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Research Paper

Influence of visibility of wind farms on noise annoyance – A laboratory experiment with audio-visual simulations

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ABSTRACT

Noise annoyance reactions in the population due to wind farms are related to visual as well as noise-related impacts of the farms. Improved understanding of these effects may support the planning of better accepted wind farms. Recently, tools for visualization and auralization of wind farms have been developed that allow mutually studying audio-visual effects on annoyance. The objective of this study was to investigate the audio-visual effects of different wind turbine noise situations on short-term noise annoyance in a psychophysical laboratory experiment, considering serial position effects (simple order and differential carryover effects). A set of 24 audio-visual situations covering a range of acoustical characteristics (sound pressure level, periodic amplitude modulation) and visual settings (landscape with visible wind turbine, landscape only, grey background) was created. The factorial design of the experiment allowed separating audio-visual effects from serial position effects on noise annoyance. Both visual and acoustical characteristics were found to affect noise annoyance, besides the participants' attitude towards wind farms. Sound pressure level and amplitude modulation increased annoyance, the presence of a visualized landscape decreased annoyance, and the visibility of a wind turbine increased annoyance. While simple order effects could be eliminated by counterbalancing, the initial visual setting strongly affected the annoyance ratings of the subsequent settings. Due to this differential carryover effect, visual effects could be assessed reliably only as long as the participants saw the initial visual setting. Therefore, the presentation order of audio-visual stimuli should be carefully considered in experimental studies and in participatory landscape planning.

1. Introduction

The production of wind energy is growing worldwide. Between 2001 and 2016, the wind power capacity increased by a factor of 20, from some 24 to 487 GW (GWEC, 2017). As a result, landscapes suffer growing visual impacts, and increasing portions of the population are exposed to wind turbine (WT) noise. The visual and noise-related impacts of wind farms have therefore been much discussed in recent years. Regarding health effects of WT noise, noise annoyance seems most prevalent (van Kamp & van den Berg, 2018).

Literature from field surveys suggests that annoyance reactions to WT noise are often stronger than to transportation noise at comparable noise levels (van Kamp & van den Berg, 2018). Annoyance to WT noise was therefore extensively studied in field surveys (e.g., Hongisto, Oliva, & Keränen, 2017; Janssen, Vos, Eisses, & Pedersen, 2011; Klæboe & Sundfør, 2016; Michaud et al., 2016) as well as in laboratory experiments (e.g., Ioannidou, Santurette, & Jeong, 2016; Lee, Kim, Choi, & Lee, 2011; Schäffer et al., 2016; Schäffer, Pieren, Schlittmeier, & Brink, 2018). The studies reveal that annoyance reactions depend on various factors. First, specific acoustical characteristics of WT noise, which mainly consists of aerodynamic broadband noise, contribute to annoyance. Here, periodic amplitude modulation (AM), i.e., quasi-periodic temporal level fluctuations sometimes encountered, is particularly important. Periodic AM occurs at the blade passing frequency (~ 1 Hz). It comprises high-frequency "swishing" sound, sometimes also referred to as "Normal Amplitude Modulation", and more impulsive, mid- to low-frequency "thumping" sound ("Other Amplitude Modulation") (Bowdler, 2008; Oerlemans, 2015). It was found to be particularly annoying (Ioannidou et al., 2016; Lee et al., 2011), possibly by provoking the subjective hearing sensation "fluctuation strength" (Fastl & Zwicker, 2007). But also spectral characteristics such as low-frequency components may affect annoyance (Møller & Pedersen, 2011; Schäffer et al., 2018). Second, the visibility of WTs plays a crucial role (Janssen et al., 2011; Michaud et al., 2016; Pedersen & Larsman, 2008). Third, the living environment of residents (hilly vs. flat terrain) may affect reactions to noise

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(Pedersen & Larsman, 2008). Finally, also personal factors such as noise sensitivity (Miedema & Vos, 2003), attitude (Pedersen & Persson Waye, 2004) or familiarity with WT noise (Maffei et al., 2015), situational factors such as economic benefit (Janssen et al., 2011), and even expectations on caused health effects (Chapman, St George, Waller, & Cakic, 2013) were shown to be linked to noise annoyance.

Specific effects on noise annoyance can be effectively studied in controlled laboratory experiments. Compared to field surveys, laboratory experiments have the advantage of high control of the (noise) exposure as well as exclusion/control of effect modifiers (e.g., visibility of WTs or living environment, see above). In the past, such experiments often focussed either on the effects of acoustical characteristics of WT noise (classically in psychoacoustic studies where visual impacts may be deliberately excluded; see, e.g., Schäffer et al., 2016) or on visual impacts of wind farms (classically in landscape and environmental sciences and planning, focusing on social acceptance and visual preferences for WTs; see, e.g., Molnarova et al., 2012; Betakova, Vojar, & Sklenicka, 2015; and Scherhaufer, Höltinger, Salak, Schauppenlehner, & Schmidt, 2018). Besides the scientific interest, the results of these studies suggest practical recommendations for site planning of wind farms, such as regarding number, height, and placement of wind turbines in a landscape. However, considering audio-visual aspects mutually in such laboratory studies is important as both contribute to the perception of the studied situations (Lindquist, Lange, & Kang, 2016).

In recent years, laboratory experiments on mutual audio-visual effects on (noise) annoyance were conducted (He, Leickel, & Krahé, 2015; Maffei et al., 2013; Preis, Hafke-Dys, Szychowska, Kociński, & Felcyn, 2016; Ruotolo et al., 2012; Sun, De Coensel, Echevarria Sanchez, Van Renterghem, & Botteldooren, 2018; Szychowska, Hafke-Dys, Preis, Kociński, & Kleka, 2018; Yu, Behm, Bill, & Kang, 2017). The studies revealed that both, acoustical characteristics and visual settings, including the visibility of the noise source, affect (noise) annoyance. Here, one should consider that the experimental design, in particular the presentation order, may strongly affect the outcomes. When a number of stimuli is subsequently presented, two serial position effects may appear: simple order and/or differential carryover effects (Cohen, 2013). Simple order effects may result, e.g., from fatigue or practice. They can be averaged out and thus eliminated by counterbalancing (Cohen, 2013), either completely or partially (Latin squares), or by randomization if samples are large. For pure psychoacoustic experiments with a large number of stimuli, randomization is common practice (e.g., Nordtest, 2002). For psychophysical experiments involving also visual stimuli, in contrast, the effect of playback order may be less straightforward. Here, differential carryover effects may occur, where the rating of the stimulus is affected by previous stimuli. Differential carryover effects differ depending on the order of the stimuli. They cannot be eliminated by counterbalancing (Cohen, 2013). Here, either a sufficiently large time delay between treatments, putting a neutral task between stimuli for distraction, or a between-subjects design (i.e., assigning different participants to different stimuli) may be necessary (Cohen, 2013). As far as we know, however, studies on audio-visual effects of environmental noise sources (including WTs) did not systematically account for this effect to date.

The objective of the present study therefore was to investigate the audio-visual effects of WT noise situations on short-term noise annoyance, considering also possible serial position effects. Our hypotheses were that (i) acoustical characteristics alone contribute to noise annoyance, and that (ii) visual settings may act as effect modifiers for noise annoyance. To test these hypotheses, different situations with WT sound covering a range of acoustical characteristics (sound pressure level, periodic AM) and visual settings (landscape with a single visible WT, landscape only, grey background) were studied in a psychophysical laboratory experiment, which allowed separating the effects of the studied variables on noise annoyance.

Table 1
Factorial design of the psychophysical tests with 24 audio-visual wind turbine (WT) stimuli covering a range of sound pressure levels (L_{Aeq}) of 33.0–49.4 dB, two situations ("no" and "with") of periodic amplitude modulation (AM) of the sound, and three visual settings (WT = landscape with WT; LS = landscape only, Grey = grey background). The table shows the L_{Aeq} in dB per variable combination (same values for the three visual settings), resulting from observer distances to the WT of 100–600 m.

Distance to WT [m]	Periodic AM					
	no			with		
	Visual setting					
	WT	LS	Grey	WT	LS	Grey
100	48.6			49.4		
200	43.6			44.6		
350	38.2			39.2		
600	33.0			34.0		

2. Methods

2.1. Experimental concept and design

In this study, 24 audio-visual stimuli were systematically varied (full factorial design) with respect to three variables: distance to the WT, periodic AM of the sound (with, without) and visual setting (landscape with visible WT, landscape only, grey background) to study their individual contribution to short-term noise annoyance (Table 1). In the following, we refer to the noise annoyance studied here as "(noise) annoyance rating" (for the individual ratings) or "short-term (noise) annoyance", sometimes omitting the term "noise" in this context for sake of brevity.

The acoustical situations were similar to those studied by Schäffer et al. (2016): The distances of the observers to the WT cover a relevant sound pressure level (L_{Aeq}) range of WT noise to which residents may be exposed (Janssen et al., 2011; Tachibana, Yano, Fukushima, & Sueoka, 2014). The situations without periodic AM represent quasi-stationary WT noise, while those with periodic AM comprise "swishing" and "thumping" sound (see above).

For the stimuli with the visual settings "Landscape only" and "Landscape with WT", a hilly, rural landscape without buildings was chosen. Hilly terrain is a major landscape type of Switzerland, besides plains and mountains (Szerencsits et al., 2009). Such a setting was found to increase the risk of annoyance to WT noise, compared to urban areas or flat terrain (Pedersen & Persson Waye, 2007). Also, WTs were found to be more visible in rural than in urban areas (Pedersen, van den Berg, Bakker, & Bouma, 2009). For the case without visible landscape, a grey background ("Grey" in Table 1) was chosen, as grey is a neutral colour with respect to feelings (Heller, 2009).

2.2. Audio-visual stimuli

The audio-visual stimuli of Table 1 were synthetized using GIS-based 3D simulations with the tools of Manyoky, Wissen Hayek, Heutschi, Pieren, and Grêt-Regamey (2014), Pieren, Heutschi, Müller, Manyoky, and Eggenschwiler (2014) and Heutschi et al. (2014), as described below. For the current study, a location in a typical Swiss hilly landscape type was chosen for simulation. In this virtual environment, a single 2.0 MW Vestas V90 turbine (three blades, hub height = 95 m, rotor diameter = 90 m) was placed. The observer was set at 1.7 m above ground and at four positions situated 100–600 m away from the WT position (Table 1). The meteorological conditions were chosen as a sunny day with strong wind conditions resulting in a rotational speed of the WT of 15 rpm.

2.2.1. Visualization

Computer-generated imagery animations were created using the game engine CRYENGINE by Crytek GmbH (2015) as described in

Manyoky et al. (2014). The procedure involved (i) import of a digital elevation model and an orthophoto of an existing landscape, (ii) removing striking and recognizable landscape elements (e.g., characteristic mountain ranges) from the background to obtain a more generic setting (Ribe et al., 2018), (iii) adding 3D models for vegetation and infrastructures (e.g., road, WT), (iv) definition of a wind speed profile for movement of the WT blades and the vegetation, and (v) visual optimisations, e.g., of the colorization of the orthophoto and vegetation models and of the lighting settings, to obtain a higher level of realism.

For the current study, the landscape type "hills" of Ribe et al. (2018), which had been created in an older CRYENGINE version, was re-established in the more recent Version 3.4.8. Into the resulting visual setting, a 3D model of the WT was either placed and animated ("Landscape with WT" in Table 1), or not ("Landscape only" in Table 1). For these two settings, images were rendered for videos (Section 2.2.3) for the four observer positions (Table 1) with a widescreen aspect ratio of 16:9 (Fig. 1). The observer direction was chosen such as to see the WT to the right hand side of the visual field, to avoid a too strong focus on the WT during the experiments. In the videos both the 3D models of moving vegetation and WT with rotating blades (in clockwise direction) were animated. The rendered sets of images were complemented with a grey background image ("grey" in Table 1).

2.2.2. Auralization

The acoustical stimuli were artificially generated using digital sound synthesis as described in Pieren et al. (2014) and Heutschi et al. (2014), with the parameter settings similar to those of Schäffer et al. (2016).

The auralization process consists of three main steps, namely, emission synthesis, propagation filtering, and reproduction rendering. The synthesis of the sound emissions of the WT was done for strong wind conditions. Periodic AM of the sound was realized with a standard deviation of the level fluctuation of 3 dB and a modulation frequency of 0.75 Hz, corresponding to the rotational speed of 15 rpm. Sound propagation effects from the source to the observer locations were simulated by digital filtering (Heutschi et al., 2014), accounting for the propagation effects geometrical spreading, air absorption, ground reflection on a grassy terrain and atmospheric turbulence. The propagation situations with distances of 100–600 m resulted in a L_{Aeq} range of ~33–49 dB (Table 1).

In a final step, the synthesized sound pressure signals were rendered for surround sound reproduction with a five-channel loudspeaker setup (cf. Section 2.3.1) to generate a realistic hearing impression with directional information. Reproduction rendering was accomplished as described in Wissen Hayek, Pieren, Heutschi, Manyoky, and Grêt-Regamey (2018), using Vector Base Amplitude Panning by Pulkki (1997). This technique allows virtual sound source positioning with a loudspeaker array by calculating the individual loudspeaker feeds. In addition to the stimuli, a reference signal with a predefined sound pressure level was created for level calibration of the playback system.

To get an audio impression of the resulting stimuli with and without periodic AM, audio examples provided as supplementary material by Schäffer et al. (2016), which are very similar to those used here, may be consulted. Fig. 2 shows exemplary level-time histories, and Fig. 3 the spectra of the resulting acoustical stimuli. The standard deviations of the FAST time-weighted level fluctuations amount to ~0.8 dB and ~2.3 dB in the situations without and with periodic AM, respectively (Fig. 2), independent of the propagation distance. Due to the distinctly stronger level fluctuations and correspondingly higher L_{AF} peaks in situations with periodic AM compared to without AM (Fig. 2), the resulting L_{Aeq} of the former are ~1 dB larger than the latter (Table 1, Fig. 3).

The WT spectra reveal considerable energy at low frequencies, with spectral variations due to the ground effect (Fig. 3). As atmospheric attenuation increases with frequency, the low-frequency content becomes more pronounced with increasing propagation distance. Accordingly, the level difference L_{C-A} between the C-weighted and A-weighted sound pressure level increases from 9 dB at 100 m to 14 dB at 600 m, and the spectral slope, i.e., the L_{eq} of the unweighted sound pressure level vs. octave band, from −2.6 dB/oct at 100 m to −5.1 dB/oct at 600 m (Fig. 3a). The slope of −4.1 dB/oct at 350 m coincides with the value observed by Tachibana et al. (2014) for residential areas around wind farms.

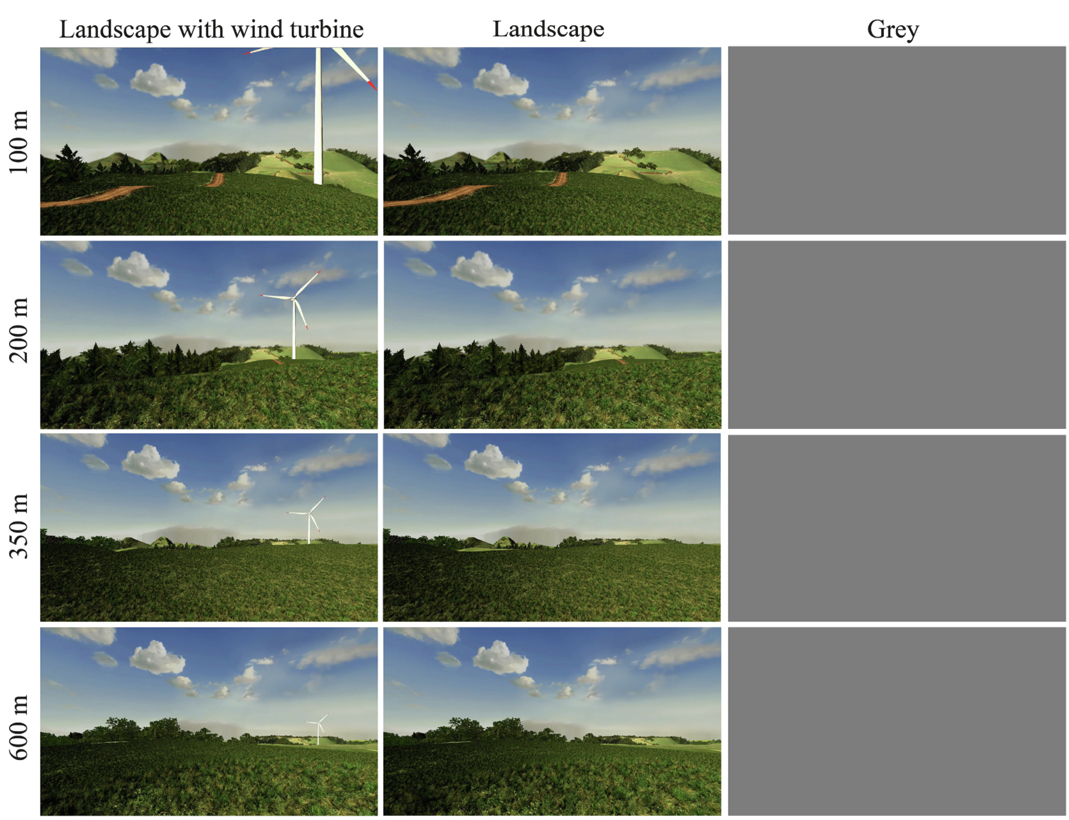

Fig. 1. Images of the visual stimuli covering three visual settings (landscape with visible wind turbine, landscape only, grey background) for distances of 100–600 m.

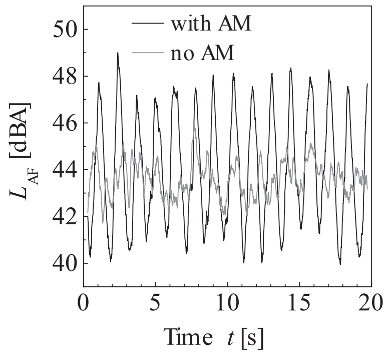

Fig. 2. Level-time histories of the A-weighted and FAST-time-weighted sound pressure level (L_{AF}) of the stimuli without ("no") and with amplitude modulation (AM), for a distance of 200 m.

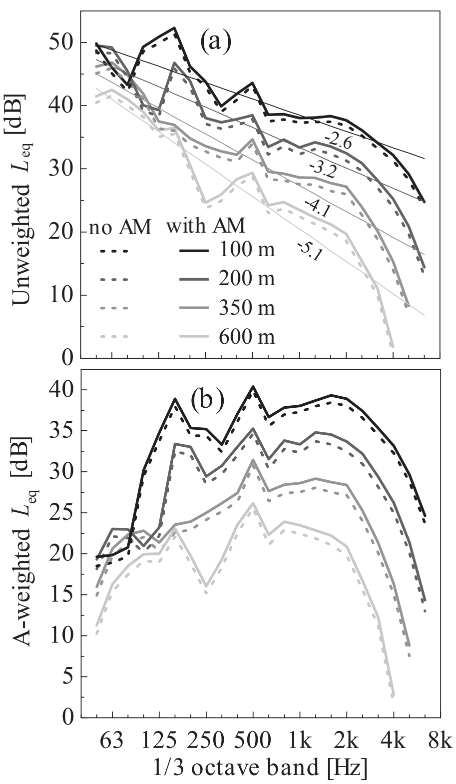

Fig. 3. (a) Unweighted and (b) A-weighted 1/3 octave band spectra (in L_{eq}) of the stimuli without ("no") and with amplitude modulation (AM), for distances of 100–600 m, in (a) with mean spectral slopes (thin solid lines: regressions per distance of the L_{eq} on 1/3 octave band) with the numbers below the lines indicating the slope in dB/oct.

2.2.3. Combination to acoustic-visual stimuli

The rendered images were stitched and encoded to videos of 21.5 s duration (stimuli of 20 s plus fade-in and fade-out), and the rendered audio data were time synchronised and linked to the videos as described in Manyoky et al. (2014) and Ribe et al. (2018). Each of the three visual settings of Table 1 was linked with two acoustical situations (with and without AM). This resulted in a total of 24 compressed videos (Multimedia container format MP4, video codec H.264, frame rate 60 fps, audio codec MPEG AAC, audio sampling rate 44.1 kHz) for playback.

2.3. Psychophysical experiments

2.3.1. Laboratory setup

The listening tests were carried out in the "Mobile Visual-Acoustic Lab" (MVAL), which is described in detail in Manyoky, Wissen Hayek, Pieren, Heutschi, and Grêt-Regamey (2016). For the experiment, the MVAL was built up in a room with low background noise and a carpet floor at the authors' institution ETH. MVAL consists of an aluminium construction (5 m × 5 m × 2.5 m) carrying black, sound absorbing curtains as walls and ceiling to exclude light and to obtain a favourable sound field. Within MVAL, five active loudspeakers (Focal CMS 50, Focal-JMlab) were arranged in a pentagon setting in a distance of 210 cm from the centre, along with a low-noise projector (Acer H6500, Acer Group) and a micro-perforated projection screen sized 2.70 m × 1.65 m. The videos were played using the VLC media player Version 2.2.4 on a laptop connected to the projector and the loudspeakers via a multichannel audio interface (Motu 896mk3, MOTU). Up to three persons simultaneously participated in the experiment. The seats were arranged at the centre of the pentagon. The audio playback chain was calibrated in level with the reference signal (Section 2.2.2) and a sound level meter located at the centre of the pentagon.

2.3.2. Experimental procedure

The experiments were conducted as a within-subject design, where all participants were exposed to all stimuli. Prior to the experiment, the participants were introduced to the research topic and task (noise annoyance rating of different situations with WT sounds). After signing a consent form to participate in the study, they answered questions on hearing and well-being as criterions for inclusion in the experiments.

The experiments were done as focused tests. The participants watched and listened to the videos, and rated them regarding noise annoyance after play-back by means of a paper-and-pencil questionnaire (supplementary data, see Appendix A). An investigator, situated at the back of the MVAL, played back the stimuli (once only), one by one, turning off the light during play back and turning it on between the stimuli for the participants to enter the ratings. Annoyance was rated with the ICBEN 11-point scale (Fields et al., 2001), where 0 represents the lowest and 10 the highest noise annoyance rating, by answering the following question (in German, modified from Fields et al., 2001): "You will be subsequently presented with 24 different situations of wind turbine sounds, which you are to rate regarding your annoyance by the sounds. What number from 0 to 10 represents best how much you felt bothered, disturbed or annoyed by the played back situation?" The experiments consisted of (i) an orientation with two stimuli to set the frame of reference, (ii) two exercise ratings to get accustomed to the task with the 11-point scale, and (iii) the actual ratings of the 24 stimuli from Table 1.

After the experiment, the participants completed a pen-and-pencil questionnaire, which assessed noise sensitivity, attitude towards wind farms, gender, age, highest educational degree achieved, landscape most frequently used for recreation, and questions about the experiment. Noise sensitivity was measured with the NoiSeQ-R by Griefahn, Marks, Gjestland, and Preis (2007) (the short form of the NoiSeQ by Schütte, Marks, Wenning, & Griefahn, 2007), which covers values of 0 (noise-insensitive) to 3 (highly noise-sensitive), and attitude towards wind farms with the questionnaire of Schäffer et al. (2016), which covers values of 0 (very negative) to 4 (very positive).

The whole test procedure lasted about one hour. Participants were compensated with 20 Swiss Francs (about 18 Euro) after completing the experiments.

2.3.3. Playback order of the stimuli

Special attention was paid to the playback order of the stimuli. Randomization is a successful strategy in many psychoacoustic experiments, including those of Schäffer et al. (2016; 2018). However for visual stimuli, some authors balanced the order of the stimuli (Ferris, Kempton, Deary, Austin, & Shotter, 2001; Maffei et al., 2013), while others randomized them, either within the same session (Szychowska et al., 2018) or over different days (Sun et al., 2018).

In a preliminary experiment preceding the present study, we played back the audio-visual stimuli of Table 1 to 40 participants (22 females, 18 males) in fully randomized order, using the same laboratory setup and experimental procedure as described above. The results are presented in Appendix B (Fig. B1). The experiment revealed that noise annoyance increases with the acoustical characteristics L_{Aeq} and periodic AM, as well as with the playback number ($p < 0.001$), which is in accordance with the findings of Schäffer et al. (2016). Further, annoyance tended to decrease with more positive attitude toward wind farms ($p = 0.051$), which corroborates the results of Schäffer et al. (2018). The visual setting, in contrast, apparently had no effect ($p = 0.15$). This finding was unexpected insofar as the visual setting differed strongly (Fig. 1) and as some participants felt that it influenced their noise annoyance rating.

For the main experiment, we therefore used a completely counterbalanced design regarding the visual setting (Cohen, 2013). The three visual settings of Table 1 were presented in three blocks in completely counterbalanced order, and the eight acoustical situations per visual setting in randomized order. With this design, the annoyance ratings of the first block correspond to a between-subject design (see above) and are free from potential visual differential carryover effects, while those of the subsequent blocks may contain such effects.

2.3.4. Participants

Forty-three participants (22 females, 21 males), all with self-declared normal hearing and feeling well and healthy, were included in the study. A large part studied or worked at the authors' institution ETH. Accordingly, the panel was quite young (19–52 years; median of 25 years) and well educated, with 67% possessing an academic degree (BSc, MSc, MAS or PhD), and another 30% studying to obtain one. The panel was moderately noise sensitive (noise sensitivity values of 0.4–2.9, median of 1.7). Further, with attitude values of 1.2–4.0 (median of 2.9), the panel was largely positive towards wind farms. The participants spent most of their spare time rather in hilly regions (50%) than in plains (35%) or mountains (15%), and somewhat more in urban (58%) than in rural areas (42%). Thus, the visual setting of the stimuli (hilly rural) corresponded to the preference of a large part of the participants. 67% of the participants had heard WT noise before.

2.4. Statistical analysis

Statistical analysis was done in IBM SPSS Version 23 and 25.

The consistency of the annoyance ratings between participants was assessed with the inter-rater reliability (Hallgren, 2012), doing a two-way random, consistency, average-measures intraclass correlation (ICC) (McGraw & Wong, 1996), where large ICC values indicate high agreement between individuals.

The noise annoyance ratings were analysed by means of linear mixed-effects models (see, e.g., West, Welch, & Gałecki, 2015), using the SPSS procedure MIXED. To that aim, the variables of Table 1 were included as fixed effects, namely, the L_{Aeq} resulting from the distance to the WT as a continuous variable, and periodic AM and visual setting as categorical variables. Potential differential carryover effects of the visual information were also considered with the variable visual setting, which describes the current visual setting and the preceding settings ("the visual history"; cf. Section 3). Given the experimental design, the variables of Table 1, as well as their interactions, were a priori tested. In addition, simple order effects (aside from differential carryover effects) of the playback number of the stimuli (continuous variable), as well as the link of the participants' characteristics to noise annoyance were studied. Finally, repeated observations (24 ratings per participant) were accounted for with a random effect for the participants. Different models of different degrees of complexity (with respect to fixed and random effects) were tested to find the optimal model with respect to completeness (include all relevant variables), performance (data representation, significance of effects) and parsimony (simplicity of the model). The goodness-of-fit of the final model was assessed with the marginal (R_m^2 for the fixed effects) and conditional coefficient of determination (R_c^2 for the fixed and random effects) (Johnson, 2014; Nakagawa & Schielzeth, 2013). Model assumptions were confirmed by means of residual plots, which did not reveal any obvious deviation from normality, and suggested constant variance as well as independence of the observations (except within participants, which was accounted for by the mixed-effect model).

3. Results and discussion

The observed annoyance ratings have an ICC of 0.989. This value lies in the excellent range (Cicchetti, 1994), indicating a high degree of agreement between participants (Hallgren, 2012). In the following account (Sections 3.1–3.3), the observed short-term noise annoyance is discussed. All effects discussed here were confirmed with the mixed-effects model analysis, the results of which are presented graphically along with the observations in Figs. 4–7, as well as described in more detail in Section 3.4. In Section 3.5, the study is brought into broader context.

3.1. Audio-visual effects

Fig. 4 shows the effects of the audio-visual stimuli on noise annoyance, for the first block (first 8 stimuli, free from potential visual differential carryover effects) as well as for the whole experiment (all 24 stimuli). Noise annoyance is strongly linked with the L_{Aeq}, increasing linearly by 1.7 units per 5 dB increase of the L_{Aeq} (Fig. 4a). This corroborates the well-known crucial role of the L_{Aeq} to be a determinant for annoyance in the laboratory (e.g., Lee et al., 2011; Schäffer et al., 2016) and also that an A-weighted metric is appropriate to predict (WT noise) annoyance reactions (Bolin, Bluhm, & Nilsson, 2014). Besides, periodic AM increases annoyance by about 0.6 units on the 11-point scale (Fig. 4b), which would also be evoked by a ~2 dB increase of the L_{Aeq}. This effect has also been amply observed in the laboratory (Hafke-Dys, Preis, Kaczmarek, Biniakowski, & Kleka, 2016; Ioannidou et al., 2016; Lee et al., 2011; Schäffer et al., 2016; 2018) as well as in the field (Bockstael et al., 2012; Pohl, Gabriel, & Hübner, 2018). The results on L_{Aeq} and periodic AM are also in line with the preliminary experiment (Section 2.3.3). The link of the annoyance to the L_{Aeq} and AM is similar in the first block and the whole experiment, except that annoyance tends to increase in the course of the experiment (Fig. 4a and b: 24 vs. 8 stimuli). This suggests a simple order effect.

Finally, the visual setting strongly affects annoyance (Fig. 4c), i.e., it acts as an effect modifier for noise annoyance. For the first block, annoyance increases in the order landscape only < landscape with WT < grey, by 1.2 units on the 11-point scale, which corresponds to ~4 dB increase of the L_{Aeq}. Increased annoyance to situations with visible noise source was also observed in a laboratory study of Yu et al. (2017) and a field experiment by Bangjun, Lili, and Guoqing (2003), while Sun et al. (2018) found the effect of visibility to depend on the participants' noise sensitivity. This corroborates findings of field surveys that the visibility of wind farms increases annoyance (Klæboe & Sundfør, 2016; Pedersen & Larsman, 2008; Pedersen & Persson Waye, 2007; Pedersen et al., 2009). It is also in line with the finding of Maffei et al. (2013) that the number of WTs increases annoyance (although the authors did not investigate the case without visible WT). In the laboratory, the visibility of the WT may have led to (conscious) recognition of WT noise as such, which in turn may increase annoyance (Szychowska et al., 2018; Van Renterghem, Bockstael, De Weirt, & Botteldooren, 2013). Also, it may have shifted the participants' focus to the WT noise, while the landscape alone distracted the participants from the sound. Such focussing apparently was strongest in the grey setting, which did not offer any visual distraction from the sound. Besides, the strong reactions to the grey setting might by caused by the fact that purely auditory situations are emotionally more engaging than videos (Richardson et al., 2018). Our results of the grey vs. landscape setting are also corroborated by Preis, Kociński, Hafke-Dys, and Wrzosek (2015), who for some of their tested cases found audio-visual stimuli of urban places to be linked with a higher comfort feeling than acoustical stimuli alone.

The strong effect of the visual setting on noise annoyance observed for the first block (Fig. 4c, left) is lost when averaging over the whole experiment (Fig. 4c, right). In the latter case, the annoyance varied only by 0.3 points on the 11-point scale between settings, and in a different order (landscape only > landscape with WT ≈ grey). This change was likely to be evoked by a differential carryover effect, which is not eliminated by (complete) counterbalancing and thus may change the overall results (cf. Section 1). The above indicated simple order and differential carryover effects are discussed in Section 3.3.

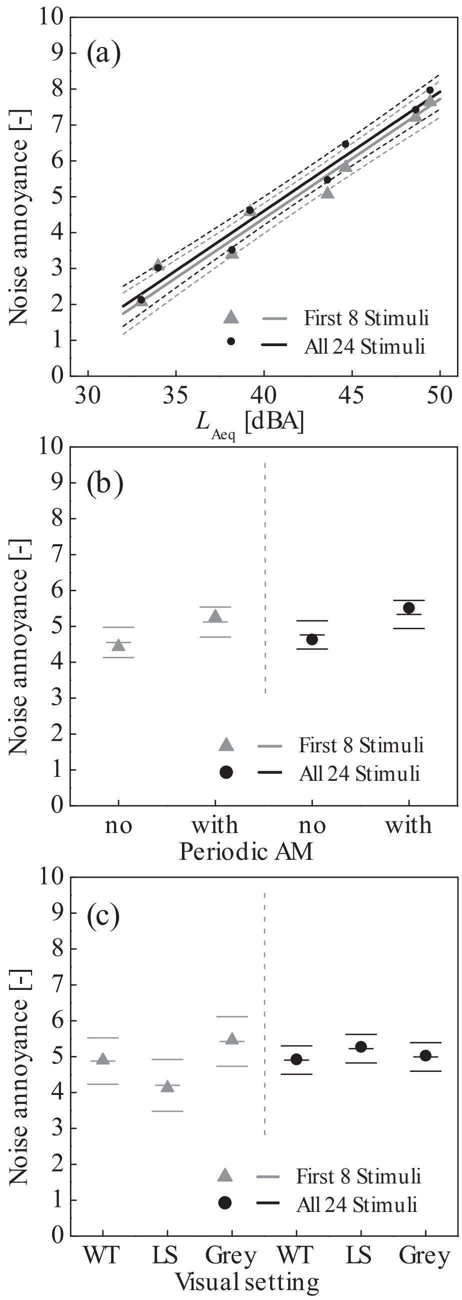

Fig. 4. Mean short-term noise annoyance as a function of the audio-visual characteristics (a) equivalent continuous sound pressure level (L_{Aeq}) (pooled data of different situations of amplitude modulation (AM) and visual settings), (b) AM (without ("no") or with; pooled data of different L_{Aeq} and visual settings) and (c) visual settings (landscape with wind turbine (WT), landscape only (LS) and grey; pooled data of different L_{Aeq} and AM), for the first block of visual setting (first 8 stimuli) and for all three blocks (all 24 stimuli). Symbols represent observations, and lines the corresponding mixed-effects model (Eq. (1)) with 95% confidence intervals, in (b) and (c) as horizontal lines. The annoyance ratings are shown at the mean playback number of either the first 8 stimuli or all 24 stimuli.

3.2. Influence of personal characteristics

The annoyance ratings were found to be lower the more positive the attitude towards wind farms, although scattering is relatively large (Fig. 5). On the 11-point scale, the ratings differ by 2.4 units within the observed range of attitude values of 1.2–4.0, corresponding to a L_{Aeq} difference of more than 7 dB. The importance of attitude was also observed by Ribe, Manyoky, Wissen Hayek, and Grêt-Regamey (2016) and Schäffer et al. (2018), as well as in the preliminary experiment (Section 2.3.3), and is also known from field surveys (Klæboe & Sundfør, 2016; Pedersen & Larsman, 2008; Pedersen & Persson Waye, 2004).

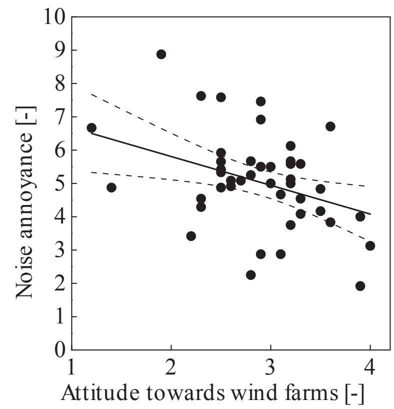

Fig. 5. Mean short-term noise annoyance (mean of all ratings per participant) as a function of the attitude towards wind farms (with values of 0 = very negative to 4 = very positive) according to Schäffer et al. (2016). Symbols represent observations, and lines the corresponding mixed-effects model (Eq. (1)) with 95% confidence intervals.

Annoyance was not linked to any other of the participants' tested characteristics (gender, age or noise sensitivity). Other laboratory studies, in contrast, found a dependency on noise sensitivity (Crichton, Dodd, Schmid, & Petrie, 2015; Sun et al., 2018) or no dependency on personal variables at all (Schäffer et al., 2016). These discrepancies may be due to the fact that in the laboratory, participants' ratings are closer to their sensory perception (corroborated also by the high ICC value found here), while in the field, personal and situational factors become much more important (Janssen et al., 2011; Michaud et al., 2016).

3.3. Simple order and differential carryover effects

Annoyance increased with the playback number of the stimuli, by about 0.6 units on the 11-point scale from the first to the twenty-fourth stimulus (Fig. 6). The same effect would also be evoked by a ~2 dB increase of the L_{Aeq}. Possibly, the participants became increasingly annoyed and/or fatigued by the stimuli, and rated the stimuli ever quicker as they got used to the sounds (practice or fatigue effect: Cohen, 2013). An increase in annoyance with playback number was also observed in the preliminary experiment (Section 2.3.3) as well as in previous laboratory experiments on noise annoyance by Schäffer et al. (2016; 2018). In contrast, an experiment with a pairwise comparison task to evaluate the subjectively perceived sound quality of speech did not reveal such effect (Sanavi, Schäffer, Heutschi, & Eggenschwiler, 2017). In fact, simple order effects were found to depend on the task and to be particularly important for simple tasks (Malhotra, 2009). This corroborates the importance of counterbalancing to eliminate such effects (Cohen, 2013).

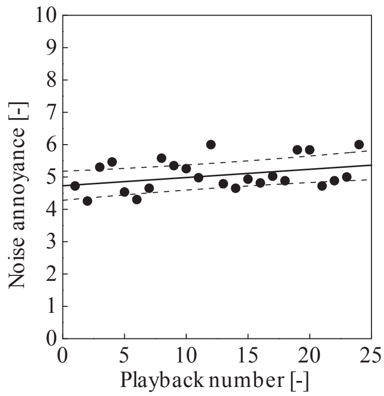

Fig. 6. Simple order effect: Mean short-term noise annoyance vs. playback number. Symbols represent observations (mean of all ratings per playback number), and lines the corresponding mixed-effects model (Eq. (1)) with 95% confidence intervals.

The potential differential carryover effects of the visual setting indicated by Fig. 4c are further presented in Fig. 7, which shows the mean annoyances per visual setting, separately for the first block of visual settings ("between-subject design", thus no visual differential carryover effect), for the second plus third block (with potential differential carryover effects), and for all three blocks. The results of the first block and of the mean of all three blocks correspond to Fig. 4c, except that the simple order effect was excluded in Fig. 7. The data of the second and third block were pooled, because the change between them was smaller than between the first and second block. This indicates that the initial and current visual settings are both determinant for ratings. This observation is congruent with findings from literature on memory, referred to as primacy and recency effect (Li, 2010; Murdock, 1962). The magnitude of annoyance of the first block strongly determines the annoyance of the following blocks. This effect of the first visual setting on annoyance seems even stronger than the effect of the current setting. Accordingly, the order of annoyance to the visual settings in the second/third block differs from the first block. This is likely to be caused by anchoring, where the magnitude of the first rating determines the magnitude of subsequent ratings (Sawyer & Wesensten, 1994). Of the possible carryover effects assimilation and contrast (Ferris et al., 2001), assimilation, i.e., bias towards the rating of the preceding (here, first) visual setting, was apparently the dominant effect here. Assimilation was also found, e.g., by Ward (1973) in a psychoacoustic experiment on loudness evaluation. As a consequence, the effect of the visual setting on the mean annoyance over the whole experiment is lost (Fig. 7, right), which was also observed in the preliminary experiment (Section 2.3.3). Even worse, the data pooled over the whole experiment suggests significant differences between visual settings in a different order than the first, unbiased block (Fig. 7). The observed carryover effect is in line with results from literature for visual assessment (Ferris et al., 2001).

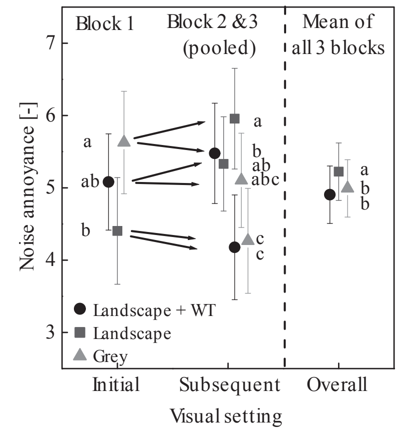

Fig. 7. Differential carryover effect: Mean short-term noise annoyance with 95% confidence intervals (mixed-effects model, Eq. (1)) as a function of the visual setting and the blocks of visual settings (initial = first block only; subsequent = second plus third block; overall = all three blocks). The data of the first block is free from differential carryover effects, while the data of the second/third block also depends on the first block, as indicated by the arrows. Values are shown at the mean playback number of all 24 stimuli to exclude the dependence on playback number (Fig. 6). For presentation purposes (better visibility of the overlapping confidence intervals) the data are slightly shifted on the x-axis. The observed mean annoyance values are very similar to the modelled values shown here except that it implicitly contains the dependency on playback number. Different letters indicate significant differences within blocks, as obtained from estimated marginal means (initial block, subsequent second plus third block) and contras analysis (overall).

Thus, the simple order effect influenced the annoyance to both, acoustical characteristics and visual setting, while a differential carryover effect was observed for the visual setting only. However, this finding cannot be generalized. First, differential carryover effects cannot be excluded a priori for acoustical stimuli. As an example, Sun et al. (2018) in their experiment presented the stimuli in different blocks over four consecutive days to minimize auditory memory of the participants. Second, the studied visual settings were either similar (landscape with vs. without WT) or without (much) information (grey). Thus, the current setting will not or only partially have erased the memory of the preceding setting(s), which might have promoted differential carryover effects. Also Maffei et al. (2013) used similar visual settings and observed only a weak effect of the number of WTs on annoyance (possibly diminished by differential carryover effects). In contrast, Szychowska et al. (2018) and Sun et al. (2018) (cf. Section 2.3.3) used very different visual settings. Here, the memory of the previous setting was probably erased by the current setting, which might have inhibited or at least reduced differential carryover effects, so that visual effects were observed over the whole experiment (contrary to our study). In conclusion, both types of serial position effects may play a role in psychophysical experiments and should be considered in experimental designs.

3.4. Statistical model

To describe the above observed effects on annoyance, the following mixed-effects model was found to be adequate:

$$Annoy_{ijk} = \mu + \beta \cdot L_{\mathrm{Aeq},ijk} + \tau_{\mathrm{AM},i} + \tau_{\mathrm{vis},j} + \gamma \cdot Ord_{ijk} + \delta \cdot Att_k + u_{0k} + u_{1k} \cdot L_{\mathrm{Aeq},ijk} + \varepsilon_{ijk}. \quad (1)$$

In Eq. (1), $Annoy_{ijk}$ is the dependent variable short-term annoyance, μ is the overall mean, τ_{AM} and τ_{vis} are the categorical variables AM (2 levels: $i = 1, 2$) and visual setting (current and first setting, described by 9 levels: $j = 1, \ldots, 9$), L_{Aeq}, *Ord* and *Att* are the continuous variables L_{Aeq}, order (playback number) and attitude towards wind farms, and β, γ and δ are their regression coefficients. The random effect terms u_{0k} and u_{1k} are the participants' random intercept and slope ($k = 1, \ldots, 43$), describing the dependence of the individual annoyance ratings on the L_{Aeq} (same model approach as by Schäffer et al., 2016), and ε_{ijk} is the error term. The index *ijk* represents the *k*th replicate observation of the *i*th AM with the *j*th visual setting. All variables of Eq. (1) are significantly linked to annoyance ($p < 0.001$ to $p = 0.01$). The model parameters are presented in Appendix C. The model explains more than 80% of the variance ($R^2_{\mathrm{m}} = 0.60$, $R^2_{\mathrm{c}} = 0.82$), indicating that it may reproduce the observations highly accurately.

3.5. Broader study context

This section aims at bringing the present study into broader context regarding (i) reproduction techniques, (ii) differences between laboratory experiments and field surveys, and (iii) practical implications.

First, our study revealed that visual impressions may strongly affect the participants' noise annoyance. However, although the audio-visual stimuli used here provided a high level of realism, the projection of the visualizations on a screen with a limited field of view does not meet human viewing habits, which may have influenced the participants' responses. For a more realistic simulation of the multisensory way in which the real environment is perceived, head-mounted displays or a Cave Automatic Virtual Environment (CAVE; e.g., Sahai et al., 2016) to present immersive virtual realities (IVR) are promising tools. They foster the participants' feeling of being present in the virtual environment (Maffei, Masullo, Pascale, Ruggiero, & Romero, 2016; Puyana-Romero, Lopez-Segura, Maffei, Hernández-Molina, & Masullo, 2017; Ruotolo et al., 2013; Yu et al., 2017). Also augmented reality (e.g., Botella et al., 2016) may provide such immersiveness. However, wearable devices such as head-mounted displays are intrusive, which in turn may affect results. Acoustically, immersiveness could be further improved by adding ambient sounds. Systematic studies on differences in results from experiments using different reproduction techniques would therefore be desirable.

Second, in interpreting the results, one should consider the inherent differences between field surveys and laboratory experiments, as discussed in detail for psychoacoustic experiments on WT noise annoyance by Schäffer et al. (2016; 2018). Laboratory experiments as performed here are an important complement to field surveys, because they allow isolating specific variables and thus systematically studying and developing a better understanding of their effects on noise annoyance (e.g., Szychowska et al., 2018; see above). However, at the same time, due to the focus on only few variables, laboratory experiments fall short of providing the whole environmental context, and hence, certain findings might not be confirmed by field surveys. For example, we observed the well-known crucial role of the L_{Aeq} in the laboratory (see Section 3.1), while its effect is weaker in the field (Brink, 2014), where other factors may play a more prominent role (e.g., Janssen et al., 2011; Michaud et al., 2016). Also, the short-term noise annoyance assessed in the laboratory is inherently different from long-term exposure in the field (Guski & Bosshardt, 1992). Therefore, it is crucial to bear in mind that results of single experiments are only revealing certain aspects of a more complex model, which needs to be built upon series of studies and meta-analyses, as proposed by Szychowska et al. (2018). The present study provides a valuable input for enhanced models, which may subsequently be validated in field surveys to prove the generalizability of the results.

Finally, the identified differential carryover effect of the first visual setting on the subsequent annoyance ratings may also have implications for planning practice, as audio-visual simulations are regarded a valuable tool for public participation in environmental planning (Maffei et al., 2016; Manyoky et al., 2016; Ribe et al., 2018). When these techniques are used, for example, to evaluate wind farm scenarios in different landscape contexts or as communication tools for residents of potential future wind parks, the presentation order of the landscapes and/or elements such as WTs (e.g., with/without) might affect the people's perception and noise annoyance, too. Hence, users of audio-visual simulations need to be aware of possible unwanted effects and of methods to avoid them. Focusing in training and teaching courses of 3D landscape simulation not only on technical but also on practical implementation aspects is, therefore, mandatory. Likewise, the presentation order should be rigorously considered in psychophysical laboratory experiments. It would be interesting to know if/how much the results of previous studies (Ferris et al., 2001; Maffei et al., 2013; Sun et al., 2018; Szychowska et al., 2018) (cf. Section 2.3.3) would have changed if the presentation order had been different.

4. Conclusions

In this study, audio-visual stimuli were systematically varied with respect to the distance of the observer from the WT, periodic AM of the sound and visual setting, accounting also for participants' personal characteristics, as well as for simple order and differential carryover effects. We are not aware of any other study on audio-visual effects of WTs, where also the playback order was explicitly accounted for.

We found that both acoustical characteristics and the visual setting affect noise annoyance, besides the participants' attitude towards wind farms. The visual setting may thus act as an effect modifier on noise annoyance. The investigated variables and their variation within the experiment ($L_{\mathrm{Aeq}} = 33$–49 dB; two situations of AM; three visual settings, playback number = 1–24; attitude value = 1.2–4.0) caused annoyance variations decreasing in the order L_{Aeq} (5.4 points on the ICBEN 11-point scale) > attitude (2.4 points) > unbiased visual setting (1.2 points, first block) > periodic AM ≈ playback number (both 0.6 points).

Our results further show that serial position effects (playback order) may affect the outcomes of psychophysical experiments. Simple order effects influenced the annoyance to both, acoustical characteristics and visual setting, while a differential carryover effect was observed for the latter only. Thus, the association of noise annoyance with acoustical characteristics can (usually) be reliably assessed by counterbalancing, eliminating simple order effects. The presentation order of visual stimuli, in contrast, needs more attention and should be explicitly accounted for in experimental designs (Nonyane & Theobald, 2007). The strength of the current study is the full control to separate the "primary" effects (Table 1) from simple order and differential carryover effects. To our knowledge, available studies from literature on audio-visual effects of environmental noise on annoyance did not explicitly investigate the latter effects to date. Whether and to what degree differential carryover effects affected their results thus cannot be answered.

In conclusion, audio-visual characteristics were found to mutually affect noise annoyance. The sound pressure level and amplitude modulation increased annoyance, the presence of a visualized landscape decreased annoyance, and the visibility of a wind turbine increased annoyance. To obtain unbiased experimental results, however, the presentation order of audio-visual stimuli needs to be carefully considered in experimental studies as well as in participatory landscape planning. As the number of audio-visual studies is increasing and findings are thought to support landscape planning and design decisions, it is essential to give these topics more consideration in future studies.

Acknowledgments

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Appendix A. Supplementary material

Supplementary data (authors' questionnaire) associated with this article can be found, in the online version, at https://doi.org/10.1016/j.landurbplan.2019.01.014.

Appendix B. Results of the preliminary experiment

See Fig. B1.

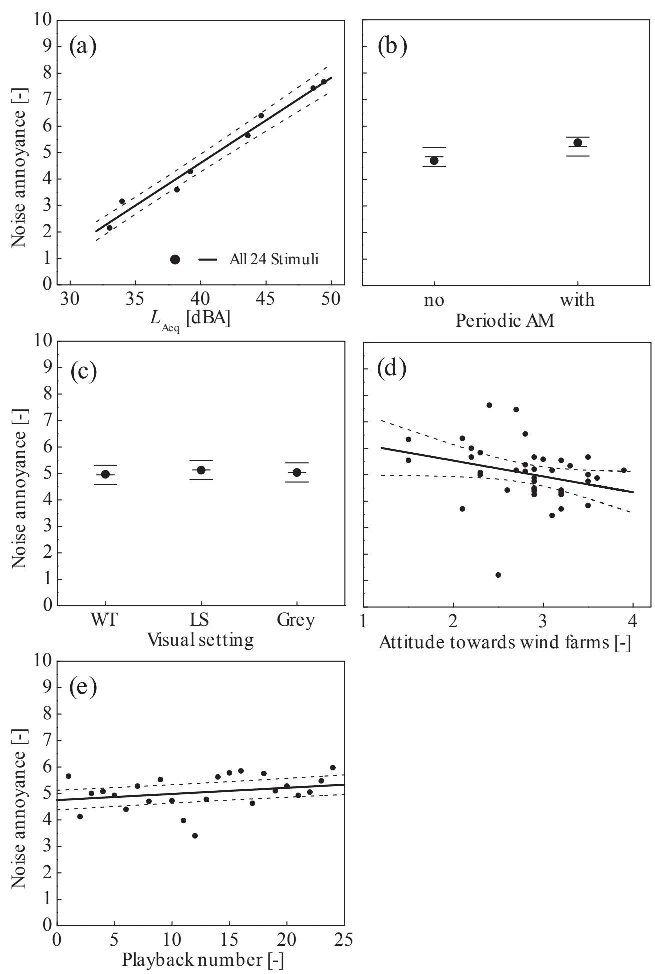

Fig. B1. Mean short-term noise annoyance as a function of (a) the equivalent continuous sound pressure level (L_{Aeq}) (pooled data of different situations of amplitude modulation (AM) and visual settings), (b) AM (without ("no") or with; pooled data of different L_{Aeq} and visual settings), (c) visual settings (landscape with wind turbine (WT), landscape only (LS) and grey; pooled data of different L_{Aeq} and AM), (d) attitude towards wind farms (mean of all ratings per participant, with values of 0 = very negative to 4 = very positive) according to Schäffer et al. (2016), and (e) playback number (mean of all ratings per playback number). Symbols represent observations, and lines the corresponding mixed-effects model with 95% confidence intervals, in (b) and (c) as horizontal lines. The annoyance ratings of (a)–(d) are shown at the mean playback number of all 24 stimuli. Note that an analogous statistical model was used here as for the main experiment (cf. Eq. (1) and Table C1), except that the visual setting was modelled simpler (3 categories only: WT, LS and grey), without accounting for differential carryover effects.

Appendix C. Linear mixed-effect model

See Table C1.

Table C1
Model coefficients with 95% confidence intervals (CI) and probability values (p) of the linear mixed-effects model for the annoyance ratings. The parameters symbols are explained in Eq. (1) in Section 3.4.

Parameter	Symbol	Coefficient	95% CI	p
Intercept	μ	−7.4373	[−10.0772; −4.7973]	< 0.001
L_{Aeq}	β	0.3322	[0.2930; 0.3713]	< 0.001
AM	$\tau_{\mathrm{AM},i=\mathrm{with}}$	0.5703	[0.4201; 0.7205]	< 0.001
	$\tau_{\mathrm{AM},i=\mathrm{no}}$	0[a]		
Visual setting (current; first)	$\tau_{\mathrm{vis},j=\mathrm{WT;none}}$	0.6773	[−0.3008; 1.6554]	0.17
	$\tau_{\mathrm{vis},j=\mathrm{WT;LS}}$	−0.2270	[−0.6274; 0.1733]	0.27
	$\tau_{\mathrm{vis},j=\mathrm{WT;Grey}}$	1.0733	[0.0454; 2.1012]	0.04
	$\tau_{\mathrm{vis},j=\mathrm{LS;none}}$	0[a]		
	$\tau_{\mathrm{vis},j=\mathrm{LS;WT}}$	0.9265	[−0.0761; 1.929]	0.07
	$\tau_{\mathrm{vis},j=\mathrm{LS;Grey}}$	1.5532	[0.5208; 2.5856]	< 0.01
	$\tau_{\mathrm{vis},j=\mathrm{Grey;none}}$	1.2232	[0.2164; 2.2301]	0.02
	$\tau_{\mathrm{vis},j=\mathrm{Grey;WT}}$	0.6999	[−0.3027; 1.7025]	0.17
	$\tau_{\mathrm{vis},j=\mathrm{Grey;LS}}$	−0.1369	[−0.5438; 0.2700]	0.51
Playback number	γ	0.0255	[0.0065; 0.0444]	< 0.01
Attitude towards wind farms	δ	−0.8647	[−1.5207; −0.2086]	0.01
Random intercept	u_{0k}^2	27.3095	[16.891; 44.1541]	< 0.001
Random slope	u_{1k}^2	0.0143	[0.0088; 0.0232]	< 0.001
Residual	ε^2_{ijk}	1.4951	[1.3656; 1.6369]	< 0.001

[a] Redundant coefficients are set to zero.

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