Urban Forestry & Urban Greening 88 (2023) 128072

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug

Original article

Road traffic noise annoyance mitigation by green window view: Optimizing green quantity and quality

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A R T I C L E I N F O

Keywords:
Audio-visual interactions
Green quality
Green quantity
Noise annoyance
Road traffic noise
Scenic beauty

A B S T R A C T

There is convincing real-life evidence that seeing outdoor vegetation through the windows of one's dwelling is able to mitigate negative health effects due to exposure to environmental noise, in particular for noise annoyance due to road traffic. However, design guidelines with respect to green quantity and quality to maximally benefit from this audio-visual interaction are currently lacking, but are mandatory when this idea is to be used in urban sound (and green) planning. Therefore, two virtual reality (VR) experiments were conducted, where participants were positioned near the window of a living room overlooking a city ring road, where the central reservation was used to design various greening scenarios. Participants were exposed to an A-weighted equivalent sound pressure level of 67 dB at eardrum (window partly opened). In the first experiment (79 participants), containing trees of two visually similar tree species, the optimal green quantity (using RGB greenness) was found to be near 30%. This effect, however, was not very pronounced and only amounted to 0.5 units on an 11-point noise annoyance scale. Only the very dense vegetation belt (50%) lead to a higher self-reported noise annoyance at the 5% statistical significance level. In the second VR experiment (62 other participants), vegetation quantity was fixed near this optimum, while green quality varied on the dimensions species richness, colorfulness, and maintenance degree. Green infrastructure containing most colors, or those containing most species, lead to a minimum in self-reported noise annoyance (0.7 units difference on the 11-point annoyance scale). Further analysis suggested that aesthetic value of the green infrastructure is the driving factor for the positive audio-visual interactions observed, consistent with the presumed mechanisms why green window view is able to reduce noise annoyance at home.

1. Introduction

The burden of disease by environmental noise is large. With every new report published by renowned institutions like the World Health Organization (WHO, 2018), the scientific evidence becomes increasingly acknowledged. Environmental noise is one of the few environmental problems that did not reach a turning point towards improvement and is even expected to keep on increasing following the European Environmental Agency (EEA, 2017). Environmental noise exposure does not only have an impact on human health (such as disturbing the essential functions sleep has for the human body, stress related symptoms linked to noise annoyance, ischemic heart diseases, tinnitus and cognitive impairment in children) (WHO, 2011), it also lowers the quality of life and well-being. Conservative estimates indicate that 1–1.5 million of healthy life years are lost every year in the western part of Europe only due to exposure to road traffic noise, already in 2011 (WHO, 2011). Of these life years lost, nearly 600,000 could be attributed to noise annoyance (WHO, 2011). Consequently, annoyance in the population is an important policy indicator with relation to environmental noise in many countries.

Especially in the urban fabric, noise is a major problem. Interviews with environmental officers at cities all over Europe learns that this issue is usually listed at a second place among pressing and current environmental issues (Van Renterghem et al., 2019). Nowadays, about 56% of the world's population is living in cities, a number that is expected to increase to 70% by 2050 (worldbank.org). This increased city densification is likely to a aggravate the environmental noise issue for the next generations of citizens.

There is convincing real-life evidence that seeing outdoor vegetation through the windows of one's dwelling is able to reduce noise annoyance. Li et al. (2010), e.g., showed that visible outdoor greenery reduces self-reported noise annoyance for residents of high-rise buildings. The category "a lot of greenery, parks and gardens" lead to a 2-point shift towards less annoyance (on an eleven-point scale) when compared to

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https://doi.org/10.1016/j.ufug.2023.128072
Received 17 May 2023; Received in revised form 30 August 2023; Accepted 1 September 2023
Available online 6 September 2023

"no greenery". Along the highly noise-exposed inner-city ring road of Ghent (Belgium), outdoor vegetation as seen from the living room showed to be a strong predictor of self-reported noise annoyance. No view on vegetation resulted in a 34% chance of being at least moderately annoyed (scoring at least 3 on a 1-to-5 scale) by road traffic noise, while this chance reduced to only 8% for respondents having extensive vegetation views (Van Renterghem and Botteldooren, 2016). Leung et al. (2017) found that the probability of high annoyance when viewing walls was 26%, while with vision on greenery this percentage reduced to only 5%. In a nation-wide noise annoyance survey performed in Switzerland (Schäffer et al., 2020), complemented with spatial green analysis at each address point, it was found that (general) neighborhood green lead to a 6 dB "equivalent noise reduction" when analyzing noise annoyance from road traffic noise sources. Further analysis by Schäffer et al. (2020) revealed that in the urban environment, actual vision on outdoor greenery was found to be more important than e.g. in a rural setting.

In the meta-analysis by Van Renterghem (2019), existing research was analyzed in view of three potentially explaining mechanisms why green window view works for noise annoyance mitigation, regardless of level reductions. These were source (in)visibility, the mere presence of visible green, and vegetation as a source of natural sounds. It was concluded that the restorative properties of visible vegetation is the dominant mechanism. Visible natural features lead to sustained attention restoration (Kaplan et al., 1989) and stress relief (Ullrich, 1991), counteracting negative outcomes of endured exposure to environmental noise (Van Renterghem, 2019).

The concept of "inattentional deafness" can be mentioned as well as an explanation; Macdonald and Lavie (2011) showed in their experiments that a demanding visual task is able to suppress noticing of a task-irrelevant auditory cue. This indicates that there is a shared attentional capacity between modalities (here vision and hearing) in our brains. When extending to environmental noise exposure, this means that an attention attracting visual could reduce the attention paid to environmental noise, which is commonly an irrelevant stimulus. Vegetation has the ability to do so. Although people do not constantly stare through the windows when being at home, both Kaplan (2001) and Ulrich (2002) found that positive effects in response to seeing vegetation already appear after very short exposures (in the order of seconds/minutes).

Although the aforementioned studies and discussions showed and explained the effect of vegetation views on noise annoyance reduction, they do not directly lead to urban greening design guidelines. This is an important condition for this positive audio-visual interaction to become part of the urban sound planning toolbox.

The previously mentioned green view noise annoyance studies at home (Li et al., 2010; Van Renterghem and Botteldooren, 2016; Leung et al., 2017; Schäffer et al., 2020) seem to suggest that the more green, the stronger the expected effect. Secondly, the situation "as is" was studied, containing a mixture of different green infrastructural elements in all cases. Although these studies were performed in fully ecologically valid contexts, systematic studies on both optimal green quantity and quality are nevertheless needed.

The aim of the current study is to explore the effect of green quantity and green quality in the window view on self-reported noise annoyance. Therefore, two virtual reality (VR) experiments were conducted, where a main benefit is having full control on the audio-visual environment. VR studies are becoming a key methodology for studies focusing on audio-visual interactions in environmental perception and soundscapes (Li and Lau, 2020). Similarly, VR environments were found to be suitable to study human-nature interactions (Annerstedt et al., 2013). The participants were positioned near the window of a virtual living room overlooking a city ring road, where the central reservation was used to design various greening scenarios. In a first experiment (experiment 1), focusing on green quantity, only trees were considered, with increasing density. In a follow-up study (experiment 2), this optimum green quantity was then used as a starting point, and the effect of green quality was investigated.

2. Methodology

2.1. Virtual reality environment

The virtual environment was a living room at the first floor of a terraced house, overlooking a road with 2 times 2 lanes, accompanied by 2 parking lanes (see Fig. 1). The vegetation was positioned along a relatively spacious central reservation. At least 1 driving direction (2 lanes) was directly visible in all scenarios; in case of low density vegetation, all 4 lanes were visible. The 3D modelling was performed with Rhinoceros and Autodesk Revit. Twinmotion was used for the rendering, having extensive vegetation libraries.

The VR environment was animated, with road vehicles passing-by on all lanes and manually tuned to have a similar averaged intensity and vehicle speed as during the recordings (see Section 2.2). The animation included occasional pedestrians and bicyclists passing by.

To be visually immersed in the virtual reality environment, the participants used a HTC Vive Pro Eye head-mounted device (resolution of 2880 ×1600 pixels, a 90 Hz refresh rate, and a field of view of 110°). Two HTC steamVR base stations were positioned on tripods and calibrated to track location.

2.2. Sound recording and reproduction

Binaural recordings where made with a head-and-torso simulator (HATS) inside a real-life dwelling (see Fig. 2) on which the modeled VR environment was partly based. A B&K type 4128 C HATS was used, including two calibrated ear simulators type B&K 4158/4159, containing each a ½" microphone, and with realistic (soft) pinnae (Shore-OO 35). A calibration signal of 94 dB (at 1 kHz) was recorded (provided by a calibrator SVANTEK SV30A) for further processing to absolute sound pressure levels.

The HATS was positioned (frontal view towards the road) at close distance from the slightly ajar window. During the recordings, the traffic was dense but freely flowing, and individual cars could not be heard. Road traffic noise dominated the acoustic environment at the recording location and other types of sounds could not be easily identified. The equivalent sound pressure level, averaged across both eardrums of the HATS, was measured at 67 dBA.

Although the participants had the freedom to visually explore the virtual living room, their position was fixed (close to the window, as during the sound recordings with the HATS), preventing level differences as would be observed when moving away from the window. Directional sound was not considered, which can be – at least to some extent - justified by the dense and continuous traffic and by the fact that participants were encouraged to look through the window given their counting task (see Section 2.3).

About 15 min of undisturbed traffic sounds were recorded, from which 5-minute fragments were selected (see Section 2.3), meaning that the sounds were similar but not identical. The recordings were appropriately filtered to have exactly the same sound fields when reproduced by the circumaural headphones (Sony MDR CD770) used in the VR environment. This operation cancels the ear canal resonance from the recordings, compensates for the non-flatness of the headphone's frequency response and accounts for the headphone's sealing. In a final step, each individual fragment was equalized to 67 dBA equivalent sound pressure level.

2.3. Exposure duration

The total duration of the experiment for a single participant was intended to be roughly one hour, including introduction, getting accustomed to the VR audio-visual environment, experiencing the

Fig. 1. Overview picture of the animated virtual exterior environment in experiment 1. The participants were positioned in the living room at the first floor inside the white building (shown at the bottom).

Fig. 2. Photograph of the head-and-torso simulator, measuring binaural road traffic sound, forming the basis for the sound reproduction in the virtual reality experiments. A frontal positioning was chosen in front of a slightly opened window in a real-life setting.

various greening scenarios, and filling in a number of surveys. Essentially, noise annoyance is a long-term construct and a long exposure duration would be needed for an accurate assessment of each scenario. At the other hand, respondents should not lose motivation during their participation. As a compromise, each participant was exposed to 5 different greening scenarios, each time for 5 min.

As an additional argument, Wu et al. (2023) found that a 5-minute exposure to virtual natural landscapes lead to the greatest stress recovery in their test panels when compared to shorter (1 min) or longer exposures (15 min). Stress reduction is thought to be a main underlying factor with relation to the noise annoyance mitigation due to green window view. In this way, effects in the VR experiment could potentially be maximized.

While experiencing the greening scenarios, people were engaged in a light cognitive task. They were tasked with counting the number of bicyclists passing by in each scenario (during the green quantity study), or alternatively, counting the occurrences of cars in a specific color (during the green quality study). This was not only to prevent boredom but ensured people were most of the time looking towards the traffic and green belt, consistent with the fact that directional audio was not accounted for.

2.4. Experiment 1: green quantity scenarios

Green quantity was assessed using the RGB greenness parameter (Ahmad et al., 2007; Richardson et al., 2007; Crimmins and Crimmins, 2008) and calculated as (G-R)+(G-B), where G, R and B are the relative intensities of the green, red and blue channels in the RGB picture, respectively. In a next step, an appropriate threshold was set. The jpeg picture format (exported from the renderings) is well suited for such an image processing (Lebourgeois et al., 2008). A more robust assessment of green vegetation is the normalized difference vegetation index (NDVI), but would require a measurement of near infrared light. Nevertheless, RGB greenness performs similar to NDVI in capturing the amount of vegetation following Richardson et al. (2007).

Two types of trees, nl. red oaks (*Quercus rubra*) and American plane trees (*Platanus occidentalis*) were chosen (see Fig. 3). These species were chosen for their big leaves allowing to achieve high RGB greenness values. Both species have a rather similar appearance. The central reservation was grass-covered in all scenarios, without bushes, and with some low herbs for a more realistic appearance. Vegetation densities for the 5 scenarios were 11.8% (scenario 1, only grass), 19.7% (scenario 2), 29.9% (scenario 3), 40.8% (scenario 4) and 51% (scenario 5), as shown in Fig. 4. In the remainder of the text, the scenarios will be indicated by rounding to multiples of 10%. Note that only green pixels were counted here in the window view (see Fig. 5), making no distinction between grass and leaves. Green scenario 5 (see Fig. 4) is extremely dense (and unrealistic) but was deliberately included in this analysis to cover the full range.

2.5. Experiment 2: green quality scenarios

In this work, quality of the green infrastructure is defined along the dimensions species richness, color richness and maintenance degree. These dimensions were chosen given their potential impact on people such as stress reduction, general health, visual preference, assigned aesthetic value, etc. (Tyrväinen et al., 2003; Todorova et al., 2004; Dallimer et al., 2012; Sang et al., 2016; Hoyle et al., 2017; Hoyle et al., 2018; Wood et al., 2018; Li et al., 2019; Houlden et al., 2021; Marselle et al., 2021; Methorst et al., 2021; Tomitaka et al., 2021; Zhang et al., 2023).

The true species richness can be directly assessed by the number of different tree species, grasses, bushes and flowers that were added to each scenario. Note that perceived species richness might deviate from the true species richness, and that perceived richness might be more important in practice (Schebella, 2019; Breitschopf and Bråthen, 2023). Color richness is defined here by the presence and the extent of colors contrasting with the greenish hues (more precisely red, orange, pink and purple). Scoring high on maintenance uses the following criteria: the grass is short and cut; there are little to no weeds and herbs present; trees, shrubs and bushes are planted in rows at more or less equal distances, and flower beds (if present) do not mix. Note that the quality dimensions used here strongly correlate.

The five greening scenarios are depicted in Fig. 6, as seen from the window in the living room shown in Fig. 7. Their properties are summarized in Table 1. Scenario 5 scores highest on species richness, containing 19 different plant species, including 7 tree species (sweet birch, grey birch, red oak, sassafras, horse chestnut, European beech, and peach tree). In contrast, scenario 1 only contains some types of grasses and two tree species. Large zones of various colors contrasting with green are found in scenario 4, followed by scenario 3. The best maintained green belt is scenario 3 given the short and cut grassland, the near absence of weeds and herbs, the large flower beds that do not mix, and where both trees and bushes are planted in straight lines at equal distance. Scenario 1 closely follows, but does not contain flower beds. Scenario 5 is clearly the least maintained and wildest vegetation belt. The vegetation quantities (see Section 2.4, including non-green vegetation) were in all scenarios near the optimum green percentage from experiment 1 (see Section 3.2 and Table 1).

2.6. Test panel recruitment

Participants were recruited by flyers, posters in university buildings, and by posts on social media platforms. The call did not mention the true goal of the experiment, but was announced generally as research on the quality of the urban living environment. Prospective participants were informed that the experiment would be performed with virtual reality equipment, and that people with (self-declared) normal hearing and normal (or corrected) vision could participate, and should be at least 18 years old. It was advertised that participants in the study would be rewarded a voucher worth 10 Euro after completion of the experiment. Two separate recruitment campaigns were held, a first one for the study with relation to green quantity, and a second one with relation to green quality. Participation in both experiments was unlikely.

The participants signed an informed consent stating that their participation was voluntary and that they could stop at any moment during the experiment, and gave their permission for use of the data collected with respect for privacy and confidentiality. The experiment was approved by the Ethical Commission of the Faculty of Arts and Philosophy at Ghent University, on the 18th of January 2021, under file number 202160.

2.7. Evaluations, audio-visual dominance test, personal characteristics, and standardized surveys

After each green scenario (shown in randomized order), the main question the participants got was: “While experiencing the last environment, to what extent were you annoyed or not annoyed by the road traffic noise?”. People had to answer on an 11-point scale (ranging from 1 to 11), with textual indication of the endpoints (“not at all annoyed” vs

Fig. 3. Rendered view from within the green belt (experiment 1).

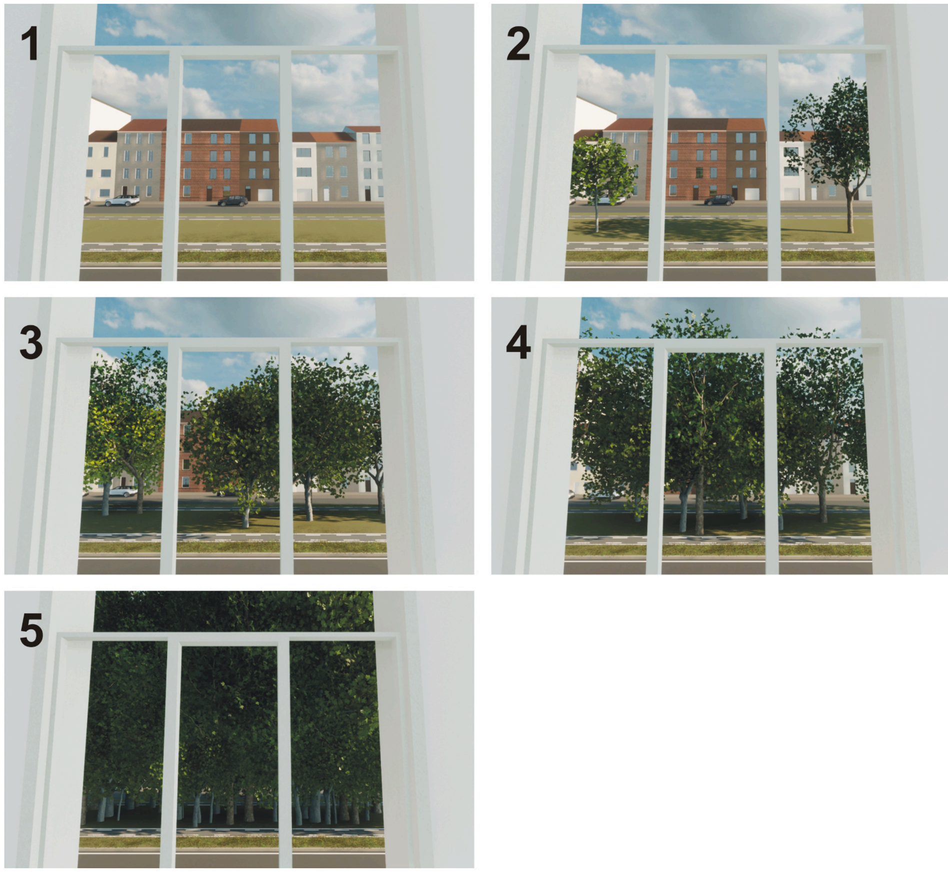

Fig. 4. Vegetation scenarios in experiment 1 as seen through the window of the virtual living room. An increasing vegetation density is modeled when going from scenario 1 (10%: no trees, only grass) to scenario 5 (50%: extremely dense vegetation scenario), at intervals of roughly 10%.

Fig. 5. The virtual reality living room with a window overlooking the green belt (experiment 1).

“extremely annoyed”).

Additional questions were asked after each scenario to prevent people focusing too much on the noise. Questions were asked relating to the quality and safety of the cycling path and the walkways. In the green quality experiment (experiment 2), people were also asked to rate the aesthetic value of the green belt (on a 5-point scale, with textual indications “not beautiful” (1), “rather not beautiful” (2), “neutral” (3), ”rather beautiful” (4), “beautiful” (5)). The follow-up of the questions after each scenario was randomized.

After having experienced all scenarios, each participant performed an audio-visual dominance/acuity test, based on an object recognition task by Giard and Peronnet (1999), and implemented by De Winne et al. (2022). In front of a computer screen, participants were randomly presented with two objects, A and B, and were asked to correctly classify

Fig. 6. Vegetation scenarios in experiment 2 as seen through the window of the virtual living room. Scenario 3 is considered the best maintained one, scenario 4 is most colorful and scenario 5 has the largest number of different plant species.

these objects as fast as possible by pressing the left or down arrow key, corresponding to object A and B, respectively. Objects were defined by visual features alone, auditory features alone or in combination. The visual part of the object consisted of a circle deforming into an ellipse, either horizontally (object A) or vertically (object B). The auditory part consisted of a pure tone of 540 Hz (object A) or 560 Hz (object B). After every trial, reaction time and response correctness were recorded. The test resulted in an average correctness scoring for audio only, video only, and audio-visual cues, together with the reaction times (6 parameters in total).

Fig. 7. The virtual reality living room with a window overlooking the green belt (experiment 2).

Table 1
Overview of the properties of the different scenarios in experiment 2, showing vegetation density and information regarding the green quality dimensions considered. When ranking, "5" means scoring highest and "1" scoring lowest among the scenarios considered.

Scenario	Vegetation percentage (all colors)	Number of species added	Species richness ranking	Green management ranking	Colors other than green/brown	Color richness ranking
1	33.7	5	1	4	None	1
2	37.9	9	2	3	small zones of pink, distributed red/orange	3
3	28.0	11	3	5	large zone of red/orange, large zone of purple	4
4	29.1	15	4	2	full purple ground cover, distributed red/orange, red trees	5
5	35.5	19	5	1	distributed purple	2

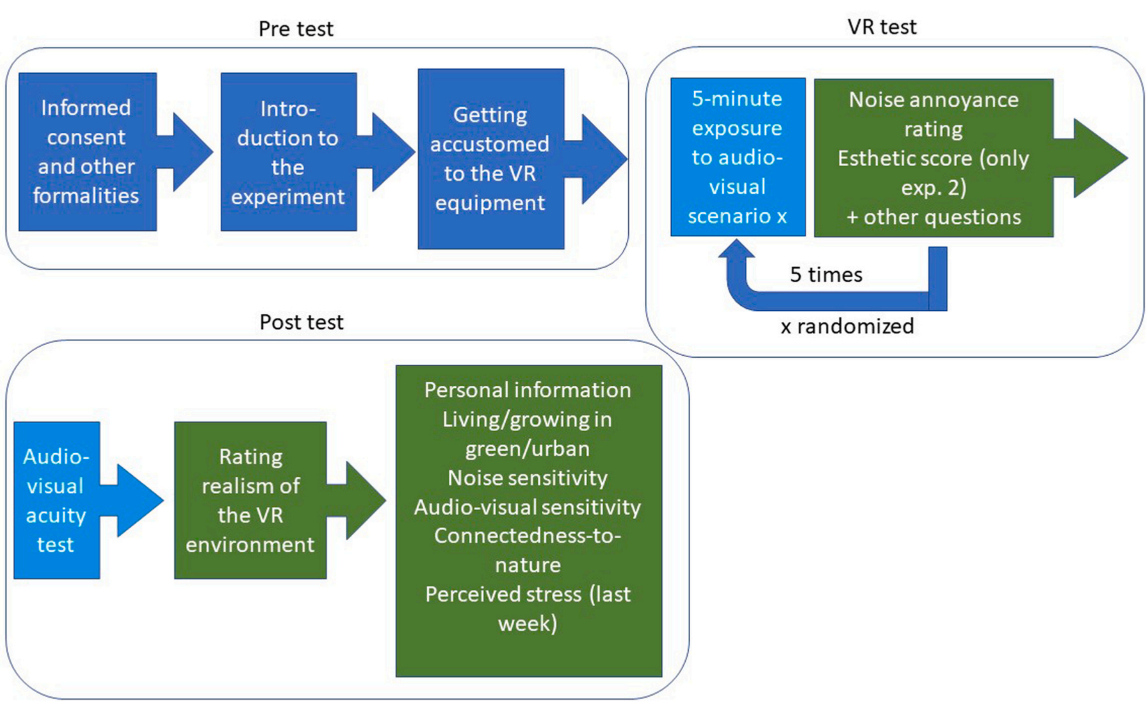

Fig. 8. Flow chart of the experimental procedure.

In a next step, people where asked for personal characteristics such as gender, year of birth, highest diploma, and professional status. Additional questions were asked to know whether participants grew up in a green environment, whether they grew up in an urban environment, whether they were currently living in a green environment, and whether they were currently living in an urban environment. Note that e.g. living in an urban environment does not necessarily exclude living in a green environment. Each time, a 5-point scale was used. People were also asked to rate the (overall) realism of the virtual reality experience ("not at all realistic", "little realistic", "neutral", "realistic", "very realistic").

Finally, some standardized and widely used sets of questions were administered. This involved a 10-item (Benfield et al., 2014) Dutch adaption (Aletta et al., 2018) of the Weinstein's noise sensitivity scale (Weinstein, 1978), 3 questions related to audio-visual sensitivity (as used in previous studies such as Aletta et al., 2018), the 14-item connectedness to nature scale (Mayer and Frantz, 2004), and the 14-item (original) perceived stress scale (Cohen et al., 1983). For the latter, the time frame was reduced to the week prior to the participation. All questionnaires contained a number of reversed questions to keep respondents attentive when answering. The experimental procedure for each test person is summarized in Fig. 8.

2.8. Data analysis

2.8.1. Artificial neural network

An artificial neural network is used to analyze the data sets gathered. Artificial neural networks (ann) are well-established supervised machine learning fitting algorithms and related functions implemented in Matlab (2022) were used. Bayesian regularization was followed by using the "trainbr" network training function. This procedure updates the weight and bias values according to Levenberg-Marquardt optimization. It minimizes a combination of squared errors and weights, and then determines the correct combination to produce a network that typically generalizes well. A main drawback, but of limited importance for this work, is the high computational cost of this particular fitting algorithm. Unless otherwise stated, standard settings in Matlab were used.

The input data of main interest in the current analysis are green quantity (experiment 1) and green quality (experiment 2). Given the strong correlation between the three green quality dimensions put forward, scenario number was directly used as an input when analyzing the second experiment. Alternatively, the scores on the aesthetic value were used. For the model construction, following features were added: audio-visual acuity (6 parameters), growing up in a green environment, growing up in an urban environment, living in a green environment, living an urban environment, noise sensitivity, audio-visual sensitivity, connectedness to nature, and perceived stress during the week prior to the experiment. These (aggregated) constructs are likely to have predictive power in an urban greening/environmental noise perception context, and allow to put green quantity/quality metrics in context. Note that these constructs might be related to age, education and gender, but potentially with a more explicit link to the audio-visual interactions studied here. A detailed analysis of these personal characteristics, however, is beyond the goal of the current paper.

The output of the ann model is the self-reported noise annoyance rating. To prevent overfitting on the data, which is a general concern in machine learning procedures (Hagan et al., 2014), the network only uses 3 layers (an input, a single hidden layer and an output layer) and 10 neurons (in experiment 2, consisting of 62 $\times$5 =310 datapoints) or 13 neurons (in experiment 1, consisting of 79 $\times$5 =395 datapoints), following recommendations by Hagan et al. (2014).

The Bayesian regularization algorithm does not (explicitly) use a validation set; 85% of the data is used for the training, while a (standard) 15% was used for testing. To have an indication of the impact of (randomly) assigning data points to the training and test set, multiple models were constructed by taking different training and test sets (50 times) using these same percentages, where the final result considered for further analysis is the average of all these models. This approach stabilizes outputs from single models and allows visualizing uncertainty on the predictions.

The current approach was chosen since artificial neural networks easily catch complex and non-linear relations between inputs and outputs. In addition, there is no need for a priori assumptions on the distribution of either the input or output data, a mixture of data types can be handled, and input parameters may be correlated. The main goal of the current analysis is to elucidate the influence of green quantity and quality within the large variation self-reported noise annoyance typically has in such experiments.

2.8.2. Wilcoxon signed-rank test

Additional statistical analysis is performed with the Wilcoxon signed-rank test. Dichotomization of the data (using median separation), distinguishing between "high" and "low" self-reported noise annoyance, will be needed given the expected strong variation in the ratings. This non-parametric test allows looking for statistically significant differences between the medians in case of paired measurements and when dealing with ordinal variables as is the case here. Where applicable, the signed-rank test will be used to complement the artificial network fitting.

3. Results

3.1. Test panels

3.1.1. Basic demographics

In Table 2, some basic demographics of the participants in experiment 1 (N = 79) and experiment 2 (N = 62) are summarized. In both experiments, there were slightly more women than men. Most participants were students (39% in experiment 1, 61% in experiment 2). Consequently, the age distribution is skewed towards younger people (most populated age category was 18–23 years). In experiment 1, the average age was 32.9 years (SD=standard deviation=13.9 years), and 27.6 years (SD=12.9 years) in experiment 2.

Overall, people declared to have grown up in a green environment (3.8 with SD=1.2 in experiment 1, and 4.1 with SD=1.0 in experiment 2). Their current living environment was rated as less green (3.1 with SD=1.3 in experiment 1, and 3.4 with SD=1.2 in experiment 2) and more urban (3.6 with SD=1.2 in experiment 1, and 3.0 with SD=1.5 in experiment 2).

3.1.2. Characterization by stress state, nature connectedness, noise sensitivity and audio-visual acuity

In Table 3, information is provided to characterize the test panels with a number of constructs that are directly or indirectly related to the experiment. Although a detailed analysis of how personal factors influence the link between green window view and noise annoyance is beyond the goal of this paper, this information should be helpful for reference and potential meta-analysis.

The perceived stress state (over the last week) is very similar in both experiments. In experiment 2, a slightly lower overall noise sensitivity and connectedness-to-nature is found. The audio-visual acuity test learns that object recognition in visual-only mode leads to a higher accuracy and is performed faster than for audio-only inputs, but audio-visual combinations lead to a slight increase in correctness and a slight decrease in reaction times. The scores on the audio-visual acuity test are almost identical in both experiments.

3.1.3. Perceived realism of the VR environment

The realism of the VR environment was rated by each participant, on a scale from 1 to 5, as summarized in Table 4. In experiment 1, 60% rated the environment at least realistic (49% "realistic" and 11% "very realistic"). In experiment 2, realism ratings were slightly lower, namely 50%, where 44% of the test panel rated the VR environment as

Table 2
Demographics of the test panel in experiment 1 (N = 79) and experiment 2 (N = 62).

		experiment 1		experiment 2	
		Number	Percentage	Number	Percentage
Gender	Male	34	43%	24	39%
	Female	44	56%	38	61%
	X	1	1%	0	0%
Age	18–23	25	32%	43	69%
	24–30	24	30%	7	11%
	30 +	30	38%	12	19%
Education	Elementary school	1	1%	2	3%
	Secondary school	12	15%	18	29%
	Bachelor	28	35%	30	48%
	Master	36	46%	11	18%
	Phd	2	3%	1	2%
Professional status	Full-time employed	33	42%	18	29%
	Part-time employed	7	9%	2	3%
	Jobseeking	2	3%	2	3%
	Student	31	39%	38	61%
	Retired	4	5%	2	3%
	Other (sick leave, career break, etc.)	2	3%	0	0%
"I grew up in a green environment"	Totally disagree (1)	4	5%	1	2%
	Disagree (2)	7	9%	5	8%
	Neutral (3)	17	22%	5	8%
	Agree (4)	25	32%	30	48%
	Totally agree (5)	25	32%	21	34%
"I grew up in an urban environment"	Totally disagree (1)	17	22%	22	35%
	Disagree (2)	20	26%	22	35%
	Neutral (3)	17	22%	10	16%
	Agree (4)	18	23%	7	11%
	Totally agree (5)	5	6%	1	2%
"I'm living in a green environment"	Totally disagree (1)	10	13%	5	8%
	Disagree (2)	23	29%	12	19%
	Neutral (3)	11	14%	10	16%
	Agree (4)	21	27%	23	37%
	Totally agree (5)	14	18%	12	19%
"I'm living in an urban environment"	Totally disagree (1)	5	6%	13	21%
	Disagree (2)	9	11%	15	24%
	Neutral (3)	14	18%	8	13%
	Agree (4)	33	42%	13	21%
	Totally agree (5)	18	23%	13	21%

Table 3
Characterization of the respondents in experiment 1 and 2 by the surveys held and the audio-visual acuity test.

	experiment 1		experiment 2	
	Mean	SD	Mean	SD
N	79		62	
Perceived Stress Scale (1–5)	2.56	0.50	2.72	0.52
Connectedness to Nature (1–5)	3.58	0.57	3.29	0.54
Noise Sensitivity (1–5)	3.58	0.69	3.25	0.68
Audiovisual Sensitivity (1–5)	3.66	0.73	3.01	0.77
Acuity test: Correctness Audio only (%)	72%	24%	71%	26%
Acuity test: Correctness Audio-Visual (%)	86%	21%	85%	21%
Acuity test: Correctness Visual only (%)	85%	20%	84%	20%
Acuity test: Reaction time Audio only (s)	0.84	0.13	0.82	0.14
Acuity test: Reaction time Audio-Visual (s)	0.68	0.13	0.67	0.14
Acuity test: Reaction time Visual only (s)	0.70	0.13	0.71	0.13

Table 4
Realism rating of the VR environment in both experiments.

		experiment 1		experiment 2	
Rating	Description	Number	Percentage	Number	Percentage
1	not at all realistic	0	0%	0	0%
2	little realistic	10	13%	3	5%
3	neutral	21	27%	28	45%
4	realistic	39	49%	27	44%
5	very realistic	9	11%	4	6%

"realistic", and 6% as "very realistic". The average score was 3.6 (SD=0.9) in the first experiment and 3.5 (SD=0.7) in the second experiment, positioning the audio-visual environments close to realistic.

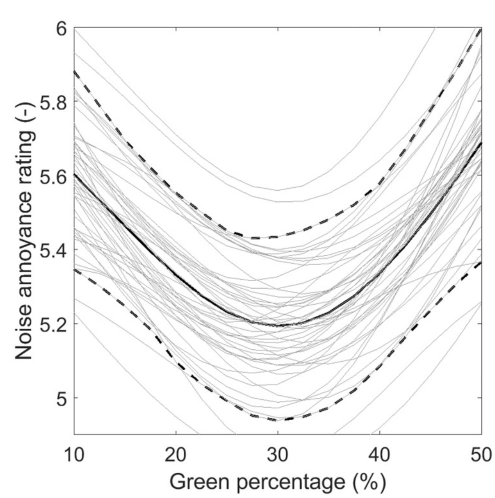

Fig. 9. Modeled (absolute) noise annoyance rating vs green percentage (full line) based on experiment 1 (green quantity study). The dashed lines delineate 90% confidence intervals on repeated model developments by bootstrapping. The thin lines show the 50 individual models on which the means and uncertainty intervals are based.

3.2. Effect of green quantity

The effect of green quantity on the self-reported noise annoyance is visualized in Fig. 9. Following the establishment of the artificial neural network model, all parameters, except for the green quantity, were set to their average value in experiment 1. The model is then ran with green quantities ranging from 10% till 50%, so covering the full extent of the evaluated scenarios, at an interval of 2.5%. A minimum in noise annoyance is found slightly above 30%, but is not very pronounced. Over the full range of green percentages considered, a difference of about 0.5 units on the 11-point annoyance scale is observed. Model performance itself is summarized in Appendix A. Overall, the root-mean-square error between measurements and predictions is near 1 unit on the 11-point annoyance scale.

The statistical analysis with the Wilcoxon signed-rank test for paired measurements is shown in Table 5. The self-reported noise annoyance at scenario 5 (highest vegetation density) shows to be different from any other scenario at the 5% significance level. Comparing scenario 1 to either scenario 2 or 4 leads to p-values close to 1, meaning very similar noise annoyance ratings. Scenario 3 (30% greenish pixels) is most different from scenario 1, although not statistically significantly different. The noise annoyance induced by scenario 2 and 4 are nearly identical ($p = 1$). These findings are consistent with the fact that there is a minimum near 30% green window view, as yet visualized by means of the artificial neural network in Fig. 9. Within the large variation in annoyance ratings, statistical significance seems difficult to reach here except for scenario 5.

3.3. Effect of green quality

The effect of green quality on the self-reported noise annoyance is illustrated in Fig. 10. After construction of the artificial neural network model, all parameters were set to their average value in experiment 2. Scenario number can be seen as an ordinal variable for species richness, see Table 1. The minimum in noise annoyance is found near scenario 4 and 5. Given the uncertainties and given that the root mean square error here is again near 1 unit on the 11-point noise annoyance scale (see Appendix A), no distinction can be made whether maximum colorfulness (scenario 4) or maximum species richness (scenario 5) is optimal. There is at least a tendency that maximizing these two quality dimensions is more important than maintenance degree. The differences observed here are somewhat stronger than when analyzing the effect of green quantity, but only account for 0.7 units on the noise annoyance scale.

The scenarios in experiment 2 show more statistical significant differences (see Table 6) than in experiment 1. Scenario 1 is different at the 5% level from scenario 3, and at the 10% level from scenario 2, and there are clear tendencies towards statistically significant differences with scenarios 4 and 5. Scenario 3 is different from all scenarios at the 5% significance level. Note that for scenarios 4 and 5, the multiple ann predictions cover a wide range of annoyance values as can be seen in Fig. 10. Although the average predictions for scenarios 4 and 5 look different from 2 when analyzing Fig. 10, the Wilcoxon signed rank test cannot distinguish between them with certainty.

A second ann model was built where the reported esthetic values of

Table 5
p-values from the Wilcoxon signed-rank tests comparing the reported noise annoyance between each individual scenario in experiment 1.

	scenario 1	scenario 2	scenario 3	scenario 4	scenario 5
scenario 1	1				
scenario 2	0.81	1			
scenario 3	0.36	0.66	1		
scenario 4	0.80	1.00	0.69	1	
scenario 5	8.0E-07	1.0E-05	3.1E-04	1.0E-05	1

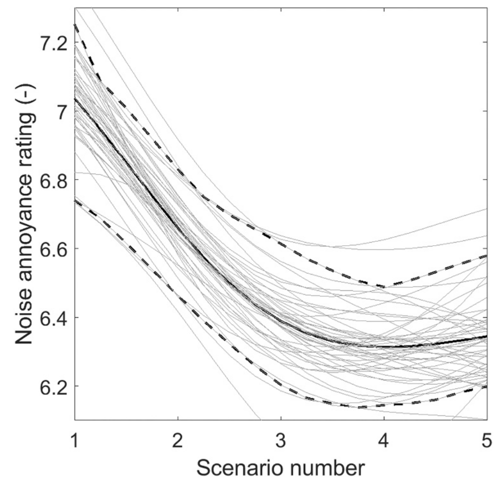

Fig. 10. Modeled (absolute) noise annoyance rating vs scenario number (full line) based on the experimental dataset 2 (green quality study). The dashed lines delineate 90% confidence intervals on repeated model developments by bootstrapping. The thin lines show the 50 individual models on which the means and confidence intervals are based. Scenario 3 is the best maintained green belt, scenario 4 the most colorful one, and scenario 5 contains most species.

Table 6
p-values from the Wilcoxon signed-rank tests comparing the reported noise annoyance between each individual scenario in experiment 2.

	scenario 1	scenario 2	scenario 3	scenario 4	scenario 5
scenario 1	1				
scenario 2	0.10	1			
scenario 3	0.04	1.4E-04	1		
scenario 4	0.30	0.58	4.4E-03	1	
scenario 5	0.12	1	8.6E-04	0.61	1

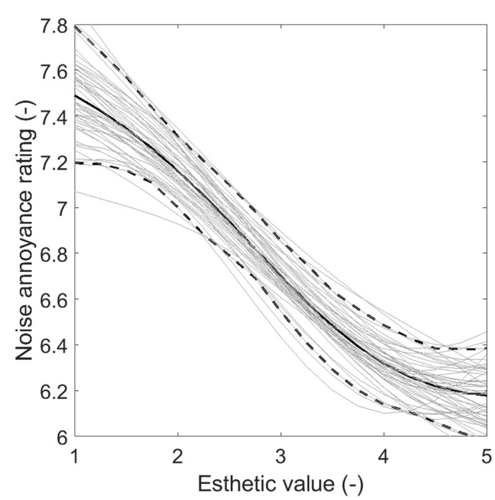

Fig. 11. Modeled (absolute) noise annoyance rating vs aesthetic value (full line) based on the experimental dataset 2 (green quality study). The dashed lines delineate 90% confidence intervals on repeated model developments by bootstrapping. The thin lines show the 50 individual models on which the means and confidence intervals are based. An esthetic value of 5 means a beautiful green belt, while 1 means “not beautiful”.

the greening scenarios were directly used as a predictor, instead of the ordinal species richness/scenario number. Fig. 11 nicely shows that the higher that esthetic value of the green belt, the lower the noise annoyance. The variation over the value range now amounts up to about 1.5 units on the noise annoyance scale, indicating that self-reported esthetic value is an important predictor for the self-reported noise annoyance.

4. Discussion

Although the test panels mainly consist of younger persons and students, especially in experiment 2, constructs such as perceived stress, noise sensitivity and connectedness to nature fall within the expected ranges for broader populations. The perceived stress values found here, e.g., are close to those reported by Cohen et al. (2012) for a sample of 2000 persons in the United States during the year 2009. Averaged over men and women, and transformed to a 1-to-5 scale as used in this work, a value of 2.58 is obtained, so in between the values of 2.56 and 2.72 in experiment 1 and 2, respectively. Note that a 10-item PSS was used in Cohen et al. (2012), while the original 14-item scale was used here. The noise sensitivities in our test panels are also consistent with other research. Scores of 3.48 and 3.45 were, e.g., reported by Van Renterghem et al. (2021), as a result of the same 10-item questionnaire conducted in 2017 (N = 181) and 2020 (N = 175), in the same country. These values are in between the scores of 3.58 and 3.25 as found here for experiment 1 and 2, respectively. Connectedness-to-nature scores over different test populations were reported in Mayer and Franz (2004). In their "Study 4", 135 respondents outside the college community were sampled, with ages ranging from 14 till 89. An average Connectedness-to-nature score of 3.52 (N = 135) was found there. In their "Study 3", math students scored on average 3.2 (N = 44), while environmental students scored on average 3.82 (N = 78). The scores in the current work are 3.58 in experiment 1, and 3.29 in experiment 2, and fit within the aforementioned value ranges.

Comparing the results from the audiovisual acuity test is not possible because of lack of reported data elsewhere for these specific metrics. Note that audiovisual performance could be linked to age (see e.g. Hasher and Zacks, 1988; Cohen and Gordon-Salant, 2017). Since the scores on the audiovisual acuity test are nearly identical in experiment 1 and 2 in the current work, consistency over both experiments is at least guaranteed.

Two separate experiments were conducted, where the green quality study started from the optimum in the green quantity study. True interactions between green quality and quantity, however, cannot be studied, which would need combining both aspects in a single experiment. But this would lead to too many scenarios to be evaluated by each participant, certainly in view of the exposure duration which was already considered short to truly assess noise annoyance.

Indeed, noise annoyance is basically a long-term construct, and as stated in its ISO certified question (ISO, 2021), the time frame over which respondents are asked to integrate their annoyance is typically one year. This contrasts strongly with the virtual reality experiment, where the exposure duration was only 5 min. To some extent, what is assessed here could be considered as “short-term annoyance”, and how this links to long-term annoyance is still unclear or under debate (Guski et al., 1999; Bartels et al., 2015; Schreckenberg et al., 2022). The short exposure duration in the current audio-visual experiment might be a main reason why the effects by green window view assessed by the real-life surveys at home (Li et al., 2010; Van Renterghem and Botteldooren, 2016; Leung et al., 2017; Schäffer et al., 2020) are much stronger.

Related to this, the effects observed might be somewhat hidden within the large natural variation in self-reported noise annoyance. The artificial neural networks constructed on the experimental data were able to visualize the influence of green quantity and green quality. Note that this fitting procedure is basically used as a data interpolation technique, rather than aiming at building a generally valid prediction model. The Wilcoxon signed rank test on the median separated dichotomized data is generally consistent with these curves, although findings at the 5% statistical significance level are observed for a limited number of scenario comparisons only. The extremely dense tree belt in scenario 5 (of 50%) lead to statistically significantly higher noise annoyance than when green quantities were between 10% and 40%. The tendency for a minimum could be seen when analyzing the p-values from the statistical testing as discussed in detail in Section 3.2. The use of the Wilcoxon signed rank test should be seen as a small complement to the artificial neural networks with a more classical statistical procedure. A one-on-one comparison between these results is clearly not possible given the strongly different approaches.

The data suggests that green quality has a stronger effect on the interplay between green window view and road traffic noise annoyance than green quantity. In this work, the different dimensions along which green quality was defined could not be singled out, although colorfulness and species richness seemed to be more effective than maintenance degree to mitigate noise annoyance. More importantly, the rated esthetic quality of the central reservation green belt showed to be a stronger predictor for noise annoyance and could be considered as an aggregator of these quality dimensions. The more beautiful the green infrastructure is perceived, the lower the noise annoyance, amounting to a difference of 1.5 units along the 11-point annoyance scale.

The effect of green quality is consistent with literature on (general) green perception, stating that preference, assigned esthetic value, and perceived restorative potential are all linked. Van den Berg et al. (2003), e.g., showed by mediational analyses that affective restoration accounted for a substantial proportion of the preference for natural over built environments in their experiments. Han (2010) found that scenic beauty, preference, and restoration are significantly and strongly correlated. Stress relief due to seeing vegetation, counteracting the (general) stress induced due to exposure to noise, has been put forward as an explaining mechanism why green window view reduces noise annoyance (Van Renterghem, 2019). More directly, a beautiful green scenery is more likely to attract attention for a longer time, so suppressing noticing of or the attention paid to environmental noise, increasing the likeliness of achieving inattentional deafness.

The interaction between green window view, exposure level and noise annoyance was not studied in this work to limit the number of scenarios to be evaluated by each participant. Here, a realistic actually measured (and rather high) sound pressure level was reproduced in the VR experiment (see Section 2.2). Following the discussion in Van Renterghem (2019), positive audio-visual interactions (or the benefits of a green window view) are expected to be stronger for higher exposure levels. However, more research is needed to confirm this statement in this specific context.

While building the artificial neural networks to predict noise annoyance, personal factors such as audio-visual acuity, characteristics of the growing-up and (current) living environment, noise sensitivity, audio-visual sensitivity, connectedness to nature, and self-reported stress status (in the week prior to the experiment) were included as features to allow putting the green quantity/quality metrics in context. A further analysis of these personal factors, and more specifically how they interact with the noise annoyance mitigation by window view greenness, deserves further study but is considered beyond the aim of the current paper.

Note that the potential impact of the vegetation belt on sound propagation from the traffic lanes behind the central reservation, and consequently, changes in level and spectrum, were not considered in this work. Especially in case of the denser tree belts, even for non-wide belts, this influence could be non-negligible (Van Renterghem, 2014). The current study, however, focusses on audio-visual interactions, and levels are kept deliberately constant. This avoids mixing up the effect of sound pressure level/spectral differences with audio-visual interactions. In the current context, however, the impact of the shielding of the far lanes on the total sound pressure level in the dwelling is probably limited. This is because the sound propagation from the closest lanes are not influenced by the vegetation belts, and given their positioning closer to the receiver, they will dominate the sound field in any case.

5. Conclusions

The effect of both green quantity and quality on self-reported noise annoyance is studied in a virtual reality living room overlooking an inner city ring road. Participants were exposed to real-life binaural road traffic noise recordings with the window partly opened, yielding an A-weighted equivalent sound pressure level of 67 dB at the eardrum. The optimum green quantity to minimize road traffic noise annoyance was slightly above 30% RGB greenness within the window pane. This effect of green quantity, ranging from 10% till 50% in this study, was not very pronounced and only accounted for 0.5 units on the 11-point noise annoyance scale. It is noteworthy that vegetation belts that are too dense should be sidestepped, which can be shown at the 5% statistical significance level. Near this optimum in green quantity, green infrastructure that is most colorful, or contains most plant species, lead to a minimum in self-reported noise annoyance, accounting for 0.7 units on the annoyance scale among the scenarios evaluated. The aesthetic value of the green infrastructure seems to be the driving factor for the positive audio-visual interactions observed, amounting to 1.5 units on the noise annoyance scale for the average participant in the test panel based on fitting an artificial neural network on the experimental data. This finding is consistent with the presumed mechanisms why green window view is able to reduce noise annoyance within domestic settings.

CRediT authorship contribution statement

Timothy Van Renterghem: Conceptualization, Writing – original draft. **Timothy Van Renterghem**, **Elin Vermandere, Maarten Lauwereys**: Data curation, Formal analysis, Methodology, Visualization, Writing – review & editing. **Elin Vermandere, Maarten Lauwereys**: Investigation.

Declaration of Competing Interest

The current research did not receive any funding. 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.

Acknowledgement

The authors are grateful to the Architectural Department of the Faculty of Engineering and Architecture, and especially Willem Bekers, for allowing to use their VR equipment and technical advice in setting up the visual virtual reality environment.

Appendix. A

In Figs. A1–3, the stated/measured (self-reported) noise annoyance ratings by the participants are opposed to the artificial neural network predicted annoyance ratings, and allows assessing the quality of the predictions over its full value range. Note that each respondent rated each of the 5 scenarios in an experiment, resulting in 5 datapoints per respondent. For the green quantity study (see Fig. A1), the green quality study using scenario number or ordinal species richness as input (see Fig. A2), and the green quality study using esthetic value as input (see Fig. A3), the overall root-mean-square errors are 1.07, 0.96 and 1.03 units on the 11-point noise annoyance scale, respectively. At very high and very low annoyance, predictions seem to be somewhat less accurate. Low noise annoyance seems to be typically overpredicted, while high annoyance seems to be somewhat underpredicted. A potential cause is an insufficient number of datapoints near these extremes.

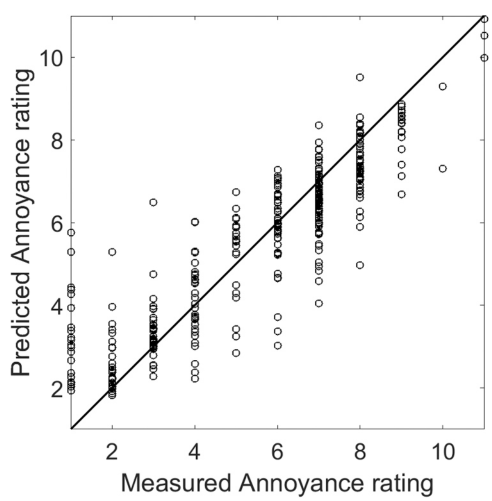

Fig A1. Measured vs predicted noise annoyance rating over the full dataset in the green quantity study (experiment 1).

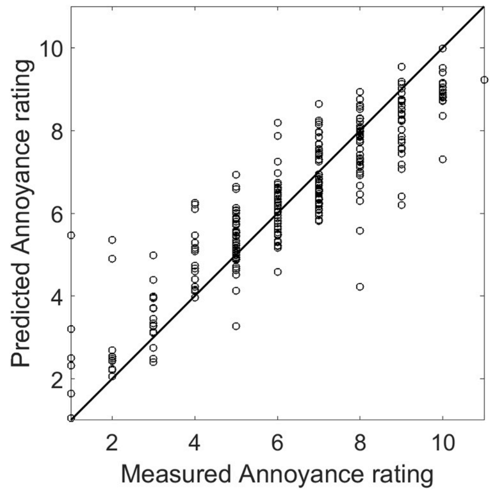

Fig A2. Measured vs predicted noise annoyance rating over the full dataset in the green quality study where scenario number was used as an input (experiment 2).

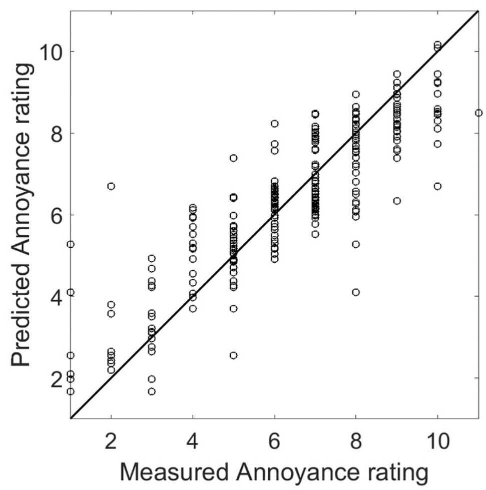

Fig A3. Measured vs predicted noise annoyance rating over the full dataset in the green quality study where esthetic value was used as an input (experiment 2).

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