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Annoyance, perception, and physiological effects of wind turbine infrasound

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ABSTRACT:

Even though some individuals subjectively associate various symptoms with infrasound, there are very few systematic studies on the contribution of infrasound to the perception, annoyance, and physiological reactions elicited by wind turbine sound. In this study, sound samples were selected among long-term measurement data from wind power plant and residential areas, both indoors and outdoors, and used in laboratory experiments. In the experiments, the detectability and annoyance of both inaudible and audible characteristics of wind turbine noise were determined, as well as autonomic nervous system responses: heart rate, heart rate variability, and skin conductance response. The participants were divided into two groups based on whether they reported experiencing wind turbine infrasound related symptoms or not. The participants did not detect infrasonic contents of wind turbine noise. The presence of infrasound had no influence on the reported annoyance nor the measured autonomic nervous system responses. No differences were observed between the two groups. These findings suggest that the levels of infrasound in the current study did not affect perception and annoyance or autonomic nervous system responses, even though the experimental conditions corresponded acoustically to real wind power plant areas.

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I. INTRODUCTION

Wind turbine sound (WTS) consists of audible, broadband aerodynamic sound, but also infrasound (IS), which is considered inaudible. The audible part of WTS is often considered more annoying than many other environmental noise sources (Janssen *et al.*, 2011). No clear scientific evidence of the possible harmfulness of IS exist (van Kamp and van den Berg, 2018). However, many non-specific symptoms such as headache and other aches, dizziness, nausea, fatigue, ear pressure sensations, tinnitus, and cardiovascular symptoms (e.g., high blood pressure, arrhythmia), have been associated with IS by many individuals living near wind power plant areas (van Kamp and van den Berg, 2018).

The dominant infrasound frequency from a wind turbine depends on operational conditions and the type of the turbine. When operating at rated power, the source of this 0.7–1.5 Hz frequency is generally considered to be the blade-tower interaction. Although the human auditory system is insensitive to the IS frequencies, it is possible to determine their detection thresholds (Leventhall, 2007; Møller and Pedersen, 2004). The hearing threshold data is typically based on pure-tone monaural stimulus. An average sound pressure level (SPL) 120.7 dB was needed for

triggering an auditory sensation at 2.5 Hz in the data presented by Kuehler *et al.* (2015), but some persons were able to detect up to 13 dB lower levels. Also, multiple harmonics may play a role in detection if their sound level exceeds the threshold. Friedrich *et al.* (2020) have shown that the threshold decreases when infrasound components are presented simultaneously. If infrasound exceeds the threshold, it may be experienced more strongly than audible sound because loudness increases more rapidly beyond threshold at a very low level compared to higher frequencies (Jurado *et al.*, 2017).

Burke *et al.* (2019), however, recently found that detection of audible synthetic pink noise was not affected by the presence of infrasound at frequencies 5 and 12 Hz, for which the average thresholds were 109 and 92 dB SPL, respectively. In a similar vein, Marquardt and Jurado (2018) found that participants were unable to discriminate whether an amplitude-modulated audible low-frequency tone at 40 and 50 phon contained an 8 Hz infrasound component or not. These studies suggest that infrasound does not contribute to the perception of audible sounds at least in the tested conditions using synthetic, artificial stimuli.

There are very few studies using wind turbine sound as stimuli. Yokoyama *et al.* (2014) used WTS samples at A-weighted levels between 27 and 56 dB and found that detection thresholds for WTS were very similar to previously

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measured thresholds for single infrasound frequencies and very high intensity levels were required before the infrasound components could be detected. [Nguyen et al. \(2019\)](#) measured the audibility of infrasound in WTS using signal detection theory measures (d'). They used 10-s samples at a sound pressure level $L_G = 48$ dB, which is below the normal hearing threshold. Detectability was above chance only in participants scoring high on the Weinstein Noise Sensitivity Scale ([Weinstein, 1978](#)). In addition, participants scoring low on this scale were biased to respond that infrasound was not present. Considering that there were only very few participants (7 per group), the results can be taken as preliminary.

In a very recent study, [Burke et al. \(2020\)](#) investigated the experienced unpleasantness of infrasound at 12 Hz and audible sound (1000 Hz and pink noise between 250 and 4000 Hz), delivered monaurally using tubes and an audiometric ear tip to ensure auditory stimulation. At the average threshold level ($L_Z = 95$ dB), the 12 Hz infrasound did not contribute to the unpleasantness of audible sound. However, at 110 dB it increased the unpleasantness of the sounds. They also found that at 95 dB, the unpleasantness ratings of 12 Hz were higher for participants with lower detection thresholds. This suggests that perceptually sensitive individuals may experience near-threshold-level infrasound more unpleasant than less sensitive individuals. [Burke et al. \(2020\)](#) point out that unpleasantness is a crucial aspect in annoyance, which is a more comprehensive concept, including, e.g., disturbance. In an annoyance rating experiment, [Møller \(1987\)](#) found that a 16 Hz infrasound exceeding about $L_Z = 100$ dB increased the annoyance of audible noise between 40 and 60 dB in free field conditions (the significance was not statistically tested, however). These two quite different studies both suggest that high levels of infrasound can exacerbate adverse experiences elicited by sound. However, such levels of IS are rarely encountered in real-life environment.

[Jurado and Marquardt \(2020\)](#) measured brain activity (so-called frequency-following responses) with EEG and showed that infrasound frequency (11 Hz) can elicit this response at least in some participants. [Weichenberger et al. \(2017\)](#) used functional magnetic imaging to investigate the brain responses to infrasound stimulation. They found that an exposure to infrasound levels near but below the hearing threshold may induce activity across several brain regions that are involved in emotional and autonomic control. They used a 12 Hz pure tone stimulus 2 dB below individual hearing thresholds of the participants, ranging between 79 and 96 dB. The extrapolation of this finding to much lower infrasound levels generated by wind turbines is not straightforward because the maximum infrasound levels at 12 Hz from near the source vary between 40 and 60 dB ([Jakobsen, 2005](#); [Jung et al., 2008](#); [Lanki et al., 2017](#)). Still, these findings imply that it may be possible to elicit physiological responses at subthreshold infrasound levels.

Most previous studies on the effects of infrasound on human perception and physiological responses have used synthetic sounds as stimuli and young individuals (often students) as participants. Several of these studies have reported

individual variation in thresholds and responses to infrasound stimulation. In order to address the question whether infrasound may have adverse effects in real-life environment, it would be important to study stimulation that corresponds to actual WTS in the vicinity of wind power plant areas, and to study individuals who live in these areas. It is possible that some individuals are more sensitive to infrasound and thus might suffer from symptoms that have been subjectively associated with infrasound. Therefore, in the current study, individuals both with and without such symptoms were studied, and recordings of WTS, reproduced at actual levels including infrasound, were used as stimuli in controlled laboratory experiments.

The present work was part of a larger research project commissioned by the Finnish Government's Analysis, Assessment and Research Activities on the potential health effects of wind turbine infrasound, published as a technical report ([Maijala et al., 2020](#)). The research project included long-term sound measurements and a questionnaire study, in addition to this experimental study reported here. The aim of the questionnaire study was to characterize the symptoms that people living near wind turbines intuitively associate with wind turbine infrasound. The aim of the long-term sound measurement campaign was to capture infrasound and audible sound from a uniform period, throughout all the seasons from residential buildings that were not occupied during the measurements, and to use the sound samples in psychoacoustical and psychophysiological studies.

The main aim was to study whether infrasound originating from wind turbines may cause adverse effects. The sound samples originally recorded inside and outside residential houses near wind turbines with the highest IS levels and amplitude modulation depth (AM) values were selected for experiments where perception, annoyance and physiological reactions to them were studied. It is noteworthy that AM of WTS was also included to the design as a factor due to the fact that increases in AM of WTS has been previously associated with higher annoyance ratings ([Lee et al., 2011](#); [Schäffer et al., 2016](#)). Five experiments were organized to answer the main research questions. The aim of the detection experiment was to examine whether infrasound in WTS could be detected. The aim of the annoyance rating experiment was to find out whether the reported annoyance of the sounds increases with AM or IS level. The aim of the blind infrasound stimulation experiment (BIS) was to examine the subjective stress level and the autonomic nervous system (ANS) responses to double-blind infrasound stimulation. The instruction test examined whether a mere instruction of the presence of infrasound could affect the stress levels or ANS responses. Finally, a standard cold-pressure test (CPT) was conducted to examine the participants' stress reactivity to aversive stimuli in general.

II. EXPERIMENTAL SETUP AND PROCEDURE

A. Infrasound test chamber and sound system

The infrasound stimuli were reproduced by exploiting the acoustical infinite baffle principle in an airtight chamber

measuring $2\text{ m} \times 3\text{ m}$ and 2.22 m high. In other words, the participants were placed inside a closed loudspeaker. Two Alpine SWR-1522D loudspeaker drivers (Alpine Electronics, Inc., Japan) were attached to a reinforced door of the infrasound chamber, see Fig. 1 and those were able to produce a sound pressure of 132 dB (122 dB in piston linear movement range) using a Brüel & Kjær type 2721 directly coupled (DC) amplifier (Brüel & Kjær, Denmark). However, due to minor air leaks of the chamber, the frequencies below 1 Hz had to be amplified to extend the frequency response down to 0.25 Hz (-3 dB). One active Genelec 8130 A monitor loudspeaker (Genelec Oy, Finland) in front of the participant was used for the upper audible frequency range (Fig. 3). The cutoff frequency was chosen to be 55 Hz . A two channel DA converter with a frequency response starting from 0.1 Hz , NuForce uDAC3 Revision 1 (NuForce Inc., USA), was used with a conventional desktop computer.

The frequency responses of both actuators and the whole sound reproduction chain were measured using a DC Siemens Scadas XS type SC-XS12-A (Siemens, USA) sound analyzer and a GRAS 47AC (GRAS Sound & Vibration, Denmark) one-half inch measurement microphone positioned in the center of the participant's head location, at ear level. The traceable infrasound response of this microphone model extends down to 0.05 Hz , and this was verified with a GRAS 42AE low frequency calibrator starting at 0.01 Hz . The same equipment was also used to record the sound samples.

Compensating inverse filters were designed to be able to reproduce the WTS samples original in frequency content and sound pressure level. The total compensated frequency response was within $\pm 1.5\text{ dB}$ between 0.27 and $10\,000\text{ Hz}$ (-3 dB , 0.25 – $12\,000\text{ Hz}$, Fig. 2).

The test chamber was designed to be well sound-proofed, but not specifically for IS frequencies. The background noise level in IS frequencies was 20 dB below the



FIG. 1. Loudspeaker drivers were attached to the reinforced door of the chamber and hidden behind a curtain during tests.

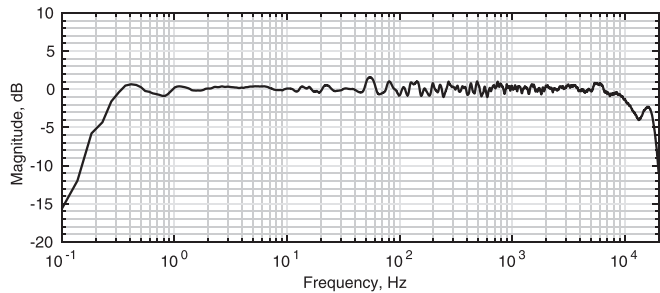


FIG. 2. Frequency response of the infrasound test chamber sound system.

highest IS stimuli level,¹ but higher than the lowest stimuli levels, so it was one of the parameters monitored and recorded by the research nurses.

A during-the-test calibration signal was generated and used before and after every test by the research nurses to check the sound pressure levels of the sound system. The during-the-test calibration signal contained two sinusoidal components¹: a 20 Hz for the IS playback channel and a 200 Hz for the Genelec channel. If the level of either of these sinusoids or the background noise level deviated from the prescribed ones, the experiment was not continued.

The WTS samples were reproduced in the infrasound test chamber with the same frequency content and SPL as at the time of recording. To minimize the possible deviations in audible frequencies, the participants were positioned to the optimal location using a cross-laser scale, see Fig. 3. SPL in the infrasound frequencies is not location-dependent in this setup.

B. Stimuli

The stimuli used in the experiments were selected from 48 kHz sound samples recorded in the project's long-term measurements from wind power production areas approximately 200 m from a wind turbine (wind power plant area, *emission*), samples recorded approximately 1.5 km away in yards of houses (yard, *immission*), and inside the houses (indoors, *immission*). The distance of 1.5 km was determined by the distance to the nearest houses. In Finland, dwellings are usually further than this. The indoor and yard measurements were done inside and outside houses that had

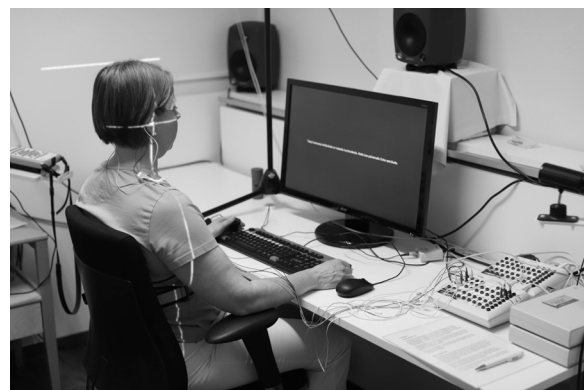


FIG. 3. A participant in the test chamber. A laser scale (lines visible on participants's face and body) was used in positioning the participant.

been abandoned by the inhabitants because they suffered from the sound of the wind turbines, which was audible even in the houses. There were 17 wind turbines (Vestas V126, Siemens SWT-3.0-DD) in each wind power plant area. The details of the measurements can be found from the technical report (Maijala *et al.*, 2020).

Stimuli for infrasound detection and annoyance experiment were selected from immission data by looking for the highest linear equivalent SPL, $L_{p,Z,600s}$, from emission data by looking for the medium SPL, and for both data, the minimum and maximum values of amplitude modulation depth. The emission data contained much more audible WTS and recorded sounds with maximum SPL would have been too disturbing compared to other samples, so we chose the medium SPL for emission data. Moreover, samples containing unrelated noise such as bird song, traffic noise, thuds, or speech were discarded. In addition to a 7.5 min stimulus, 10 s stimuli were selected.¹ A 10-s stimuli contains ten cycles of the dominant 1 Hz frequency component of WTS. Previous studies have also used stimuli durations allowing at least ten cycles at the lowest frequency (Burke *et al.*, 2019; Friedrich *et al.*, 2020; Kuehler *et al.*, 2015; Marquardt and Jurado, 2018). Sixty independent WTS samples were used in infrasound detection and annoyance experiments.¹

Sound samples were filtered at both infrasound range and low audible range, using a low-pass and a high-pass filter at 20 Hz, and a high-pass filter for 100 Hz. The filters were implemented as infinite impulse response (IIR) and finite impulse response (FIR) filters. The type of the low-pass and high-pass filters was a fourth-order IIR with a 0.5 dB pass-band ripple and the type of all the compensating, inverse filters was FIR with lengths between $2^{14} - 1$ and $2^{18} - 1$.

In addition to WTS, a nature sound condition (ocean beach sounds) was used as a control, reference condition (five independent samples in total) in annoyance experiments. Ocean beach sounds were selected as neutral or more pleasant reference sounds because Szychowska *et al.* (2018) found that sounds of calm waves at the sea side had lower annoyance ratings than wind turbine sounds.

In the blind infrasound stimulation experiment (BIS), continuous infrasound lasted 7.5 min since no responses were required from the participant in this passive listening condition. In general, the duration of the sound samples was selected to accommodate the need to have long enough samples and at the same time to keep the experiment within reasonable and practical time limits.

The linear, A- and G-weighted sound pressure level ranges of the selected sound stimuli are shown in Table I.

All the stimuli were adjusted in level so that the sound system maintained the original sound pressure level, which was sample specific. For example, the linear equivalent sound pressure level for the indoors stimulus used in the 7.5-min blind infrasound stimulation (BIS) test was 89 dB.¹

C. Participants

A letter of invitation was sent with the survey of the questionnaire study to 4847 citizens living near wind power

TABLE I. Sound pressure levels of the selected sound stimuli.

Location, condition	$L_{p,A}$	$L_{p,Z}$
Wind power plant	47–57 dB	52–77 dB
Yards of houses	42–59 dB	46–82 dB
Inside the houses	41–43 dB	74–89 dB
Ocean beach, control	34–45 dB	45–72 dB
For more details, see the supplement. ¹		

production areas. In addition, participants were invited through local newspapers and personal telephone calls. Due to the challenge of recruiting symptomatic individuals (long distance from home to the test laboratory and cancellations), group sizes were smaller than planned. 27 individuals were willing to participate in the laboratory experiment. Before the experiment, an extensive health questionnaire was sent to the participants. 11 participants (7 females) reported experiencing symptoms due to infrasound from wind turbines, and 15 (8 females) reported they had no symptoms related to wind turbines. Symptomatic participants were on average 58.0 years old (range 41–71), and asymptomatic participants were on average 53.7 years old (range 30–72 years). Wind turbine related symptoms (WTRS) will be used for self-reported symptoms in this paper. The group of participants with WTRS will be called *symptoms* group, and those without WTRS will be called *no symptoms* group.

The participants' travel costs and accommodation were compensated. The experiment was conducted in accordance with the Declaration of Helsinki, and the ethical statement was obtained from the ethical board of the Helsinki University Hospital.

D. Course of the laboratory study

The five blocks of the laboratory study are shown in Table II. Physiological responses of the autonomic nervous system (ANS) were recorded during all experimental conditions. Self-reported levels of stress were obtained before the experiment and after each experiment on a scale from 1 to 10 (1 = no stress, 10 = extreme stress).

In the first block (blind infrasound stimulation, BIS), the participants watched a silenced video that consisted of clips of natural scenes and animals living peacefully in their natural environment. The clips did not include any disturbing animal behavior. This block was divided into two testing conditions (BIS test 1 and BIS test 2). In the BIS test 1, the participants were presented with infrasound stimuli, a 20 Hz

TABLE II. List of the experiments in chronological order.

Experiment	Duration	Infrasound
Blind infrasound stimulation test 1-2	7.5/5 min	yes/no
Infrasound detection experiment 1-5	9 min	yes
Annoyance experiment 1-6	10 min	yes/no
Baseline recording within the CPT	5 min	no
CPT	3 min	no
Instruction test 1-2	5 min	no

low-pass filtered from wind turbine sound stimulus for 7.5 min, and in the BIS test 2, they were watching the video for 5 min without any acoustic stimulus. Participants were instructed that the experimenters were carrying out baseline measurements for physiological responses during this 12.5-min block. The participants were thus not aware that they were presented any acoustic stimuli during this block. The order of BIS tests 1 and 2 was counterbalanced between the participants.

Two psychoacoustical experiments followed the BIS block. The first psychoacoustical experiment was the infrasound detection experiment and the second was the annoyance rating experiment. The procedure of these two experiments are presented in better detail in Sec. III. The annoyance rating experiment was followed by the CPT that lasted for 3 min. Baseline recordings for physiological measurements of the CPT were carried out before the CPT and lasted for 5 min. The participants watched a silent video during this baseline measurement. Finally, in the instruction test 1, the participants were told that they would be presented with wind turbine infrasound for 5 min, and in the instruction test 2 also lasting 5 min, they were told that the infrasound was not present. Neither of these instruction tests included any infrasound. The order of these tests was counterbalanced between the participants.

The experiments were conducted as double-blind. Neither the participants nor the research nurses conducting the measurements were aware which stimuli and blocks contained infrasound.

III. PSYCHOACOUSTICS

A. Infrasound detection experiment

1. Procedure

A two-interval same-different task was used. In a same trial (50% of trials) participant was sequentially presented with two identical wind turbine sound samples, separated with 500 ms of silence. In a different trial, one of the samples (chosen randomly) was high-pass filtered. Each stimulus was presented for 10 s. Then, a response screen was shown, and the participant's task was to indicate by using the keyboard whether the sounds were identical or not. After the response, there was a random delay of 200–400 ms before the start of the next trial.

Three stimulus conditions were tested: 40 trials had noise samples obtained from a wind power plant, 40 from yards near residential dwellings and 40 were selected from recordings inside the residential houses.

In the experiment, 50% trials had two identical, unfiltered samples whereas 50% of the trials had one filtered sample. In the wind power plant area and yard conditions, both 20 Hz high-pass filter and 100 Hz high-pass filter were used. In indoors condition only 20 Hz filter was used. Various stimulus conditions were randomly interleaved. The total number of trials per condition was 40. Experiment

consisted of 5 blocks of 24 trials and each block lasted about 9 min.¹

The order of the blocks and the trials within the blocks was randomized. Participants had possibility to rest between the blocks. Before the actual experiment, a practice block was presented. The practice block contained three trials and it was not included in the final data analysis.

2. Preprocessing of experimental data and statistical analysis

Detectability of infra- and low-frequency wind turbine sound components was analyzed using signal detection theory measures (Macmillan and Creelman, 2004). The analysis allows to separate the true sensory-based sensitivity for stimulus (discriminability index d') independently of participant's subjective response criterion (i.e., the bias towards particular response). For the analysis, we first calculated the proportion of "different" responses in the different trials (hit rate, p_{11}). This was then compared with the proportion of "different" responses in same trials (false alarm rate, p_{10}). Discriminability index d' was obtained from the Z-scores of hit and false alarm rates by

$$d' = Z(p_{11}) - Z(p_{10}), \quad (1)$$

where Z is the inverse of the standard cumulative normal distribution. d' can be interpreted as true sensory response separation between the same and different trials, divided by the common standard deviation of the response.

3. Results

Data from one participant was lost because of a technical problem and the results of the remaining 26 participants are presented in the following. The results of the detection experiment are shown in Fig. 4, which shows sensitivity (d') to high-pass filtered sound samples from wind power plant area, yard, and indoors separately for the WTRS group that reported wind turbine related symptoms (*symptoms*) and for the group that reported no such symptoms (*no symptoms*). To test whether average sensitivity in each condition was above chance level ($d' = 0$), one sample t -tests were used, corrected for multiple comparisons using false discovery rate correction (Benjamini and Hochberg, 1995) so that q , the type I error rate was $q \leq 0.01$.

Average sensitivity for 20 Hz infrasound was low (wind power plant area: $d' = 0.21$, $SD = 0.44$; yard: $d' = 0.21$, $SD = 0.45$; indoors: $d' = -0.17$, $SD = 0.45$) and not statistically significantly greater than 0. The test had sensitivity to detect d' of approximately 0.30 (circa 56% correct responses) at 0.8 statistical power.

Sensitivity for 100 Hz-filtered samples was larger on average, and wind power plant area 100 Hz condition sensitivity was significantly above chance ($d' = 0.92$, $SD = 0.95$). In the yard condition, 100 Hz samples were not discriminated above the chance level ($d' = 0.52$, $SD = 0.86$).

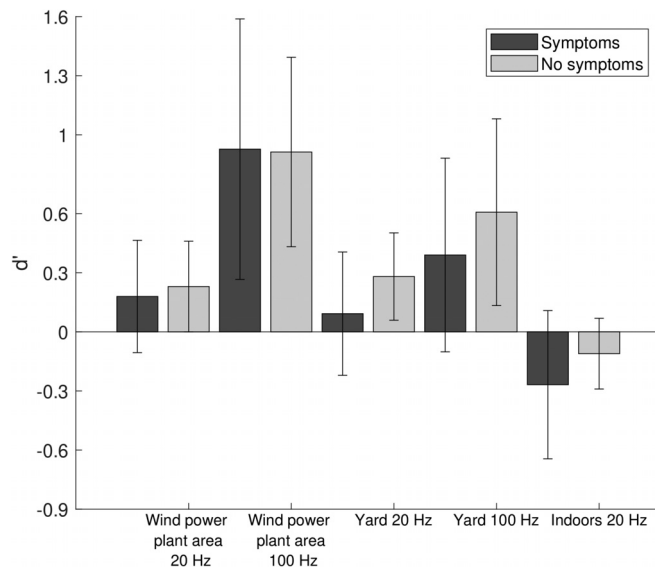


FIG. 4. Infrasound sensitivity for the WTRS group that reported wind turbine related symptoms (*symptoms*) and for the group that reported no such symptoms (*no symptoms*). 95% confidence intervals are shown by the error bars.

Sensitivity to infrasound showed no systematic differences between groups, even though the *symptoms* group seemed less sensitive to infrasound overall. The statistical significance of the difference was tested using ANOVA where stimulus condition was the within-subjects variable, and group the between-subjects variable. Greenhouse-Geisser correction was used because of the lack of sphericity. The effect of stimulus condition was statistically significant $F(2.158, 51.801) = 4.502$; $p = 0.044$; $\eta_p^2 = 0.219$ but the difference between groups was not $[F(1, 24) = 0.400$; $p = 0.533$; $\eta_p^2 = 0.016]$.

B. Annoyance experiment

1. Procedure

The task in this experiment was to rate the annoyance of wind turbine and reference sounds. In each trial, a test sound was presented for 10 s followed by a response screen where the participant was asked to rate the annoyance of the sound using keyboard numeric keys and an 11-point scale from 0 (not annoying) to 10 (very annoying). Wind turbine sound recording site (wind power plant area or yard) and AM depth (minimum or maximum) was varied. Infrasound trials were presented in separate blocks that lasted approximately 10 min so that infrasound would have adequate time to influence physiological measurements. Every other block contained infrasound and every other high-pass filtered WTS at 20 Hz cut off. Presentation order was varied between participants. Each block consisted of 50 trials where different stimulus conditions (wind power plant area, yard, and nature sounds as well as maximum and minimum AM) were presented randomly interleaved.

2. Results

The results of wind turbine sound annoyance are shown in Fig. 5 depicting the average ratings for sounds recorded in wind power plant area, yard, and the reference sound, presented either unfiltered with infrasound frequencies or without infrasound, separately for the *symptoms* and *no symptoms* group. The effect of sound AM depth was tested by comparing samples gathered from maximum AM and minimum AM.

Statistical significance of the ratings was assessed using ANOVA. Recording site (two levels), amplitude modulation depth (two levels), and presence of infrasound (two levels) were used as within-subjects factors and WTRS as the between-subjects factor (two levels: *symptoms/no symptoms*). The effect of recording site was statistically significant $[F(1, 24) = 67.394$; $p < 0.001$; $\eta_p^2 = 0.737]$. As also seen in Fig. 5, wind power plant area recording sites showed the highest annoyance ratings, followed by yard and nature sound. In addition, the effect of amplitude modulation depth was significant $[F(1, 24) = 58.853$; $p < 0.001$; $\eta_p^2 = 0.710]$. Amplitude modulation depth had an effect, especially in the yard condition. On the other hand, the presence of infrasound did not have a statistically significant effect on reported annoyance $[F(1, 24) = 0.788$; $p = 0.382$; $\eta_p^2 = 0.032]$. The *symptoms* group seemed to rate the sounds more annoying than the *no symptoms* group. However, the difference was not statistically significant: $F(1, 24) = 2.270$; $p = 0.145$; $\eta_p^2 = 0.086$.

IV. PSYCHOPHYSIOLOGY AND SUBJECTIVE STRESS

In order to examine whether the wind turbine infrasound or related annoyance could affect the ANS, electrocardiography (ECG) and electrodermal activity (EDA) were continuously recorded (0–125 Hz, $F_s = 500$ Hz) using a

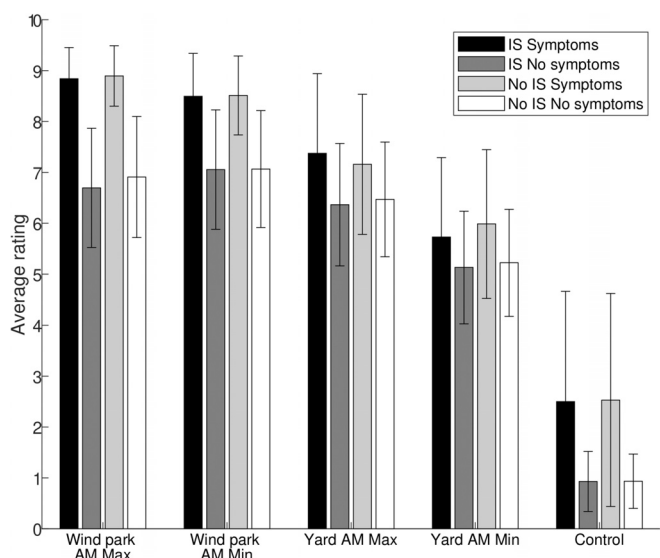


FIG. 5. Annoyance ratings of WTS by symptoms: group that reported wind turbine related symptoms (*symptoms*) and group that did not report symptoms (*no symptoms*).

NeurOne EXG40 amplifier. Two disposable Ambu BluSensor electrodes were placed at the lower left rib cage and upper right collarbone for ECG measurement. Two electrodes were placed to the non-dominant hand, on the palmar side of the proximal phalanges of the index and the middle fingers for the EDA measurement.

The ECG and the EDA were recorded during various experimental conditions. First, it was examined whether the ANS responses differ in the presence (BIS test 1) and in the absence (BIS test 2) of the wind turbine infrasound. The participants were instructed to watch a silent video film and they were told that their baseline physiology would be recorded. During one block, the 7.5-min BIS test stimulus was played in the background, while there was no stimulation during the other (5 min) block. The order of the blocks was counterbalanced between participants. Second, ECG and EDA were recorded during the wind turbine infrasound detection experiment and the annoyance rating experiment. The objective was to examine the differences between blocks containing infrasound and those without infrasound, as well as the potential group differences in ANS reactivity while evaluating wind turbine stimuli. Third, participants' ANS stress reactivity was examined with a standard CPT. In this test, a 5-min baseline (BL) physiology recording was followed by a 3-min cold water immersion (4–5 °C), where the participants' dominant hand was immersed, up to the wrist, in a water bucket. Last, ECG and EDA were recorded during two 5-min blocks, without any sound stimulation, but differing with respect to the instruction given. During one block they were told that there would be infrasound stimulation (instruction test 1) in the background, and during the other that no stimulation would be presented (instruction test 2). Again, the participants watched a silent video during the measurements and the order of the blocks was counterbalanced.

During the course of the whole study, the participants were asked to report their stress level (Stress inquiry) at eleven occasions with a scale from 0 (not at all) to 10 (very much).

A. Preprocessing of experimental data

The continuous ECG data were analyzed via MATLAB® (The MathWorks, Inc., 2016). Mean heart rate (HR) and the root mean square of successive inter-beat-intervals (RMSSD, describing heart rate variability) during each stimulation block were extracted using complete MATLAB implementation of Pan Tompkins ECG QRS detector (Sedghamiz, H, 2014). The EDA data were analyzed using the Ledalab-toolbox (v3.4.8) for MATLAB. The number and the sum amplitude of spontaneous skin conductance response (SCR) spikes were separately extracted for each stimulation block.

B. Statistical analysis

For the cardiac features HR and RMSSD two-tailed t-tests were conducted to compare differences between

groups (two-sample t-tests assuming unequal variances) and between conditions (paired t-tests). The within-participant comparisons were conducted for the *symptoms* and *no symptoms* group separately, but also for all participants together.

First, the HR and RMSSD were compared between the infrasound block (BIS test 1) and the no-infrasound block (BIS test 2). Second, the HR and the RMSSD during those three blocks of the annoyance rating experiment that included infrasound were compared to those three blocks that did not include infrasound. Third, the HR and the RMSSD during the detection experiment were compared between the *symptoms* and *no symptoms* groups. Fourth, the HR and the RMSSD during the baseline recording before the cold water immersion (BL) were compared to those during the cold water immersion (CPT), and also between groups. Finally, the HR and the RMSSD were compared between the two instructions (instruction test 1 and 2) when no stimulation was factually presented.

For the EDA, two-way analyses of variance (ANOVA) were used to compare the effects of test condition and participant group (*symptoms* and *no symptoms*) on the number of SCR spikes and on the sum amplitude of SCR spikes. The first comparison included the first two passive conditions (BIS tests 1 and 2), the baseline condition (BL) preceding the cold water immersion, and the cold water immersion (CPT). The second comparison compared the three blocks including infrasound to those without infrasound in the annoyance rating experiment. The third comparison examined the difference between the two instructions (instruction tests 1 and 2) in the absence of stimulation. The statistical analyses were performed primarily via R (R Development Core Team, 2019).

C. Results

1. Cardiac features HR and RMSSD

The cardiac activity did not differ between the groups, nor between any of the compared experimental conditions, except for the HR during the cold water immersion. For both groups, the HR increased significantly from the baseline measurement to the water immersion [*no symptoms* group: mean HR during baseline 64 bpm vs mean HR during water immersion 73 bpm, $t(17) = -5.25$, $p < 0.001$; *symptoms* group mean HR during baseline 69 bpm vs mean HR during water immersion 75 bpm, $t(9) = -4.82$, $p < 0.001$].

2. SCR

The main effect of condition (BIS tests 1 and 2, and the baseline and water immersion during CPT) was significant for both measures [number of spikes: $F(3) = 20.21$, $p < 0.001$; amplitude sums: $F(3) = 10.63$, $p < 0.001$]. Tukey *post hoc* tests revealed that the activity was increased during the cold water immersion as compared with the BIS tests and the baseline for both measures ($p < 0.001$). No differences were observed between the BIS conditions (BIS test 1 and BIS test 2), nor the participant groups (*symptoms* and *no symptoms*). Further, no statistically significant differences

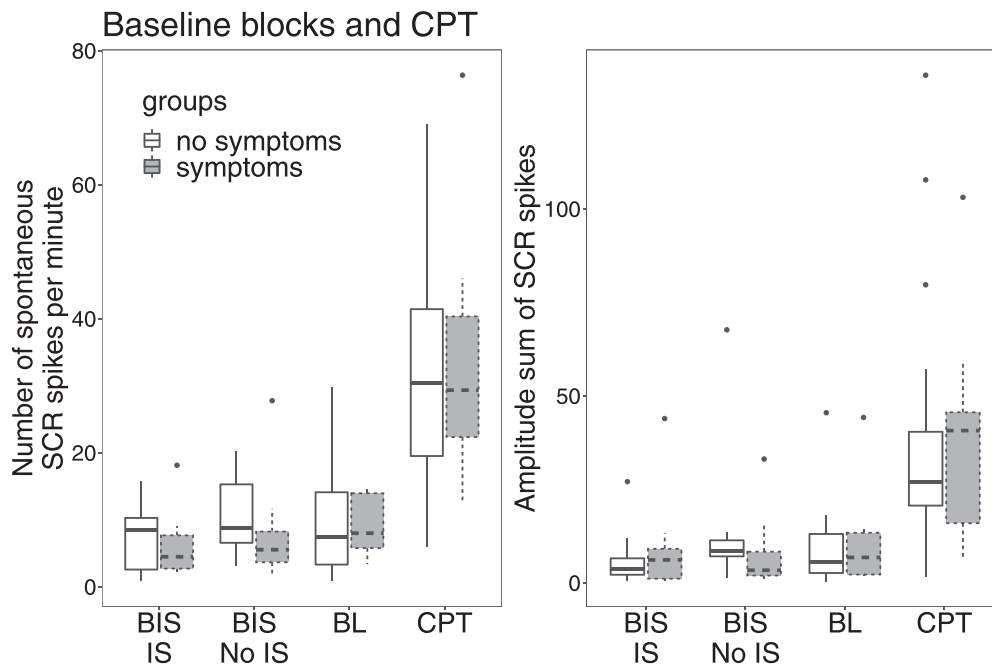


FIG. 6. The number and sum amplitude of SCR peaks between the BIS, BL, and the CPT conditions. BIS conditions are reclassified based on infrasound presentation.

were observed in any other comparisons. The number and sum amplitude of SCR peaks between the baseline conditions and during the water immersion in CPT is shown in Fig. 6. Figure 7 shows SCR peaks during different blocks of the annoyance experiment and is classified based on the presence of infrasound. The instruction test, with classification based on whether the participant was or was not told whether infrasound would be presented during the block is depicted in Fig. 8.

D. Self-reported stress

In the beginning of the study and during the BIS test both groups reported low stress ratings (mean of the group *symptoms*: 1.1, *no symptoms*: 1.5). *No symptoms* group did not show an increase in stress level during the course of the study, with average stress rating of 0.8 at the end of the study. *Symptoms* group, however, gave high stress level ratings during the study with an average of 4.2 at the end. The difference in the increase in self-reported stress during the

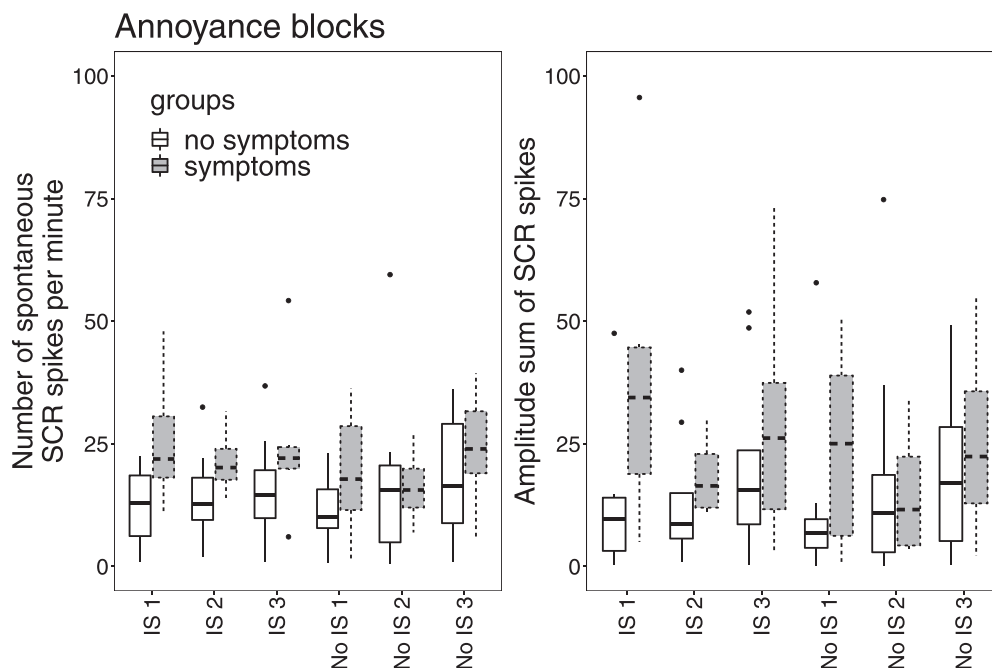


FIG. 7. The number and sum amplitude of SCR peaks in the annoyance test conditions, reclassified based on infrasound presentation.

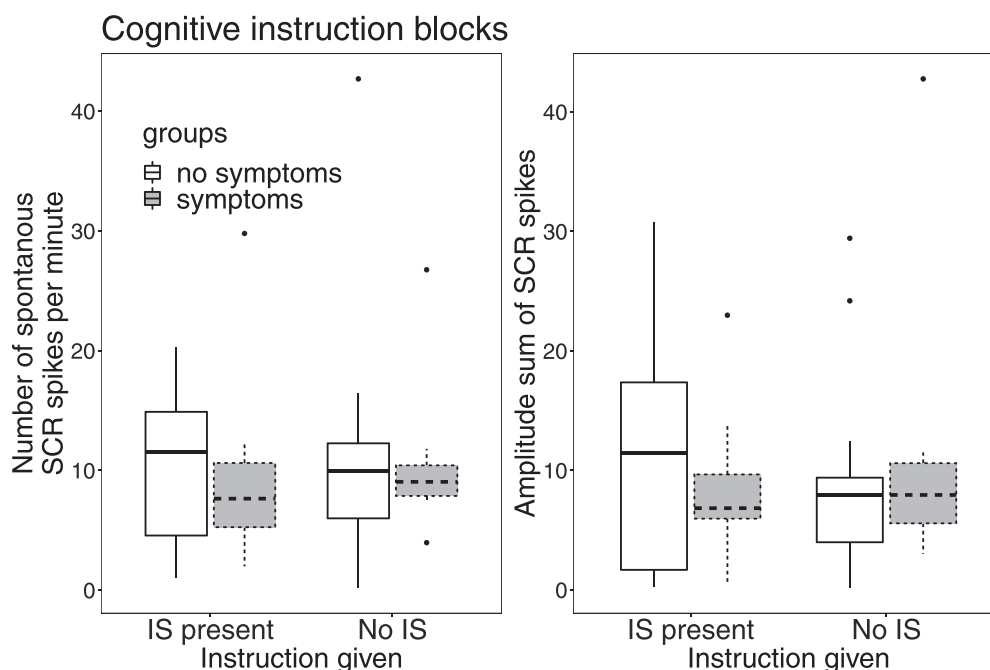


FIG. 8. The number and sum amplitude of SCR peaks in the instruction test blocks.

course of the study (first stress inquiry at the beginning of the study—the last at the end of the study) between groups was statistically significant $t(23) = 4.09$; $p < 0.001$.

Moreover 55% of the *symptoms* group reported symptoms during the experiments, whereas these were absent in the *no symptoms* group.

V. DISCUSSION

The aim of this study was to investigate whether infrasound can be perceived, and whether it increases annoyance of wind turbine sound. In addition, the study explored whether the ANS reacts to audible and inaudible wind turbine sounds and its components.

In the detection experiment, signal detection theory measures were used to analyze the perceptual sensitivity to infrasound in wind turbine sound samples that were accurately reproduced in controlled laboratory conditions. The results did not show statistically significant sensitivity to the presence of infrasound in any of the stimulus conditions (wind power plant area, yard, indoors sounds). This finding was supported by the fact that participants did not report perceiving infrasound even during the 7.5-min exposure in the BIS test. Sensitivity for audible low-frequency (below 100 Hz) sound was, however, above chance level (except for the yard stimuli). This shows that participants could perform the discrimination task correctly when stimuli included audible low frequency components. The current finding that sensitivity to infrasound was extremely poor in the presence of audible sound is in agreement with previous studies showing very high thresholds to infrasound using synthetic stimuli (Burke *et al.*, 2019; Marquardt and Jurado, 2018) and WTS in tasks specifically instructing participants to listen to whether infrasound is present or not (Nguyen *et al.*,

2019; Yokoyama *et al.*, 2014). None of the previous studies present such low frequencies that was studied in the current work. In this study, the maximum energy of the original signal was below 1 Hz in almost all of the stimuli containing infrasound. However, even the highest levels were all below the known detection threshold. The current same-different task allowed the participant to utilize all sensory information (e.g., vibrations), and still sensitivity was poor. Moreover, when sensitivity was compared between the participant groups (*symptoms* and *no symptoms*), no differences were found. In other words, the group reporting wind turbine related symptoms did not present increased sensitivity to infrasound or low-frequency sound.

When investigating the annoyance related to various characteristics of wind turbine sound (i.e., presence of infrasound, level of amplitude modulation depth and stimulus condition), the presence of infrasound had no effect on experienced annoyance. The annoyance ratings were similar with and without infrasound. The influence of infrasound on annoyance was absent in both groups. These observations do not support the suggestion that infrasound would be a core element in annoyance associated with wind turbine sound. This is at least the case in the current conditions using several minutes of high SPL ($L_{p,Z} = 89$ dB) wind turbine infrasound exposure, meanwhile in real-life conditions the exposure is very long-term (days to even years). Still, individuals with WTRS report experiencing symptoms even in brief situations where infrasound is present. The current study aimed to simulate such situations in a controlled way. It should also be noted that previous laboratory studies using synthetic sounds have shown that higher levels (above 100 dB) of IS may contribute to annoyance ratings (Burke *et al.*, 2020; Møller, 1987).

The stimulus condition and amplitude modulation of WTS influenced annoyance ratings in both groups of participants. The participants rated the maximum AM stimuli more annoying than the minimum AM stimuli. This finding is in line with previous studies showing that amplitude modulation of wind turbine noise increases annoyance (Lee *et al.*, 2011; Schäffer *et al.*, 2016). Regarding the stimulus condition, the stimuli recorded in wind power plant area were rated more annoying than the yard stimuli and the control stimuli (beach sound). It is likely that this is because the stimuli recorded in the power plant area provided more intensive turbine noise than the other stimuli. Consequently, they were rated more annoying.

The findings of the psychoacoustical experiments were supported by the psychophysiological recordings of the autonomic nervous system (cardiac and electrodermal) activity. No differences were found between the infrasound and no-infrasound conditions, nor between the conditions with the instruction that infrasound was present or absent. Thus, no signs of physiological arousal were found in this study. This is in contrast to the proposition (Bauer *et al.*, 2015; Salt and Kaltenbach, 2011) that wind turbine infrasound could increase arousal and elicit physiological stress responses even in situations when the infrasound is not perceived, or when its presence is assumed. In addition, there were no significant differences between the ANS reactivity of the groups of participants. Hence, the WTRS group (*symptoms*) was not found deviantly reactive to stressful stimuli, whether they were wind turbine sounds, wind turbine infrasounds, or a stressful sensory stimuli in another sensory modality (cold water immersion). One should, however, bear in mind, that the methods to measure the physiological effects of wind turbine infrasound in this study (autonomic nervous system responses) differ from those of previous studies (auditory and central nervous system) and therefore they cannot be directly compared (Bauer *et al.*, 2015; Salt and Kaltenbach, 2011).

Do these results mean that there is no difference in reactions to wind turbine sound between the participant groups with and without WTRS? Self-reported stress levels were different between the groups as soon as the participants became aware that stimuli contained wind turbine infrasound—but not during the preceding BIS test. Many participants in the group with WTRS also expressed adverse symptoms during the experiments, which were absent in the group without WTRS. These findings suggest that the group with WTRS (*symptoms*) reacted differently under conditions in which they expected infrasound to be present. In this case, the symptoms are likely to be triggered by other factors than the physical qualities of the sound. Similar symptoms have also been shown to emerge with other environmental factors such as electromagnetic fields at very low exposure levels or in situations where a person feels exposed to them (Das-Munshi *et al.*, 2006; Eltiti *et al.*, 2015; Rubin *et al.*, 2011; Witthöft and Rubin, 2013). In a similar manner, some of the symptoms subjectively attributed to wind turbine infrasound may be related to

experiencing wind turbines as disruptive and considering them a health risk.

The general lack of reactions to infrasound in the current experiments should also be considered in the light of the exact experimental conditions. The aim was to record and reproduce real environmental wind turbine sounds accurately, and this was achieved through considerable efforts. This allowed investigation of the effects of WTS as it is present in the actual environment where people live and operate in the vicinity of wind power parks. This means that the levels of audible sound and infrasound were quite moderate. However, at considerably higher intensities, it would probably be possible to elicit some reactions. It remains for future laboratory studies to investigate higher intensities of WTS beyond those found in real-life environment.

VI. CONCLUSION

An extensive study involving both psychoacoustical and psychophysiological measurements of the autonomic nervous system was carried out to investigate whether infrasound in wind turbine noise may have some adverse effects on humans. The participants represented individuals who experienced symptoms from wind turbines and those without symptoms.

The stimuli for the experiments were selected from long-term wind turbine sound measurements indoors and outdoors of houses from which residents had moved away due problems they related to infrasound, as well as measurements in the actual wind power plant area. The highest levels of linear sound pressure and amplitude modulation depth were searched among the recordings. An infrasound test chamber was prepared with a capacity to produce an almost flat frequency response between 0.25 and 12 000 Hz at all sound pressure levels produced by wind turbines. Five experiments were conducted: detection, annoyance rating, blind infrasound stimulation, instruction, and a standard CPT.

Detection of infrasound was not above chance level, and participant groups with or without symptoms did not differ in their ability to detect it. The presence of infrasound made no difference to how annoying the participants perceived sounds, regardless of symptoms. Higher sound pressure levels and amplitude modulation depth increased the annoyance of the audible sound. There was no difference in the stress-related responses of the autonomic nervous system as to whether or not there was infrasound in the sound sample, or whether a claim was made that infrasound was present. The participants' autonomic nervous system stress reactivity in cold water immersion was as expected: for both groups, the cardiac and the skin conductance responses reacted significantly from the baseline. The group with WTRS reported more stress and symptoms than the control group during the experiment.

In the conditions used in the current study, infrasound did not contribute to the detection, annoyance, or physiological reactions to wind turbine sound.

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¹See supplementary material at <https://www.scitation.org/doi/suppl/10.1121/10.0003509> for frequency-domain figures and experiment structure and details.

- Bauer, M., Sander-Thömmes, T., Ihlenfeld, A., Kühn, S., Kühler, R., and Koch, C. (2015). "Investigation of perception at infrasound frequencies by functional magnetic resonance imaging (fMRI) and magnetoencephalography (MEG)," in *Proceedings of the International Congress on Sound and Vibration*, p. 1–6.
- Benjamini, Y., and Hochberg, Y. (1995). "Controlling the false discovery rate: A practical and powerful approach to multiple testing," *J. R. Stat. Soc. B* **57**(1), 289–300.
- Burke, E., Hensel, J., Fedtke, T., Uppenkamp, S., and Koch, C. (2019). "Detection thresholds for combined infrasound and audio-frequency stimuli," *Acta Acust. Acust.* **105**(6), 1173–1182.
- Burke, E., Uppenkamp, S., and Koch, C. (2020). "A psychoacoustical study to investigate the perceived unpleasantness of infrasound combined with audio-frequency sound," *Acta Acust.* **4**(5), 1–12.
- Das-Munshi, J., Rubin, G. J., and Wessely, S. (2006). "Multiple chemical sensitivities: A systematic review of provocation studies," *J. Allergy Clin. Immun.* **118**(6), 1257–1264.
- Eltiti, S., Wallace, D., Russo, R., and Fox, E. (2015). "Aggregated data from two double-blind base station provocation studies comparing individuals with idiopathic environmental intolerance with attribution to electromagnetic fields and controls," *Bioelectromagnetics* **36**(2), 96–107.
- Friedrich, B., Joost, H., Fedtke, T., and Verhey, J. L. (2020). "Spectral integration of infrasound at threshold," *J. Acoust. Soc. Am.* **147**(3), EL259–EL263.
- Jakobsen, J. (2005). "Infrasound Emission from Wind Turbines," *J. Low Freq. Noise Vib. Act. Control* **24**(3), 145–155.
- Janssen, S. A., Vos, H., Eisses, A. R., and Pedersen, E. (2011). "A comparison between exposure-response relationships for wind turbine annoyance and annoyance due to other noise sources," *J. Acoust. Soc. Am.* **130**(6), 3746–3753.
- Jung, S. S., Cheung, W.-S., Cheong, C., and Shin, S.-H. (2008). "Experimental identification of acoustic emission characteristics of large wind turbines with emphasis on infrasound and low-frequency noise," *J. Korean Phys. Soc.* **53**(4), 1897–1905.
- Jurado, C., Gallegos, P., Gordillo, D., and Moore, B. C. J. (2017). "The detailed shapes of equal-loudness-level contours at low frequencies," *J. Acoust. Soc. Am.* **142**(6), 3821–3832.
- Jurado, C., and Marquardt, T. (2020). "Brain's frequency following responses to low-frequency and infrasound," *Arch. Acoust.* **45**(2), 313–319.
- Kuehler, R., Fedtke, T., and Hensel, J. (2015). "Infrasonic and low-frequency insert earphone hearing threshold," *J. Acoust. Soc. Am.* **137**(4), EL347–EL353.
- Lanki, T., Turunen, A., Majjala, P. P., Heinonen-Guzejev, M., Kännälä, S., Toivo, T., Toivonen, T., Ylikoski, J., and Yli-Tuomi, T. (2017). "Tuulivoimaloiden tuottaman äänen vaikutukset terveyteen" ["Health effects of sound produced by wind turbines"], Technical report 28, Ministry of Economic Affairs and Employment.
- Lee, S., Kim, K., Choi, W., and Lee, S. (2011). "Annoyance caused by amplitude modulation of wind turbine noise," *Noise Control Eng. J* **59**(1), 38–46.
- Leventhall, G. (2007). "What is infrasound?," *Prog Biophys Mol Bio* **93**(1), 130–137.
- Macmillan, N. A., and Creelman, C. D. (2004). *Detection Theory: A User's Guide* (Psychology Press, Hove, UK), pp. 1–444.
- Majjala, P., Turunen, A., Kurki, I., Vainio, L., Pakarinen, S., Kaukinen, C., Lukander, K., Tiittanen, P., Yli-Tuomi, T., Taimisto, P., Lanki, T., Tiippana, K., Virkkala, J., Stickler, E., and Sainio, M. (2020). "Infrasound does not explain symptoms related to wind turbines," Technical Report No. 2020:34, Prime Minister's Office.
- Marquardt, T., and Jurado, C. (2018). "Amplitude modulation may be confused with infrasound," *Acta Acust. Acust.* **104**(5), 825–829.
- Møller, H. (1987). "Annoyance of audible infrasound," *J. Low Freq. Noise Vib. Act. Control* **6**(1), 1–17.
- Møller, H., and Pedersen, C. S. (2004). "Hearing at low and infrasonic frequencies," *Noise Health* **6**(23), 37–57.
- Nguyen, D. P., Hansen, K., Zajamsek, B., Micic, G., and Catcheside, P. (2019). "Wind farm infrasound detectability and its effects on the perception of wind farm noise amplitude modulation," in *Proceedings of Acoustics 2019*, Vol. 10, pp. 1–8.
- R Development Core Team. (2019). *R: A Language and Environment for Statistical Computing, Version 3.6.1* (R Foundation for Statistical Computing, Vienna, Austria).
- Rubin, G. J., Hillert, L., Nieto-Hernandez, R., van Rongen, E., and Oftedal, G. (2011). "Do people with idiopathic environmental intolerance attributed to electromagnetic fields display physiological effects when exposed to electromagnetic fields? A systematic review of provocation studies," *Bioelectromagnetics* **32**(8), 593–609.
- Salt, A. N., and Kaltenbach, J. A. (2011). "Infrasound from wind turbines could affect humans," *Bull. Sci. Technol. Soc.* **31**, 296–302.
- Schäffer, B., Schlittmeier, S. J., Pieren, R., Heutschi, K., Brink, M., Graf, R., and Hellbrück, J. (2016). "Short-term annoyance reactions to stationary and time-varying wind turbine and road traffic noise: A laboratory study," *J. Acoust. Soc. Am.* **139**(5), 2949–2963.
- Sedghamiz, H. (2014). *Matlab Implementation of Pan Tompkins ECG QRS Detector*.
- Szychowska, M., Hafke-Dys, H., Preis, A., Kociński, J., and Kleka, P. (2018). "The influence of audio-visual interactions on the annoyance ratings for wind turbines," *Appl. Acoust.* **129**, 190–203.
- The MathWorks, Inc. (2016). MATLAB® Version 9.1.0.441655 (R2016b), Natick, MA, USA.
- van Kamp, I., and van den Berg, F. (2018). "Health Effects Related to Wind Turbine Sound, Including Low-Frequency Sound and Infrasound," *Acoust. Austr.* **46**(1), 31–57.
- Weichenberger, M., Bauer, M., Kühler, R., Hensel, J., Forlim, G. C., Ihlenfeld, A., Ittermann, B., Gallinat, J., Koch, C., and Kühn, S. (2017). "Altered cortical and subcortical connectivity due to infrasound administered near the hearing threshold—Evidence from fMRI," *PLoS One* **12**(4), e0174420–19.
- Weinstein, N. D. (1978). "Individual differences in reactions to noise: A longitudinal study in a college dormitory," *J. Appl. Psychol.* **63**(4), 458–466.
- Witthöft, M., and Rubin, G. J. (2013). "Are media warnings about the adverse health effects of modern life self-fulfilling? An experimental study on idiopathic environmental intolerance attributed to electromagnetic fields (IEI-EMF)," *J. Psychosom. Res.* **74**(3), 206–212.
- Yokoyama, S., Sakamoto, S., and Tachibana, H. (2014). "Perception of low frequency components in wind turbine noise," *Noise Control Eng. J.* **62**(5), 295–305.