.

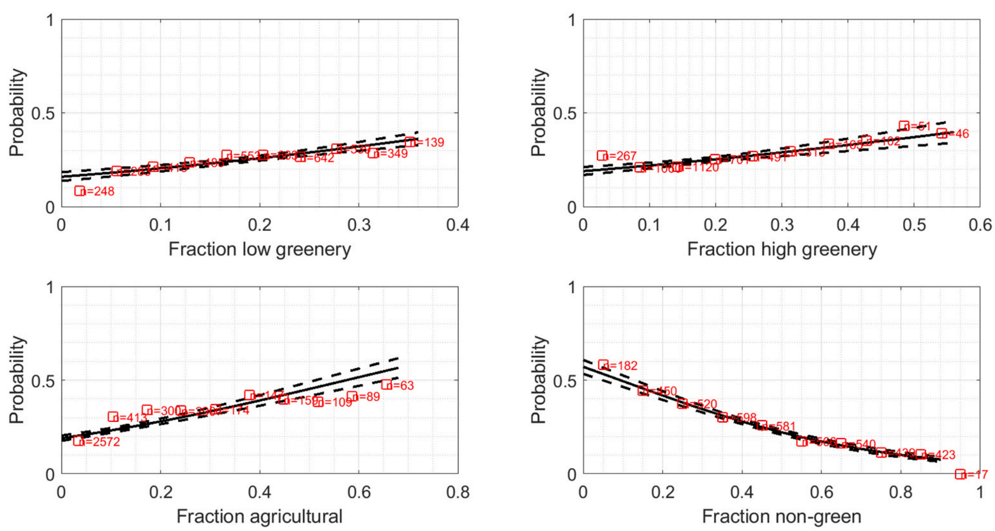

Fig. 12. See caption of Fig. 11, but now for hearing natural sounds "at least to a high degree".

noise shifts the centroid on the soundscape rose from the chaotic toward the pleasantness axis. This shift highlights that pleasantness and annoyance are not straightforward opposites; rather, soundscape evaluation is multidimensional and better understood through distinct perceptual attributes. Moreover, the exact interpretation of these terms can vary across different languages (Aletta et al., 2024). Other descriptors such as familiarity (Kirmse et al., 2009), perceived soundscape restoration potential (Payne, 2013) and appropriateness (Yang et al., 2024), as summarized in Tarlao et al. (2023), could be useful as well for a finer description of the perceived sonic environment. Notably, brief and deliberate listening to traffic-dominated environments may elicit a perception of chaos rather than annoyance, suggesting that short-term exposure does not always result in high annoyance ratings.

Interestingly, the most positive effects of hearing natural sounds on perceived pleasantness, calmness, and reduced annoyance were observed when traffic noise levels were moderate rather than extreme. This aligns with the notion that when traffic noise is dominant, natural sounds are likely less audible. Conversely, in environments where traffic noise is nearly absent, the soundscape is already favorable, and additional natural sounds provide only marginal benefits. These findings are consistent with previous research on soundscape augmentation using natural sounds. For example, Van Renterghem et al. (2020) found that introducing natural sounds via hidden loudspeakers in an urban park was particularly effective for individuals who originally perceived road traffic noise as loud. Similarly, Hong et al. (2021) reported a greater improvement in overall soundscape quality and a stronger reduction in perceived (noise) loudness at their noisier site. Fraisse et al. (2024) also demonstrated that their natural sound art installation had the most positive impact in acoustically poor environments.

The findings in this work align well with the large-scale soundscape study by Aletta et al. (2023), which surveyed over 2000 participants in preselected parks and urban squares across Europe and China. Consistent with our results, they found that pleasantness and calmness increased significantly, while annoyance decreased significantly, with a greater presence of natural sounds. Notably, in their European cities, the positive correlation between perceived pleasantness and natural sounds was stronger than in China. Our study reinforces the pivotal role of natural sounds in shaping outdoor soundscapes and extends this understanding beyond public spaces to everyday living environments.

The data shows that effectively hearing natural sounds influence calmness and pleasantness in a similar way. This is consistent e.g. with the analysis of Aletta et al. (2023) showing that both soundscape dimensions correlate well and both load on the so-called ISO-pleasantness dimension (Mitchell et al., 2022). The current work confirms that this also holds when looking at hearing natural sounds as drivers for calmness and pleasantness. Nevertheless, given their relevance for environmental noise policy and urban planning, it was chosen to analyze both indicators separately.

5.2. Data collection

The high number of participants in this study was likely achieved by minimizing participant tasks and limiting additional data collection. As a result, the dataset does not allow for an analysis of how personal factors interact with the positive effects of hearing natural sounds. In particular, a construct such as connectedness to nature (Mayer and Frantz, 2004) may play a role, potentially influenced by early-life natural experiences (Rosa et al., 2018) and personal memories (Smalley et al., 2022). Similarly, noise sensitivity (Weinstein, 1978; Kliuchko et al., 2016) could be a major factor as well.

In our methodology, participants were explicitly asked to focus on the surrounding sounds. This may differ from typical outdoor experiences, where sound perception is often more subconscious in the absence of distinct sound events. While our findings highlight the significant impact of natural sounds on the perception of environmental soundscapes, they do not allow us to assess the broader influence of sound on overall environmental quality in the living environment.

The current data collection does not allow for a detailed analysis of the relative importance of different natural sound types. The question frames natural sounds as a broad category, providing a few examples, such as bird songs, wind and rain. However, different natural sounds might impact the auditory experience in distinct ways. Their spectro-temporal characteristics vary, and could lead to both energetic and informational masking. For example, bird songs cause mainly informational masking, as they do not overlap with road traffic noise spectra, whereas wind-induced vegetation noise may include low frequencies, contributing to energetic masking. Note that the open-ended question on the most liked sound during the soundwalk (see Appendix A) might contain hints to specific natural sounds, but this is not further investigated.

The soundwalks were primarily conducted during the daytime and likely under favorable weather conditions. This aligns with typical outdoor behavior, as people are naturally more inclined to be outside in such circumstances. Regression analysis (see Appendix C) indicated that the time of day had no significant overall effect on the degree to which natural sounds were heard, and was therefore excluded from further analysis. However, for specific types, such as bird songs, the dawn chorus (Bruni et al., 2014) might still be relevant but was not captured, as no distinction between different natural sound types could be made.

Hearing road traffic likely depends on the hour of the day, such as during rush hour. Since this study focuses on the impact of natural sounds, road traffic hearing is included as a confounder to account for its co-occurrence with natural sounds. Additional analysis showed that interactions between road traffic hearing and time of day, as well as three-way interactions with natural sound hearing, had p-values exceeding 0.5, suggesting only random variation rather than a systematic effect on the soundscape quality.

5.3. Green infrastructure facilitates hearing natural sounds

The Flemish Green Maps provide spatially detailed land use categorization in the region considered. The fractions of low-greenery, high-greenery and agricultural surfaces around the respondents were calculated at high spatial resolution (i.e. 2 m). As the fractions of these green surfaces increase around a dwelling, the odds of perceiving natural sounds rise substantially, easily exceeding 10. All the aforementioned green surface types strongly increase the chance of hearing natural sounds. However, unlike the logistic regression models that use hearing natural sound scores as predictors, we now use fractions. A one-unit increase (as assumed in the odds ratios) now represents a shift from the complete absence of a land use class to full presence.

The agricultural class can also be associated with hearing natural sounds. While this category may represent vegetated surfaces, it can equally indicate the presence of agricultural buildings such as stables. But also such infrastructure can contribute to the broadly defined concept of natural sounds, for example, through sounds produced by livestock. Nonetheless, agricultural land use is generally expected to consist primarily of arable land and pastures.

A drawback of the Flemish Green Maps is that water bodies are not identified separately and are classified as non-green. However, water features can contribute to both biophony (e.g., as a habitat for birds and amphibians) and geophony (e.g., flowing water and breaking waves). If bluespace were excluded from the non-green category, the negative impact of non-green land use on the likelihood of hearing natural sounds would likely be even stronger.

Notably, green features within a broader 500 m radius appear more relevant than those in the immediate vicinity. This larger area may serve as a more significant source of natural sounds capable of reaching the listener. Extending this range further seems unnecessary, as a 500 m propagation distance already corresponds to a geometric divergence attenuation of 65 dB in case of point source behavior. However, propagation losses vary depending on the sound source. Lower-frequency sounds are more likely to travel greater distances, particularly in open environments. While bird songs with main acoustic energy at a few kilohertz are quickly absorbed by air (ISO, 1993), this does not mean that distant bird songs are inaudible. Studies have shown that such sounds can still be perceived by attentive listeners even at signal-to-noise ratios as low as −10 dB (Oldoni et al., 2013), helped by the salient and intermittent character of bird songs. Future analyses could explore more complex geospatial factors, such as connectivity between greenery types and minimum cluster sizes, to potentially better predict the likelihood of hearing natural sounds.

In environmental noise perception, audio-visual interactions could be relevant as well, especially with relation to green infrastructure (Viollon et al., 2002; Pheasant et al., 2008; Preis et al., 2015; Van Renterghem, 2019; Li and Lau, 2020). In common urban audio-visual incongruent settings, complexity was shown to further increase (Van Renterghem and Lippens, 2024). However, including visibility analysis, which could be automated based on available data sources (see e.g. Vervoort et al., 2024), is considered outside the scope of the current paper.

6. Conclusions

Hearing natural sounds enhances the soundscape qualities pleasantness and calmness in everyday living environment. In addition, the (short-term) annoyance experienced outdoors is consistently reduced, still in a very robust way, but somewhat less strong. The types of green infrastructures identified by the Flanders Green Maps (more precisely low greenery, high greenery and agricultural land use) all contribute strongly to effectively hearing natural sounds as opposed to non-green zones. The surface fractions taken by these green infrastructures within 500 m around the dwelling show to be stronger predictors compared to only considering greenery in the direct vicinity.

The impact of effectively hearing natural sounds strongly interacts with effectively hearing road traffic, the latter being a main constituent of the sonic environment in the region under study. At the most common (i.e. intermediate) traffic hearing scores, increasingly hearing natural sounds strongly enhances soundscape pleasantness and calmness, while annoyance is consequently reduced. At very low road traffic hearing scores, positive soundscapes are always warranted. In traffic noise dominated environments, in contrast, soundscape quality is always poor. But also in these two extremes, increasingly hearing natural sounds still leads to statistically significant improvements, albeit rather small.

Human hearing of natural sounds, whether through biophony or geophony, is directly linked to the presence of nearby green infrastructure and serves as a strong contributor to improving environmental noise perception, even in areas with high road traffic. The provision of natural sounds can thus be recognized as a robust and accessible ecosystem service of green infrastructure, enhancing human-perceived environmental quality.

CRediT authorship contribution statement

Timothy Van Renterghem: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Investigation, Formal analysis. **Ablenya Barros:** Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Data curation, Conceptualization. **Jonas Lembrechts:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Cedric Vuye:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT-4 to enhance readability, optimize text flow, and condense the writing. Only individual paragraphs were separately submitted, with explicit instructions not to alter the content or intended meaning. All AI-assisted revisions were subsequently reviewed and, where necessary, edited by the authors. The authors takes full responsibility for the final content of this publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

A.1. Introduction

From the hum of passing cars and the chime of streetcars to the chirping of birds and the chatter of neighbors, sound surrounds us everywhere. But how does environmental noise impact our well-being and health? The University of Antwerp, the Antwerp University Hospital, and De Morgen invite you to explore this question with us in "De Oorzaak".

In this survey, we want to learn about your soundscape—the unique mix of sounds in your surroundings at a given moment. To participate, simply step outside for 2 to 5 min and take a soundwalk. This means walking or standing still, tuning in to the sounds around you, and actively observing.

At the end of the survey, we will ask for your location and record the time of your participation. To ensure the most accurate results, please complete the questionnaire immediately after your soundwalk while your impressions are still fresh.

The survey takes about 5 min to complete, and you are welcome to participate multiple times at different locations or times. Want to make it even more enjoyable? Share the experience with colleagues, friends, or family and compare your impressions!

A.2. Ethics clearance and acknowledgements

- ▢ I hereby confirm that I have read, understood and approved the Information Form. I agree with the way my data will be processed.
- ▢ I am 18 years old or older

If you have questions about the study or your rights as a study participant now, during or after your participation, please contact deoorzaak@uantwerpen.be, or view our frequently asked questions at www.deoorzaak.be. De Oorzaak is an initiative from:

Universiteit Antwerpen

UZA

DeMorgen.

With support from

A.3. Questions

To what extent did you hear the following sounds during your soundwalk?

	Not at all	A little	Moderately	A lot	Dominates completely
Traffic (road traffic, air traffic, rail traffic,...)	○	○	○	○	○
Human sounds (voices, shouts, laughter,...)	○	○	○	○	○
Music (from loudspeaker, instrument, ...)	○	○	○	○	○
Natural sounds (birds, rain, wind, ...)	○	○	○	○	○
Industry (machines, forklifts, ...)	○	○	○	○	○
Construction and/or maintenance work (grass cutting, drilling machines, yard machines, ...)	○	○	○	○	○
Alarms/priority vehicles	○	○	○	○	○
Silence	○	○	○	○	○

To what extent do you agree or disagree that the sound environment during your soundwalk was…

	Strongly disagree	Disagree	Neither agree, nor disagree	Agree	Strongly agree
Pleasant	○	○	○	○	○
Chaotic	○	○	○	○	○
Vibrant	○	○	○	○	○
Uneventful	○	○	○	○	○
Calm	○	○	○	○	○
Annoying	○	○	○	○	○
Eventful	○	○	○	○	○
Monotonous	○	○	○	○	○

Which was your **favorite sound** heard during the soundwalk? [open question].
Which sound did you like **the least** during the soundwalk? [open question].
Enter the location closest to your soundwalk? [Street and number, Postal code, Municipality].
What is your gender? ["Man", "Woman", "Non-binary", "I prefer not to say"].
What is your birth year?

Appendix B

Figs. B1 and B2 display maps illustrating the extent to which natural and traffic sounds are heard. Figs. B3 to B5 show the perceived soundscape ratings in terms of pleasantness, calmness, and annoyance.

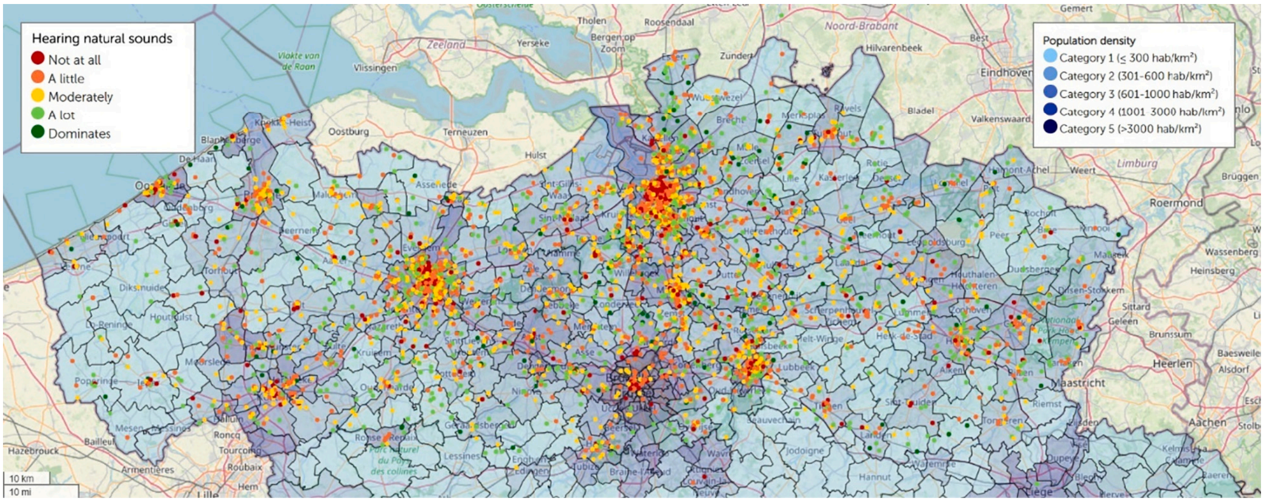

Fig. B1. Geographical spread of hearing natural sound categories across the sampled region, overlayed on the agglomeration population density map.

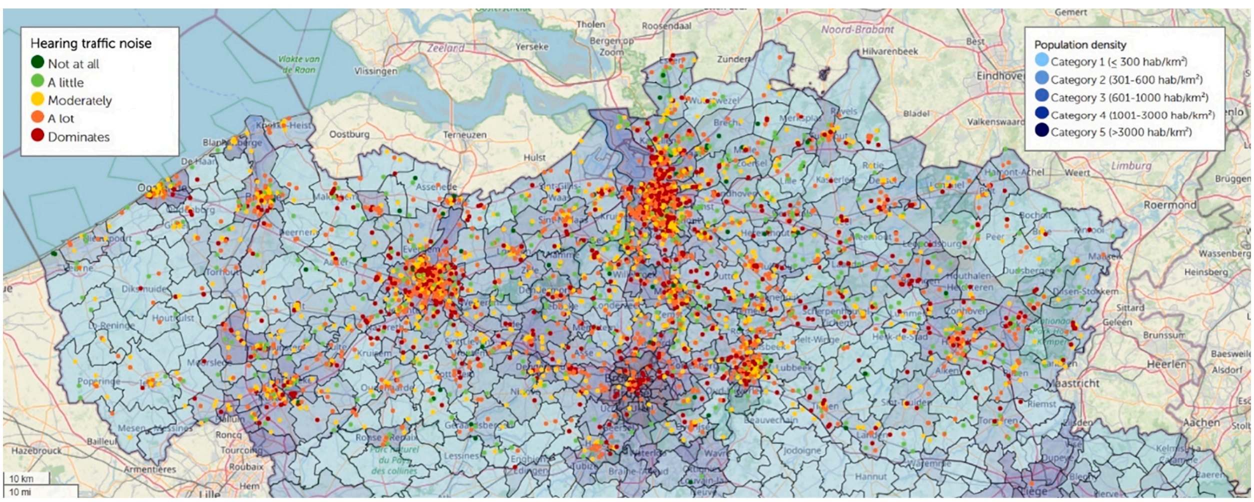

Fig. B2. Geographical spread of hearing traffic sound categories across the sampled region, overlayed on the agglomeration population density map.

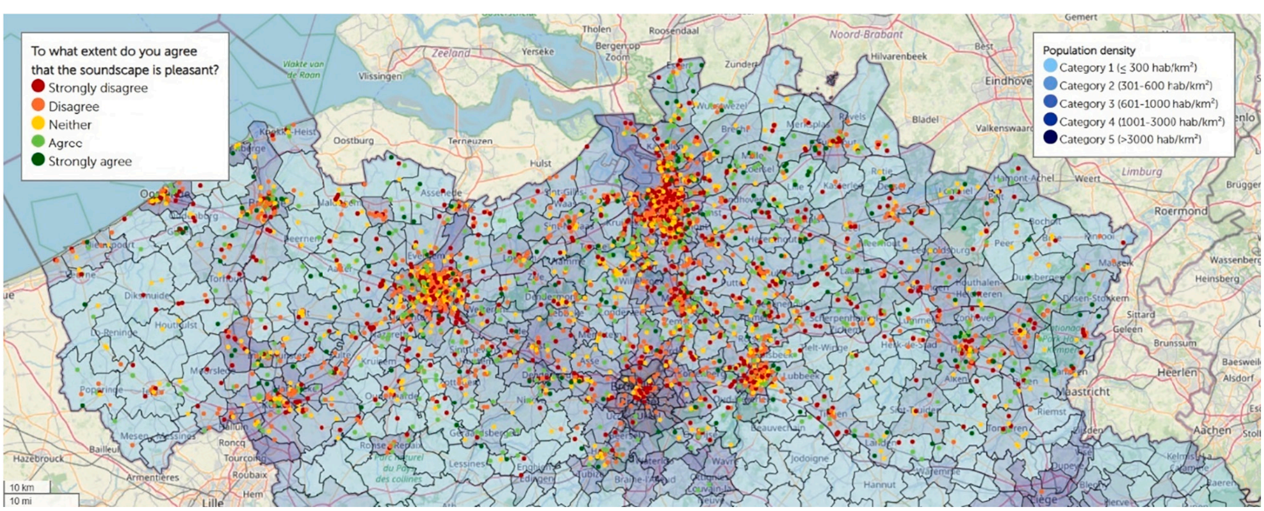

Fig. B3. Geographical spread of the pleasantness scores across the sampled region, overlayed on the agglomeration population density map.

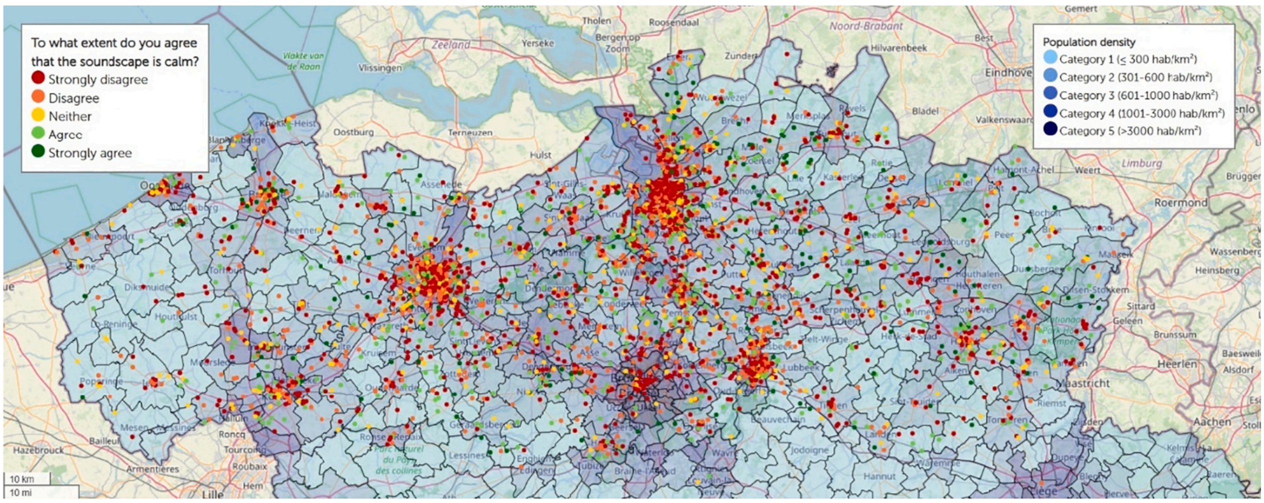

Fig. B4. Geographical spread of the calmness scores across the sampled region, overlayed on the agglomeration population density map.

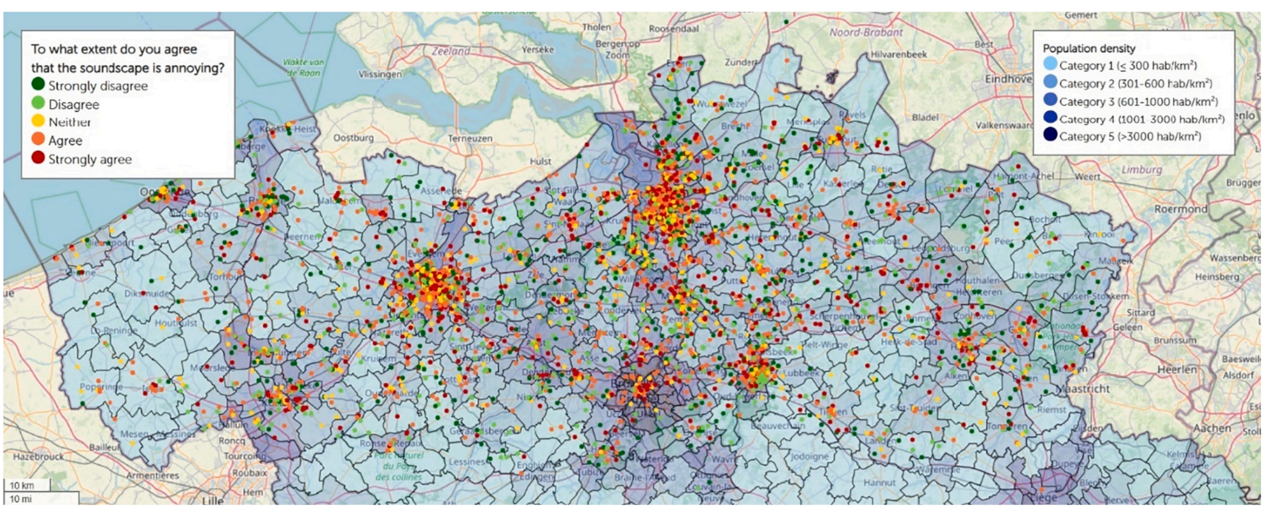

Fig. B5. Geographical spread of the annoyance scores across the sampled region, overlayed on the agglomeration population density map.

Appendix C

Hearing natural sounds, especially biophony, may vary by time of day. At night, lower anthropophony (e.g., reduced human activity) and geophony (e.g., lower wind speeds) could reduce overall sound levels. However, since the data reflects human perception, responses decline sharply at night, with most collected during the day (Fig. C1). Time of day is not a significant predictor for hearing a lot of natural sounds ($p = 0.927$) or moderately hearing them ($p = 0.189$). As a result, it is excluded from further analysis on soundscape perception.

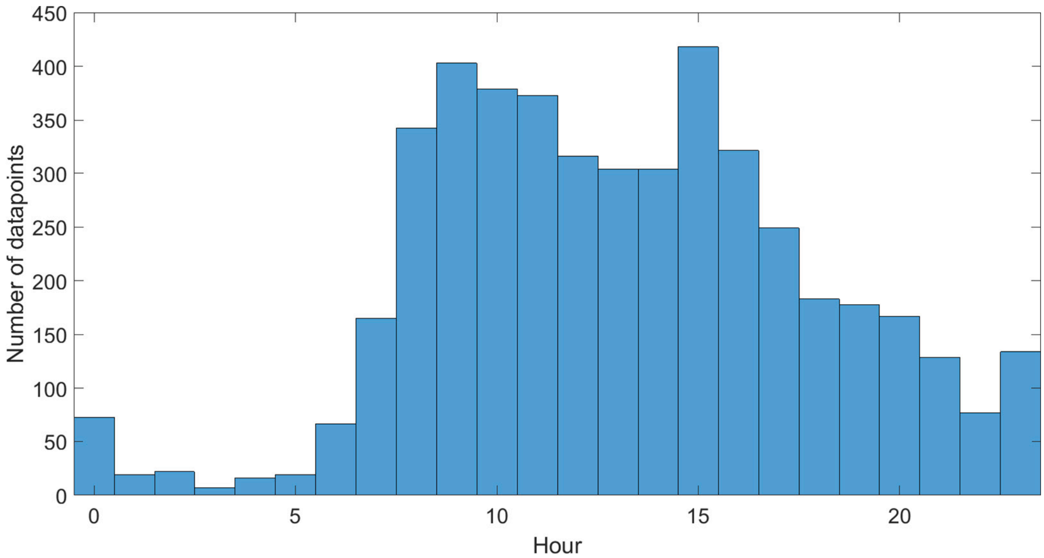

Fig. C1. Histogram showing the distribution of the number of datapoints over the hours of the day.

Appendix D

Tables D1 and D2 provide the *p*-values of paired *t*-tests to allow analyzing significant differences in the means (over all participants) for hearing natural sounds and hearing road traffic, between the different scores. In the tables below, "*" indicates statistically significance at the 0.05 level, "**" at the 0.01 level, and "***" at the 0.001 level. In Table D3, the mean scores and standard deviations are presented in numerical format, corresponding to Figs. 3 and 4.

Table D1
p-Values of paired *t*-tests to evaluate statistically significant differences between the mean ratings of the various natural sound hearing scores.

Pleasant	1	2	3	4	5	**Vibrant**	1	2	3	4	5
1	1	2.1E-15***	7.8E-59***	1.7E-122***	7.0E-51***	1	1	0.58	0.78	2.2E-03**	9.2E-10***
2		1	1.7E-28***	8.7E-96***	3.6E-40***	2		1	0.69	2.6E-07***	7.1E-12***
3			1	6.0E-28***	6.4E-27***	3			1	2.2E-06***	2.0E-11***
4				1	1.3E-11***	4				1	1.4E-06***
5					1	5					1

Eventful	1	2	3	4	5	**Chaotic**	1	2	3	4	5
1	1	0.86	0.49	0.76	0.22	1	1	1.3E-09***	3.5E-33***	8.6E-68***	1.4E-29***
2		1	0.20	0.49	0.22	2		1	1.8E-17***	7.8E-58***	8.2E-21***
3			1	0.62	0.08	3			1	1.0E-15***	6.9E-11***
4				1	0.14	4				1	2.8E-03**
5					1	5					1

Annoying	1	2	3	4	5	**Monotonous**	1	2	3	4	5
1	1	3.7E-07***	5.7E-30***	1.4E-63***	1.8E-32***	1	1	0.72	0.14	1.1E-11***	1.7E-09***
2		1	3.6E-18***	6.4E-57***	2.9E-25***	2		1	0.11	2.3E-19***	3.6E-10***
3			1	5.3E-15***	1.2E-14***	3			1	1.4E-13***	1.6E-08***
4				1	1.3E-05***	4				1	0.02*
5					1	5					1

Uneventful	1	2	3	4	5	**Calm**	1	2	3	4	5
1	1	0.02*	7.9E-08***	1.0E-07***	0.01**	1	1	3.3E-17***	5.2E-70***	1.4E-142***	7.5E-47***
2		1	1.0E-05***	1.6E-05***	0.08	2		1	4.7E-32***	3.6E-103***	4.6E-38***
3			1	0.86	0.93	3			1	9.8E-31***	3.5E-25***
4				1	0.86	4				1	8.0E-10***
5					1	5					1

Table D2
p-Values of paired *t*-tests to evaluate statistically significant differences between the mean ratings of the various traffic sound hearing scores.

Pleasant	1	2	3	4	5	Vibrant	1	2	3	4	5
1	1	0.08	4.7E−08***	1.4E−16***	1.6E−22***	1	1	0.04*	0.09	0.31	0.12
2		1	6.9E−43***	3.2E−175***	6.2E−279***	2		1	0.19	1.3E−04***	0.10
3			1	2.1E−95***	6.3E−255***	3			1	2.8E−03**	0.64
4				1	9.7E−96***	4				1	0.03*
5					1	5					1

Eventful	1	2	3	4	5	Chaotic	1	2	3	4	5
1	1	0.76	0.12	5.4E−03**	5.9E−03**	1	1	0.93	1.3E−03**	2.1E−12***	7.3E−19***
2		1	4.7E−05***	1.0E−17***	1.4E−14***	2		1	2.2E−28***	2.3E−164***	4.4E−268***
3			1	3.0E−08***	2.9E−06***	3			1	9.8E−89***	8.6E−208***
4				1	0.99	4				1	2.9E−56***
5					1	5					1

Annoying	1	2	3	4	5	Monoto nous	1	2	3	4	5
1	1	0.33	7.6E−07***	2.2E−15***	4.7E−21***	1	1	0.03*	3.9E−03**	4.7E−04***	3.2E−07***
2		1	4.8E−36***	1.9E−148***	1.3E−229***	2		1	0.05	3.7E−05***	7.8E−20***
3			1	1.4E−69***	1.4E−165***	3			1	0.01*	1.0E−17***
4				1	1.0E−46***	4				1	7.3E−12***
5					1	5					1

Un eventful	1	2	3	4	5	Calm	1	2	3	4	5
1	1	0.15	0.87	0.02*	4.5E−03**	1	1	0.03*	9.6E−11***	6.8E−19***	4.9E−23***
2		1	1.4E−06***	7.5E−32***	2.5E−35***	2		1	2.7E−55***	2.1E−183***	7.2E−252***
3			1	2.0E−17***	4.7E−21***	3			1	2.0E−79***	8.2E−185***
4				1	0.02*	4				1	1.7E−59***
5					1	5					1

Table D3
Mean scores (with 1 meaning "totally disagree" to 5 meaning "totally agree") on the soundscape perceptual attributes for different groupings. The standard deviations are put in between brackets.

	Natural = 1	Natural = 2	Natural = 3	Natural = 4	Natural = 5
Pleasant	1.7 (0.9)	2.1 (1.1)	2.6 (1.1)	3.1 (1.2)	3.8 (1.1)
Vibrant	3.0 (1.2)	2.9 (1.1)	2.9 (1.0)	3.1 (1.0)	3.6 (1.0)
Eventful	3.0 (1.1)	3.0 (1.0)	3.0 (1.0)	3.0 (1.0)	3.1 (1.1)
Chaotic	3.6 (1.2)	3.3 (1.2)	2.9 (1.3)	2.4 (1.3)	2.1 (1.3)
Annoying	3.9 (1.2)	3.6 (1.3)	3.2 (1.3)	2.7 (1.4)	2.2 (1.3)
Monotonous	2.7 (1.2)	2.6 (1.2)	2.6 (1.1)	2.2 (1.1)	2.0 (1.1)
Uneventful	2.0 (1.2)	2.2 (1.1)	2.4 (1.2)	2.4 (1.2)	2.3 (1.2)
Calm	1.4 (0.8)	1.7 (1.0)	2.2 (1.2)	2.8 (1.3)	3.6 (1.3)

	Traffic = 1	Traffic = 2	Traffic = 3	Traffic = 4	Traffic = 5
Pleasant	4.0 (1.2)	3.7 (1.1)	3.0 (1.0)	2.2 (0.9)	1.5 (0.7)
Vibrant	3.2 (1.2)	2.9 (1.1)	3.0 (1.0)	3.1 (1.0)	3.0 (1.2)
Eventful	2.7 (1.2)	2.7 (1.0)	2.9 (0.9)	3.1 (0.9)	3.1 (1.1)
Chaotic	1.8 (1.2)	1.8 (1.0)	2.4 (1.1)	3.3 (1.1)	3.9 (1.0)
Annoying	1.8 (1.2)	2.0 (1.2)	2.8 (1.2)	3.6 (1.1)	4.2 (1.1)
Monotonous	1.9 (1.1)	2.3 (1.1)	2.4 (1.0)	2.5 (1.1)	2.8 (1.3)
Uneventful	2.5 (1.2)	2.7 (1.2)	2.5 (1.1)	2.1 (1.1)	2.0 (1.2)
Calm	3.9 (1.2)	3.5 (1.2)	2.6 (1.2)	1.8 (0.9)	1.3 (0.6)

	Traffic = 2				
	Natural = 1	Natural = 2	Natural = 3	Natural = 4	Natural = 5
Pleasant	2.6 (1.2)	3.4 (1.2)	3.7 (0.9)	4.1 (0.8)	4.2 (1.0)
Vibrant	2.8 (1.3)	2.6 (1.0)	2.7 (1.0)	3.1 (1.0)	3.6 (1.1)
Eventful	2.7 (1.1)	2.6 (1.0)	2.6 (1.0)	2.8 (1.0)	3.1 (1.1)
Chaotic	2.7 (1.4)	2.0 (1.2)	1.7 (0.9)	1.5 (0.7)	1.7 (1.1)
Annoying	3.0 (1.6)	2.4 (1.4)	2.0 (1.1)	1.7 (0.9)	1.8 (1.1)
Monotonous	2.7 (1.3)	2.6 (1.1)	2.4 (1.1)	2.0 (1.0)	1.9 (1.2)
Uneventful	2.6 (1.3)	2.7 (1.2)	2.9 (1.2)	2.7 (1.1)	2.3 (1.3)
Calm	2.3 (1.1)	3.1 (1.3)	3.5 (1.0)	4.0 (1.0)	4.0 (1.1)

	Traffic = 3				
	Natural = 1	Natural = 2	Natural = 3	Natural = 4	Natural = 5
Pleasant	2.3 (1.0)	2.7 (1.0)	3.1 (1.0)	3.5 (0.9)	3.8 (1.1)
Vibrant	2.8 (1.1)	2.9 (1.0)	2.9 (0.9)	3.1 (1.0)	3.5 (1.0)
Eventful	2.7 (1.0)	3.0 (0.9)	2.9 (0.9)	2.9 (1.0)	3.1 (1.1)
Chaotic	2.9 (1.2)	2.6 (1.1)	2.3 (1.1)	2.0 (1.0)	2.5 (1.3)
Annoying	3.4 (1.2)	3.0 (1.2)	2.7 (1.2)	2.4 (1.2)	2.3 (1.2)
Monotonous	2.6 (1.1)	2.6 (1.0)	2.5 (1.0)	2.1 (1.0)	1.9 (1.0)
Uneventful	2.4 (1.1)	2.4 (1.0)	2.5 (1.1)	2.5 (1.1)	2.4 (1.1)
Calm	1.8 (0.9)	2.2 (1.0)	2.7 (1.1)	3.1 (1.1)	3.4 (1.3)

	Traffic = 4				
	Natural = 1	Natural = 2	Natural = 3	Natural = 4	Natural = 5
Pleasant	1.8 (0.8)	2.0 (0.8)	2.2 (0.9)	2.6 (1.0)	3.1 (1.0)
Vibrant	3.1 (1.1)	3.0 (1.0)	3.0 (1.0)	3.2 (0.9)	3.5 (0.8)
Eventful	3.1 (1.0)	3.1 (0.9)	3.2 (0.9)	3.1 (0.9)	3.1 (0.9)
Chaotic	3.7 (1.0)	3.4 (1.0)	3.2 (1.1)	2.9 (1.2)	2.5 (1.2)
Annoying	3.9 (1.0)	3.7 (1.0)	3.5 (1.1)	3.3 (1.2)	3.0 (1.3)
Monotonous	2.5 (1.1)	2.5 (1.1)	2.6 (1.1)	2.4 (1.1)	2.0 (0.8)
Uneventful	1.9 (1.0)	2.1 (1.0)	2.2 (1.1)	2.2 (1.1)	2.3 (1.0)
Calm	1.3 (0.6)	1.5 (0.8)	1.9 (0.9)	2.3 (1.1)	2.9 (1.2)

Appendix E

This appendix presents the logistic regression model parameters, for the different models constructed in this work. Table E1 shows results for high and moderate pleasantness, Table E2 for high and moderate calmness, and Table E3 for high and moderate annoyance, all with hearing natural sounds as the key predictor. Tables E4 and E5 provides model parameters for predicting hearing natural sounds to a large extent and to a moderate extent, respectively, using land use fractions as input variables. In the tables below, "*" indicates statistically significance at the 0.05 level, "**" at the 0.01 level, and "***" at the 0.001 level.

Table E1
Overview of the logistic model parameters for predicting pleasantness based on hearing natural sounds.

OUTCOME: high pleasantness		Coeff.	Standard error	*t*-Value	*p*-Value	
MODEL 1: single variable	(Constant)	−3.9076	0.131	−29.8	6.5E−195	***
	hearingnaturalsounds	0.9233	0.040	23.2	1.1E−118	***
MODEL 2: adjusted for hearingroadtraffic	(Constant)	1.1482	0.207	5.6	2.7E−08	***
	hearingnaturalsounds	0.8224	0.047	17.6	3.0E−69	***
	hearingroadtraffic	−1.4401	0.051	−28.0	9.5E−173	***
MODEL 3: including interactions	(Constant)	2.1217	0.534	4.0	7.0E−05	***
	hearingnaturalsounds	0.5027	0.167	3.0	2.6E−03	**
	hearingroadtraffic	−1.7644	0.173	−10.2	2.7E−24	***
	hearingnaturalsounds × hearingroadtraffic	0.1053	0.053	2.0	0.05	*

OUTCOME: moderate pleasantness		Coeff.	Standard error	*t*-Value	*p*-Value	
MODEL 1: single variable	(Constant)	−2.2324	0.095	−23.4	7.5E−121	***
	hearingnaturalsounds	0.7249	0.032	22.3	2.5E−110	***
MODEL 2: adjusted for hearingroadtraffic	(Constant)	2.9598	0.190	15.6	6.8E−55	***
	hearingnaturalsounds	0.6115	0.038	16.0	8.8E−58	***
	hearingroadtraffic	−1.3446	0.044	−30.6	3.7E−205	***
MODEL 3: including interactions	(Constant)	2.2432	0.469	4.8	1.7E−06	***
	hearingnaturalsounds	0.8784	0.166	5.3	1.2E−07	***
	hearingroadtraffic	−1.1452	0.127	−9.0	1.6E−19	***
	hearingnaturalsounds × hearingroadtraffic	−0.0739	0.045	−1.7	0.10	

Table E2
Overview of the logistic model parameters for predicting calmness based on hearing natural sounds.

OUTCOME: high calmness						
MODEL 1: single variable	(Constant)	−4.2396	0.143	−29.8	1.7E−194	***
	hearingnaturalsounds	0.9576	0.042	22.6	5.3E−113	***
MODEL 2: adjusted for hearingroadtraffic	(Constant)	0.5046	0.214	2.4	0.02	*
	hearingnaturalsounds	0.8354	0.048	17.3	9.4E−67	***
	hearingroadtraffic	−1.3416	0.052	−26.0	7.3E−149	***
MODEL 3: including interactions	(Constant)	1.6539	0.545	3.0	2.4E−03	**
	hearingnaturalsounds	0.4680	0.166	2.8	4.8E−03	**
	hearingroadtraffic	−1.7338	0.181	−9.6	1.0E−21	***
	hearingnaturalsounds × hearingroadtraffic	0.1242	0.054	2.3	0.02	*

OUTCOME: moderate calmness						
MODEL 1: single variable	(Constant)	−3.1744	0.111	−28.5	1.0E−178	***
	hearingnaturalsounds	0.8508	0.036	23.9	4.2E−126	***
MODEL 2: adjusted for hearingroadtraffic	(Constant)	1.8566	0.191	9.7	2.7E−22	***
	hearingnaturalsounds	0.7616	0.042	18.2	1.0E−73	***
	hearingroadtraffic	−1.3817	0.046	−29.7	1.7E−194	***
MODEL 3: including interactions	(Constant)	2.6338	0.490	5.4	7.7E−08	***
	hearingnaturalsounds	0.4925	0.160	3.1	2.1E−03	**
	hearingroadtraffic	−1.6199	0.147	−11.0	2.3E−28	***
	hearingnaturalsounds × hearingroadtraffic	0.0816	0.047	1.7	0.08	

Table E3
Overview of the logistic model parameters for predicting annoyance based on hearing natural sounds.

OUTCOME: high annoyance		Coeff.	Standard error	*t*-Value	*p*-Value	
MODEL 1: single variable	(Constant)	1.5339	0.088	17.4	1.6E−67	***
	hearingnaturalsounds	−0.5215	0.030	−17.2	5.9E−66	***
MODEL 2: adjusted for hearingroadtraffic	(Constant)	−2.8178	0.179	−15.8	6.5E−56	***
	hearingnaturalsounds	−0.3512	0.034	−10.3	1.0E−24	***
	hearingroadtraffic	1.0609	0.038	27.7	4.3E−169	***
MODEL 3: including interactions	(Constant)	−1.5100	0.410	−3.7	2.3E−04	***
	hearingnaturalsounds	−0.8369	0.144	−5.8	6.5E−09	***
	hearingroadtraffic	0.7067	0.107	6.6	3.5E−11	***

(*continued on next page*)

Table E3 (*continued*)

OUTCOME: high annoyance		Coeff.	Standard error	*t*-Value	*p*-Value	
	hearingnaturalsounds × hearingroadtraffic	0.1325	0.038	3.5	4.9E−04	***

OUTCOME: moderate annoyance						
MODEL 1: single variable	(Constant)	2.4963	0.102	24.5	9.0E−133	***
	hearingnaturalsounds	−0.6199	0.033	−18.8	1.1E−78	***
MODEL 2: adjusted for hearingroadtraffic	(Constant)	−1.7146	0.180	−9.5	1.3E−21	***
	hearingnaturalsounds	−0.4534	0.037	−12.3	8.8E−35	***
	hearingroadtraffic	1.0729	0.040	27.0	1.0E−160	***
MODEL 3: including interactions	(Constant)	−0.8293	0.414	−2.0	0.05	*
	hearingnaturalsounds	−0.7651	0.138	−5.6	2.8E−08	***
	hearingroadtraffic	0.8104	0.117	6.9	3.8E−12	***
	hearingnaturalsounds × hearingroadtraffic	0.0930	0.039	2.4	0.02	*

Table E4

Overview of the logistic model parameters for predicting hearing a lot of natural sounds based on the fraction of land use features within radii of 500 m, 250 m and 125 m. MODEL1 uses the fraction of (separate) green features, MODEL2 uses (separate) green features in combination with hearing road traffic, and MODEL4 uses all green features (except for the non-greenery fraction) as predictors.

		500 m					250 m					125 m				
OUTCOME: hearing at lot of natural sounds		Coeff.	Standard Error	t-value	p-value		Coeff.	Standard Error	t-value	p-value		Coeff.	Standard Error	t-value	p-value	
MODEL 1: single variable	(Constant)	−1.6654	0.090	−18.6	3.9E-77	***	−1.6346	0.080	−20.4	1.1E-92	***	−1.5742	0.072	−21.9	9.6E-107	***
	low_green	3.0468	0.413	7.4	1.7E-13	***	2.6894	0.342	7.9	3.6E-15	***	2.3149	0.288	8.0	9.9E-16	***
MODEL 2: adjusted for hearingroadtraffic	(Constant)	0.0437	0.150	0.3	0.77		0.0544	0.146	0.4	0.71		0.1031	0.142	0.7	0.47	
	low_green	2.8695	0.422	6.8	1.0E-11	***	2.4346	0.349	7.0	2.8E-12	***	2.0289	0.293	6.9	4.7E-12	***
	hearingroadtraffic	−0.4718	0.034	−13.7	9.3E-43	***	−0.4612	0.034	−13.4	7.9E-41	***	−0.4558	0.035	−13.2	1.2E-39	***
MODEL 1: single variable	(Constant)	−1.4569	0.071	−20.6	4.8E-94	***	−1.4184	0.064	−22.2	7.5E-109	***	−1.3960	0.057	−24.5	2.1E-132	***
	high_green	1.8543	0.323	5.7	9.1E-09	***	1.7355	0.293	5.9	3.3E-09	***	1.7445	0.254	6.9	5.9E-12	***
MODEL 2: adjusted for hearingroadtraffic	(Constant)	0.1760	0.137	1.3	0.20		0.2151	0.134	1.6	0.11		0.2514	0.131	1.9	0.05	
	high_green	1.9833	0.329	6.0	1.7E-09	***	1.8397	0.299	6.2	7.7E-10	***	1.7942	0.259	6.9	4.5E-12	***
	hearingroadtraffic	−0.4659	0.035	−13.5	3.0E-41	***	−0.4649	0.035	−13.4	4.5E-41	***	−0.4665	0.035	−13.5	2.1E-41	***
MODEL 1: single variable	(Constant)	−1.4501	0.046	−31.4	1.4E-216	***	−1.3689	0.043	−32.0	2.6E-224	***	−1.2747	0.040	−31.9	1.1E-222	***
	agricultural	2.5202	0.193	13.1	5.5E-39	***	2.6315	0.207	12.7	6.9E-37	***	2.2566	0.210	10.7	7.5E-27	***
MODEL 2: adjusted for hearingroadtraffic	(Constant)	0.0537	0.132	0.4	0.68		0.1520	0.130	1.2	0.24		0.3025	0.127	2.4	0.02	*
	agricultural	2.2424	0.198	11.3	1.2E-29	***	2.3726	0.213	11.2	6.7E-29	***	2.0492	0.216	9.5	2.6E-21	***
	hearingroadtraffic	−0.4118	0.035	−11.8	4.9E-32	***	−0.4199	0.035	−12.0	2.2E-33	***	−0.4387	0.035	−12.7	1.0E-36	***
MODEL 1: single variable	(Constant)	0.2859	0.077	3.7	2.1E-04	***	0.2883	0.079	3.7	2.4E-04	***	0.2180	0.078	2.8	5.0E-03	**
	non_green	−3.0834	0.170	−18.1	2.2E-73	***	−2.8753	0.161	−17.9	2.7E-71	***	−2.6115	0.151	−17.3	5.0E-67	***
MODEL 2: adjusted for hearingroadtraffic	(Constant)	1.5375	0.139	11.1	1.4E-28	***	1.5762	0.140	11.3	2.2E-29	***	1.5491	0.140	11.1	2.0E-28	***
	non_green	−2.8049	0.173	−16.2	2.5E-59	***	−2.6321	0.164	−16.1	3.3E-58	***	−2.3934	0.154	−15.6	1.3E-54	***
	hearingroadtraffic	−0.3861	0.035	−11.0	5.2E-28	***	−0.3942	0.035	−11.2	2.8E-29	***	−0.4045	0.035	−11.5	7.8E-31	***
MODEL 4: full model	(Constant)	−1.2989	0.184	−7.1	1.5E-12	***	−1.1095	0.173	−6.4	1.4E-10	***	−0.9128	0.165	−5.5	3.1E-08	***
	low_green	2.9559	0.463	6.4	1.7E-10	***	2.8768	0.378	7.6	2.9E-14	***	2.7781	0.317	8.8	2.1E-18	***

(*continued on next page*)

Table E4 (*continued*)

		500 m					250 m					125 m				
OUTCOME: hearing at lot of natural sounds		Coeff.	Standard Error	t-value	*p*-value		Coeff.	Standard Error	t-value	p-value		Coeff.	Standard Error	t-value	p-value	
	high_green	3.2227	0.287	11.2	2.4E-29	***	2.8479	0.255	11.2	5.4E-29	***	2.4604	0.223	11.0	2.4E-28	***
	agricultural	2.6909	0.188	14.3	1.5E-46	***	2.5680	0.189	13.6	4.6E-42	***	2.2786	0.185	12.3	5.2E-35	***
	hearingroadtraffic	−0.3999	0.036	−11.3	2.0E-29	***	−0.4041	0.036	−11.4	5.2E-30	***	−0.4098	0.036	−11.5	9.1E-31	***

Table E5
See Table E4, but now for at least moderately hearing natural sounds.

		500 m					250 m					125 m				
OUTCOME: moderately hearing natural sounds		Coeff.	Standard Error	t-value	p-value		Coeff.	Standard Error	t-value	p-value		Coeff.	Standard Error	t-value	p-value	
MODEL 1: single variable	(Constant)	−0.6550	0.074	−8.8	1.3E-18	***	−0.5778	0.066	−8.7	2.7E-18	***	−0.4678	0.060	−7.9	3.8E-15	***
	low_green	4.3436	0.363	12.0	6.2E-33	***	3.7851	0.304	12.5	1.2E-35	***	3.1595	0.260	12.1	6.2E-34	***
MODEL 2: adjusted for hearingroadtraffic	(Constant)	0.9939	0.139	7.2	8.1E-13	***	1.0538	0.136	7.8	7.7E-15	***	1.1205	0.133	8.4	3.5E-17	***
	low_green	4.2761	0.372	11.5	1.3E-30	***	3.6386	0.310	11.7	9.7E-32	***	2.9739	0.266	11.2	4.9E-29	***
	hearingroadtraffic	−0.4424	0.032	−14.0	1.5E-44	***	−0.4333	0.032	−13.7	7.1E-43	***	−0.4196	0.032	−13.3	1.8E-40	***
MODEL 1: single variable	(Constant)	−0.2293	0.061	−3.7	1.8E-04	***	−0.1969	0.055	−3.6	3.8E-04	***	−0.1174	0.049	−2.4	0.02	*
	high_green	2.0860	0.299	7.0	3.0E-12	***	2.0192	0.276	7.3	2.5E-13	***	1.6414	0.242	6.8	1.2E-11	***
MODEL 2: adjusted for hearingroadtraffic	(Constant)	1.4088	0.130	10.9	1.5E-27	***	1.4367	0.127	11.3	1.2E-29	***	1.5186	0.125	12.1	7.8E-34	***
	high_green	2.3029	0.309	7.5	9.0E-14	***	2.2168	0.286	7.8	8.8E-15	***	1.7410	0.250	7.0	3.4E-12	***
	hearingroadtraffic	−0.4531	0.031	−14.4	5.9E-47	***	−0.4508	0.031	−14.3	1.3E-46	***	−0.4472	0.031	−14.3	3.5E-46	***
MODEL 1: single variable	(Constant)	−0.1768	0.038	−4.7	2.7E-06	***	−0.1010	0.035	−2.9	4.2E-03	**	−0.0258	0.034	−0.8	0.44	
	agricultural	2.8439	0.205	13.9	1.1E-43	***	3.0439	0.234	13.0	9.9E-39	***	2.8270	0.248	11.4	4.4E-30	***
MODEL 2: adjusted for hearingroadtraffic	(Constant)	1.3112	0.126	10.4	1.7E-25	***	1.4109	0.124	11.4	7.3E-30	***	1.5218	0.123	12.4	3.1E-35	***
	agricultural	2.6019	0.209	12.5	1.3E-35	***	2.8102	0.237	11.8	2.5E-32	***	2.6466	0.251	10.5	6.3E-26	***
	hearingroadtraffic	−0.3944	0.032	−12.4	1.9E-35	***	−0.4032	0.032	−12.7	4.7E-37	***	−0.4150	0.032	−13.1	1.7E-39	***
MODEL 1: single variable	(Constant)	1.6180	0.079	20.6	6.2E-94	***	1.6788	0.082	20.5	2.8E-93	***	1.6420	0.082	20.0	5.7E-89	***
	non_green	−2.9594	0.147	−20.1	7.7E-90	***	−2.8978	0.145	−20.0	2.5E-89	***	−2.7170	0.139	−19.6	2.2E-85	***
MODEL 2: adjusted for hearingroadtraffic	(Constant)	2.9664	0.143	20.7	3.2E-95	***	3.0580	0.146	21.0	1.1E-97	***	3.0391	0.146	20.9	9.3E-97	***
	non_green	−2.7580	0.150	−18.4	1.6E-75	***	−2.7228	0.147	−18.5	2.6E-76	***	−2.5547	0.141	−18.1	5.9E-73	***
	hearingroadtraffic	−0.3897	0.033	−11.9	1.4E-32	***	−0.3962	0.033	−12.1	1.1E-33	***	−0.4003	0.033	−12.3	1.1E-34	***
MODEL 4: full model	(Constant)	0.0802	0.156	0.5	0.61		0.2322	0.150	1.6	0.12		0.3650	0.145	2.5	0.01	*
	low_green	3.4256	0.389	8.8	1.2E-18	***	3.3239	0.320	10.4	3.1E-25	***	3.1715	0.273	11.6	3.4E-31	***
	high_green	2.8443	0.283	10.0	9.5E-24	***	2.6314	0.254	10.4	3.8E-25	***	2.2365	0.219	10.2	1.5E-24	***
	agricultural	2.6111	0.187	14.0	2.3E-44	***	2.6148	0.199	13.2	1.6E-39	***	2.5146	0.200	12.5	4.2E-36	***
	hearingroadtraffic	−0.3893	0.033	−11.8	2.3E-32	***	−0.3934	0.033	−12.0	3.7E-33	***	−0.3856	0.033	−11.8	3.2E-32	***

Data availability

Data will be made available on request.

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