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Author(s)	Garcia-Guerrero, Santiago;Manohare, Manish;O'Hora, Denis;King, Eoin A.
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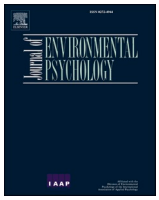

Annoyance and memory performance in the presence of wind turbine sound

Santiago Garcia-Guerrero [a,*], Manish Manohare [b], Denis O'Hora [a], Eoin A. King [b]

[a] School of Psychology, University of Galway, Ireland
[b] School of Engineering, University of Galway, Ireland

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ABSTRACT

Wind energy is a critical component in the clean energy transition and the acceptance of wind turbines depends on understanding the impacts of wind turbines on local communities. There is concern that wind turbine sound may affect the health of local residents. One vector through which sound can affect the human body is via the induction of neural frequencies that compete with endogenous and task-specific frequencies. The current study assessed the effects of concurrent wind turbine sound on memory performance to investigate such effects. 46 participants each completed 304 memory trials under varying conditions of wind-turbine sound. Participants performed as expected in the memory task, with greater memory load reducing recognition accuracy, but there were no effects of wind turbine sound properties on performance. Subjective annoyance by wind turbine sound was low, but it was consistently related to acoustic properties of the sound samples, specifically loudness, sharpness, roughness and fluctuation strength. Annoyance by wind turbine sound slightly increased during the task suggesting prolonged exposure may contribute to an accumulation of annoyance over time. Annoyance did not affect memory performance. The current findings support the position that wind turbine noise may induce annoyance, but they do not support the position that wind turbine noise interferes with healthy human brain function.

1. Introduction

Wind energy is one of the most viable technological means for obtaining renewable energy and reducing environmental pollution from alternative fossil fuels (Dincer, 2011; Kaldellis & Zafirakis, 2011; Kaygusuz, 2004). However, wind turbines generate sound which can be a concern for nearby residents (Horbaty et al., 2012; McKenna et al., 2016; Saidur et al., 2011), leading to a lack of acceptance and opposition of wind farms development (Diógenes et al., 2020; Toke et al., 2008). One specific concern of communities near wind farms is that wind turbine sound may disturb mental and physical health (e.g., Pierpont, 2009). Consequently, numerous studies in the past two decades have investigated the relationships between various health outcomes and exposure to wind turbine sounds.[1] Typical indicators of interest include, mental health factors, such as sleep disturbance, anxiety, and sensitivity to noise, and physical factors, such as cardiovascular disease and metabolic effects (Karasmanaki, 2022; Knopper & Ollson, 2011; Van Kamp & Van Den Berg, 2018). Exposure to WTS does not have direct physically harmful effects on people (Van Kamp & Van Den Berg, 2018, 2021), nor has it been found to be related to self-reported symptoms such as migraines (Michaud et al., 2016; cf. Müller et al., 2023). However, annoyance and sleep disturbance are often associated with WTS (Karasmanaki, 2022; Van Kamp & Van Den Berg, 2018).

1.1. Background

Wind turbines produce a complex mix of—primarily aerodynamic—tonal, broadband, low-frequency, and impulsive sounds (Bowdler, 2008; King et al., 2012; Oerlemans, 2015; Saidur et al., 2011; van den Berg, 2013, pp. 17–20). Additional factors, such as amplitude modulation, infrasound, rhythmic pressure pulses, and fluctuation strength, can exacerbate annoyance (Palmer, 2017; Schäffer et al., 2019a; Van Kamp & Van Den Berg, 2018). Amplitude modulation (AM), characterised by fluctuating sound levels (due to the speed of rotating

* Corresponding author. University of Galway (Ireland), University Road, postcode H91 TK33; School of Psychology; office AMB, 2054, Ireland.
E-mail address: santiago.garciaguerrero@universityofgalway.ie (S. Garcia-Guerrero).

[1] In this paper the word 'sound' is preferred as an objective term for acoustic waves; whereas 'noise' is a subjective term referring to a stimulation which causes interference, is unwanted and perceived negatively (cf. Borg, 1981; Muzet, 2007; Stallen, 1999).

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turbine blades), is a key factor in wind turbine noise annoyance, even at low A-weighted levels (especially during periods with strong modulation depths; Attenborough & Renterghem, 2021). Although not fully understood yet (Hansen et al., 2017; Larsson & Öhlund, 2014), AM has been highlighted as a feature that that might induce wind turbine noise annoyance (Ioannidou et al., 2016; Lee et al., 2011; Pedersen, 2011; Pohl et al., 2018).

Wind turbine sound (WTS) is characteristically below community sources of noise (e.g., traffic), yet a greater proportion of people get annoyed by WTS than by typical community noises (Haac et al., 2019; Michaud et al., 2016; Van Kamp & Van Den Berg, 2018). Moreover, different acoustic properties of WTS, at the same L_{Aeq} level, have been found to generate different ratings of annoyance (Waye & Öhrström, 2002). For example, Waye and Öhrström (2002) found wind turbine sounds described as "swishing", "lapping" or "whistling" are more annoying than sounds described as "grinding" and "low frequency". Likewise, Large and Stigwood (2014) departing from the tendency of our brains to synchronise with in external signals (see Trainor & Hannon, 2013), identify the irregular rhythmic attributes of WTS (lacking in patterns and symmetry), as well as variable amplitude modulation features, as key factors contributing to people finding WTS annoying, intrusive or difficult to ignore. This suggests that the issue of noise from wind turbines is not simply a matter of noise level reduction, but also matter of sound quality, with a particular focus on acoustic characteristics that may increase noise annoyance (e.g., rhythmic pressure pulses on buildings; Large & Stigwood, 2014; Van Kamp & Van Den Berg, 2018).

Negative reactions to wind turbine noise constitute a psychological stressor (e.g., Bakker et al., 2012; Hübner et al., 2019; Ouis, 2001; Pohl et al., 2018; Stallen, 1999), and "noise annoyance" is specifically included in the WHO's definition of health as an "environmental health burden" (Fritschi et al., 2011, p. xvi). In the same way, wind turbine noise annoyance is said to include negative feelings such as dissatisfaction, disturbance, displeasure, irritation and nuisance (WHO, Environmental Noise Guidelines, 2018; Ouis, 2001; see also Pierpont, 2009 for a hypothetical definition of "Wind-Turbine Syndrome").

There is, however, more to wind farm-related annoyance than meets the ear. Subjective and social factors are associated with wind farm annoyance including attitudes towards wind turbines and green energy (Freiberg et al., 2019; Hübner et al., 2019; Michaud, Keith, et al., 2016; Müller et al., 2023), perceived landscape impact (Pedersen et al., 2009; Pedersen & Waye, 2004), economic benefit (Freiberg et al., 2019; Michaud, Keith, et al., 2016), fairness of the planning phase (Pohl et al., 2018; Radun et al., 2019), perceived lack of control (Doolan, 2013; Stallen, 1999), sensitivity and decreased ability to ignore noises (Hiller & Goebel, 2007), and negative expectations or nocebo effects generated by unfavorable publicity within communities (Crichton et al., 2014) among others.

While sound parameters alone are not sufficient to explain the impact of wind turbine annoyance on communities (cf. Hoen et al., 2019; Hongisto et al., 2017; Hübner et al., 2019; Müller et al., 2023), noise concern is often posed as a basis for development opposition (Diógenes et al., 2020), and noise is a major contributor to the annoyance reported by wind farm community residents (Müller et al., 2023; Van Kamp and Van Den Berg, 2021). Understanding WTS audibility and its relation to noise annoyance can facilitate alignment between the environmental benefits of renewable energy developments and the interests/concerns of communities potentially affected by wind farms (Haac et al., 2019).

Despite the focus on noise annoyance, there is a lack of standardization in annoyance measurement. Indeed, the majority of studies take the conceptualization of annoyance for granted (see Michaud et al., 2016; Stallen, 1999). Subjective responses to the acoustic environment are typically assessed using social surveys including indicators that can be quite generic (see Haac et al., 2019; Janssen et al., 2011; Karasmanaki, 2022; Michaud et al., 2016). Annoyance, however, is a complex and highly subjective construct; somebody's favourite music can be somebody else's noise nuisance, and a moderate level of perceived annoyance might be another person's extreme level (Premalatha et al., 2014; see also Job, 1999; Stansfeld, 1992 for a conceptualization of noise sensitivity).

Albeit not often the focus of the available research (cf. Bakker et al., 2012; Blanes-Vidal & Schwartz, 2016), annoyance can be conceptualised as mediated by and/or moderating other psychological processes (Pohl et al., 2018). For example, noise may cause annoyance indirectly by impairing concentration and attention (Hübner et al., 2019; Stansfeld & Matheson, 2003), rather than being inherently annoying. Self-report data from community studies (Müller et al., 2023; Pohl et al., 2018) suggest that WTS-annoyance affects performance, manifested in a lack of concentration. Data from experimental research on similar annoyance indicators could validate the correspondence between reported subjective experiences and objective task-performance metrics on tasks requiring concentration.

Plenty of areas remain unexplored in wind turbine psychoacoustics (Knopper & Ollson, 2011; cf. Ioannidou et al., 2016) and little attention has been given to the potential effects of WTS over subtle cognitive processes such as concentration or memory (see Ruotolo et al., 2012; Yu et al., 2017 for exceptions). Not only is this an understudied area of research within the wind turbine literature (see Karasmanaki, 2022 for a review; cf. Pierpont, 2009), but robust evidence from environmental noise pollution suggests a strong correlation between noise sources (e.g., traffic) and negative effects on cognitive processes, in particular among primary school children (including sustained attention, memory, language comprehension, concentration, auditory/speech discrimination; see Evans & Lepore, 1993; Stansfeld & Matheson, 2003 for reviews). It is unknown to what extent the types and sound levels characteristic of wind turbines are analogue to typically researched noise pollution sources in this respect.

Our sensory systems are constantly bombarded by dynamic stimuli. Our eyes and ears are attuned to specific frequencies of electromagnetic radiation and air pressure fluctuations, respectively. Brainwaves (viz., neural oscillations) underlie our perception of the world, with different frequencies associated with various cognitive states. Gamma waves (γ; oscillations around 35 Hz) are dominant during intense cognitive activity, while beta waves (β; 12–35 Hz) are associated with anxiety and external attention. Sleep stages are characterised by different frequency patterns, including delta waves (δ; .5–4 Hz; Abhang et al., 2016). External rhythmic stimuli, such as flickering lights or sounds, can influence brainwave patterns.

The brainwave entrainment hypothesis (also known as neural synchronization or cortical entrainment) suggests that external stimuli presented at specific rhythms stimulates the brain to match the frequency of the stimulation (Ingendoh et al., 2023; Will & Makeig, 2012). For example, binaural beats (which involve presenting slightly different tones to each ear) can influence brainwave activity in targeted frequency ranges (Ingendoh et al., 2023). Likewise, isochronic tones are produced by oscillating the amplitude of any sound on and off at a specific rate—normally a rate equivalent to that of a desired brainwave state (Huang & Charyton, 2008). Consequently, a sine wave oscillating on and off eight times per second (8 Hz) could entrain the brain to an alpha state (8–10 Hz). Given that certain cognitive activities are supported by endogenous neural frequency patterns, it is possible for external rhythmic stimulation (e.g., visual or auditory fluctuations) to facilitate or disturb such patterns, enhancing or interfering with cognition (Du Bois & Elliott, 2017; Elliott & Müller, 2003).

For example, Henry et al. (2014) conducted a study in which participants' task was to identify near-threshold gaps (i.e., short pauses) in auditory stimuli, while recording electroencephalography (EEG) data. The auditory stimuli were simultaneously modulated in frequency (3.1 Hz) and amplitude (5.075 Hz), to assimilate the rhythmic structure of natural speech. The authors found that participants' performance in target-detection depended on the specific phase–phase relationship

between entrained neural oscillations in both frequency bands (see also Kösem et al., 2018).

Furthermore, specific oscillations of neural excitability are known to influence different cognitive processes (Henao et al., 2020; Herrmann et al., 2016; Lakatos et al., 2008). Attentional and memory processes have been linked to theta and alpha frequency bands respectively (Friese et al., 2013; Hanslmayr et al., 2019; see Helfrich et al., 2019; Klimesch, 2012 see for reviews). For example, Roberts et al. (2018) studied memory retrieval processes by exposing participants to rhythmic auditory and visual stimulation. In one of their experiments, the entrainment group was exposed to audiovisual stimuli at 5.5 Hz, whereas subjects in the control group received white noise. Their data confirmed increased memory performance due to theta entrainment. Likewise, Köster et al. (2019) promoted neural entrainment by manipulating rhythmic visual stimulation. Their results suggested enhanced memory formation processes when theta (3–8 Hz) and gamma waves (40–120 Hz) oscillated together in a synchronized manner.

While previous research has provided valuable insights focusing on conventional sound pressure metrics (e.g., L_{Aeq}), there is insufficient data—other than loudness—relating WTS psychoacoustics to subjective annoyance (cf. Waye & Öhrström, 2002). To fully comprehend subjective responses to objective phenomena, it is necessary to include psychoacoustic units that reflect the difference between *sensing* sound and *perceiving* noise (e.g., sones). Moreover, as WTS propagates spatially from the turbines the acoustic features do not decay in lockstep with sound-pressure, so understanding the role of acoustic features in annoyance will enable more precise mapping of the impacts of WTS. Concurrently, research on health effects in relation to WTS exposure has primarily focused on broad health indicators or nosological symptoms (see McCunney et al., 2014; Woodland et al., 2024), leaving unexplored the potential role that WTS acoustics could play in cognitive processes. Ecologically relevant, novel activities demand significant attentional resources. Given the nature of wind turbines' aerodynamic noise (e.g., Van Treuren, 2018), there is a direct relation between the rate at which wind turbines can produce sounds and how such sound frequencies can influence brain activity. To address the current gap in the WTS literature, laboratory paradigms offer a controlled methodology for investigating memory processes associated with such cognitive demands.

The present study sought to relate subjective annoyance to specific acoustic characteristics of WTS (*loudness*, *sharpness*, *roughness,* and *fluctuation strength*), and experimentally assessed the effect of these WTS acoustics on working-memory. Specifically, this research explored the following questions:

1. To what extent do loudness, roughness, sharpness, and fluctuation strength contribute to perceived annoyance by wind turbine sound?
2. Does exposure to wind turbine sound impair performance on a visual working-memory task?
3. Does the presence of certain acoustic characteristics in WTS, or the experience of annoyance, impair performance on a visual working-memory task?

2. Method

This research was approved by the Research Ethics Committee of the University of Galway (in line with the Helsinki declaration of ethical standards and the Irish Psychological Society). In addition, preliminary research plans of this study were pre-registered via the Open Science Framework (OSF) site associated with this research project: https://osf.io/gf5dp.

2.1. Participants

Forty-eight participants were recruited for this experiment through a combination of social media posts, university posters and announcements. The data of two participants were lost due to problems with the computer's recoding setting; consequently, 46 participants were retained (mean age = 26 [range 18–65], 23 females). This sample was deemed appropriate (see Brysbaert & Stevens, 2018) for the mix-effects repeated-measures multifactorial design employed (wherein all participants are randomly exposed to all stimuli).

Participation criteria specified individuals who were not diagnosed with hearing-related issues, psychological disorders (e.g., depression, stress, post-traumatic stress disorder, anxiety), or cardiovascular problems.

2.2. Experimental setting, apparatus and stimuli

Before completing the experimental task, all participants were asked to answer an online questionnaire including basic demographics, the Weinstein Noise Sensitivity Scale (WNSS; Weinstein, 1978) and a scale on attitudes towards wind turbines (see supplementary material S1 for questionnaires used).

For the experimental task, participants sat inside a purpose-specific sound chamber (RT60 < 1s; see Fig. 1). The visual stimuli were displayed on a 22-in digital monitor (1920 x 1080 resolution, refresh rate 60 Hz), located in front of the user (≈60 cm). Also, a single speaker (Genelec 8330) was used to reproduce the auditory stimuli, located further behind the computer screen (1.40 cm). The exact sound pressure levels produced by the speaker were calibrated at the listener's position using a calibrated class-1 sound level meter. The task was programmed using PsychoPy® (v2023.2.3; Peirce, 2007), and run from a standard laptop.

The visual stimuli consisted of slides (1280 x 720 px) containing two columns (10 cm off-centre) of four coloured squares (75 x 75 px; see supplementary material S2 for more details). Consequently, each of the squares of the visual stimuli as presented to the participants was of 2.2 visual angles (23 × 23 mm; $\theta = 2^{\circ}\ 11'.\ 76''$).

The auditory stimuli employed were extracted from an available dataset collected at Knocknalour, Gibbet Hill, Ballynancoran and Ballycadden wind farms in County Wexford, Ireland (RPS group, 2017). This dataset consists of a year-long continuous monitoring of the wind turbine sounds conducted at 14 locations (see supplementary material S3). Using a Bruel & Kjaer 2250 sound level meter, the wind turbines sound measurement was set for Fast Time Weighting, with a collection of spectra data for 1/3 Octave bands from 6 Hz to 20 kHz. Audio recording (24-bit rate) of 10 min each were conducted at various intervals during different periods. The sound level meter was positioned at a height of 1.2–1.5 m above ground, as specified in ETSU-R-97. The recordings used for this study were recorded at an average distance of 500 m from the source.

From this collection of 10-min recordings, eighteen 90-s audio tracks were presented during the memory task. In order to effectively sample the range of acoustic parameters within the whole set, clusters of recordings were derived based on the psychoacoustic dimensions of interest. Informed by previous research, and common metrics in the evaluation of aural environments (Maffei et al., 2013; Zwicker & Fastl, 2013), we chose *loudness*, *sharpness*, *roughness*, and *fluctuation strength* as our main metrics of interest in the characterisation of wind turbine noise—heretofore referred to collectively as acoustic properties of wind turbine sound (i.e., WTS acoustics). Amplitude modulation (based on both frequency modulation and depth modulation) was also explored.

Loudness is measured in sones (i.e., sound levels as perceived and experienced by the listener); where 1 sone of loudness corresponds to 1 kHz tone at 40 dB (ISO 532-1, 2017, p. 532). Sharpness (i.e, the sensation of high frequency content in the sound signal) is measured in acum which is equal to narrow-band noise (one critical band wide) at a centre frequency of 1 kHz with a level of 60 dB (DIM, 2009). Fluctuation strength is measured in vacils and describes the slow amplitude modulation of signal in the range on 0–30 Hz, with special emphasis on those near 4 Hz. Roughness, measured in aspers, is the fast amplitude modulation of the signal within the range of 15–300 Hz, the most sensitive

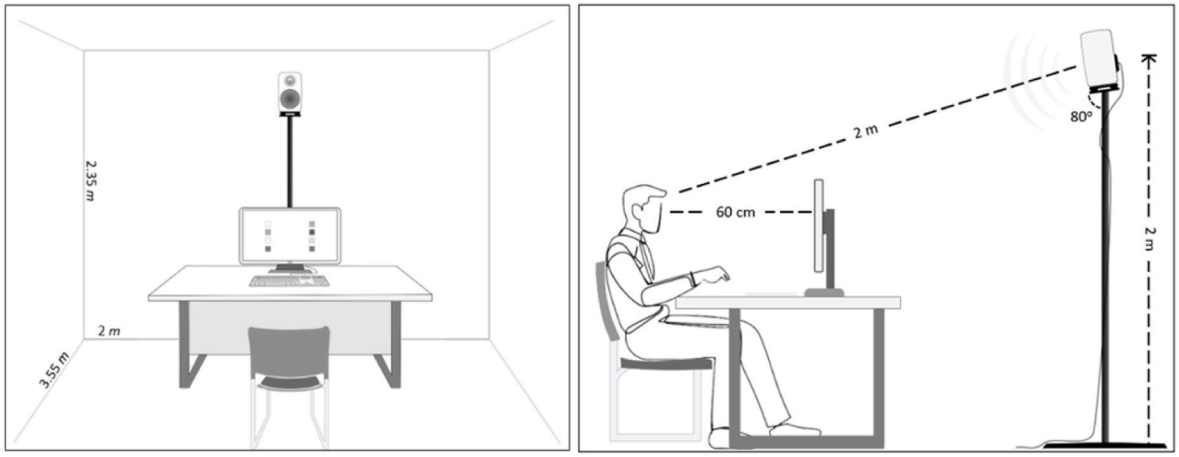

Fig. 1. Behavioural laboratory layout: *left*. Dimensions of the sound-chamber and position of the experimental hardware; *right*. Relative positioning of the experimental equipment with respect to participants.

fluctuation frequency for the roughness metric being around 70 Hz (Zwicker & Fastl, 2013).

The auditory stimuli were selected from three clusters in the full set of recordings: *C1*, high level of loudness and fluctuation strength; *C2*, moderate loudness, and *C3*, low loudness and fluctuation strength.[2]

2.3. Assessments and measures

Two scales were used: (a) the Weinstein Noise Sensitivity Scale (WNSS; Weinstein, 1978), and (b) a scale assessing attitudes towards wind turbines (Schäffer et al., 2019). The WNSS measures individual differences in sensitivity to noise and it is considered an antecedent of noise annoyance; it addresses affective reactions and attitudes to both general noise and daily environmental sounds. This 6-point Likert scale (strongly disagree = 0; strongly agree = 5) has strong internal consistency (α = .86) as well as satisfactory psychometric properties. The attitudes towards wind turbines scale (see also Schäffer et al., 2016), is a 5-point Likert scale (entirely disagree = 1; entirely agree = 5) consisting of ten statements enquiring about emotional, cognitive and behavioural responses to wind turbines. Memory performance and subjective annoyance by wind turbine sound were measured using a computer-based task (see next section). Ratings of annoyance were obtained via direct input from participants during the experimental task. Each audio sample of wind turbine sound was rated in terms of experienced annoyance along a 5-point verbal-numerical rating scale (1 = Not all all, 2 = Slightly, 3 = Moderately, 4 = Strongly, 5 = Extremely).

2.4. Computer task and procedure

The Visuospatial Working-Memory Task (VSWMT) is based on tasks from both Vogel et al. (2001) and Sauseng et al. (2009; experiment 2). This task required participants to observe and compared two sets of visual stimuli and determine whether they were identical or not (see Fig. 2).

In the VSWMT participants attended to a set of coloured squares presented in one visual hemifield and simultaneously ignored another set of coloured squares in the opposite visual hemifield (i.e., side of the screen). Task difficulty depended on (a) the number of squares to be retained in memory (2 or 4), and (b), the number of squares to be ignored (2 or 4). Four visual stimuli arrangements were used: (a) two items in the attended hemifield and two in the unattended hemifield (two relevant, two distractors), (b) two items in the attended visual field and four in the unattended visual field (two relevant, four distractors), (c) four relevant items and two irrelevant items, or (d) four relevant and four irrelevant items.

While the visual stimuli were being presented, different audio samples of WTS were played to the participants. Both the visual and auditory stimuli were pseudo-randomised during the task (i.e., randomly selected but without replacement).

Each trial block started and finished with 5 s during which only a WTS track was played—to draw initial attention to the auditory stimuli. On each trial, a fixation dot was briefly presented in the centre of the screen (1600 ms), immediately after which an arrow pointing to either the left or right appeared for 200 ms (50 % of trials towards each direction). Such an arrow cued participants into which side of the screen they had to pay attention to (i.e., the column of squares, left or right, of the incoming visual arrangement). Next, a *sample* array of visual stimuli—to remember—appeared for 200 ms, followed by a black screen "retention" period lasting 1 s, whereupon a second *test* array of visual stimuli appeared for 2 s. On 50 % of the trials, such a test array was characterised by a change in colour of one of the squares—with respect to the sample stimuli. During the 2-s presentation of the test array, participants had to indicate whether the test stimuli was different from the sample stimuli by pressing the keyboard's spacebar. During the practice version only, participants responses were followed by a 1-s written feedback depending on their responses.

At the end of each trial-block, the following question appear at the top of the screen: "Thinking about the sound you heard during the last block of trials, how much did it bother, disturb or annoy you?", and below the respective 5-point verbal-numerical rating scale (1 = Not all all; 5 = Extremely) as a refence for participants to press the corresponding keyboard numeral (see supplementary material S4 for the task instructions).

2.5. Data processing

Most data analyses were conducted via generalized and mixed-effects regression models, using *R* 4.3.3 (R Core Team, 2024), and the ordinal package (v2023.12–4; Christensen, 2023).

Such statistical models represent several advantages over traditionally used methods such as relaxing the assumption of independence among observations (thereby preventing false positives due to population or relatedness structure) and increased power (see Baayen et al., 2008; Brauer & Curtin, 2018; Yang et al., 2014 for a more thorough

[2] The procedure involved in the selection of the stimuli is beyond the scope of this paper, hence, it is the focus of another paper (see supplementary material S3 for essential information). However, just as with all materials from the current study, such an information will be accessible in due time via the OSF site: https://osf.io/qp8rz/.

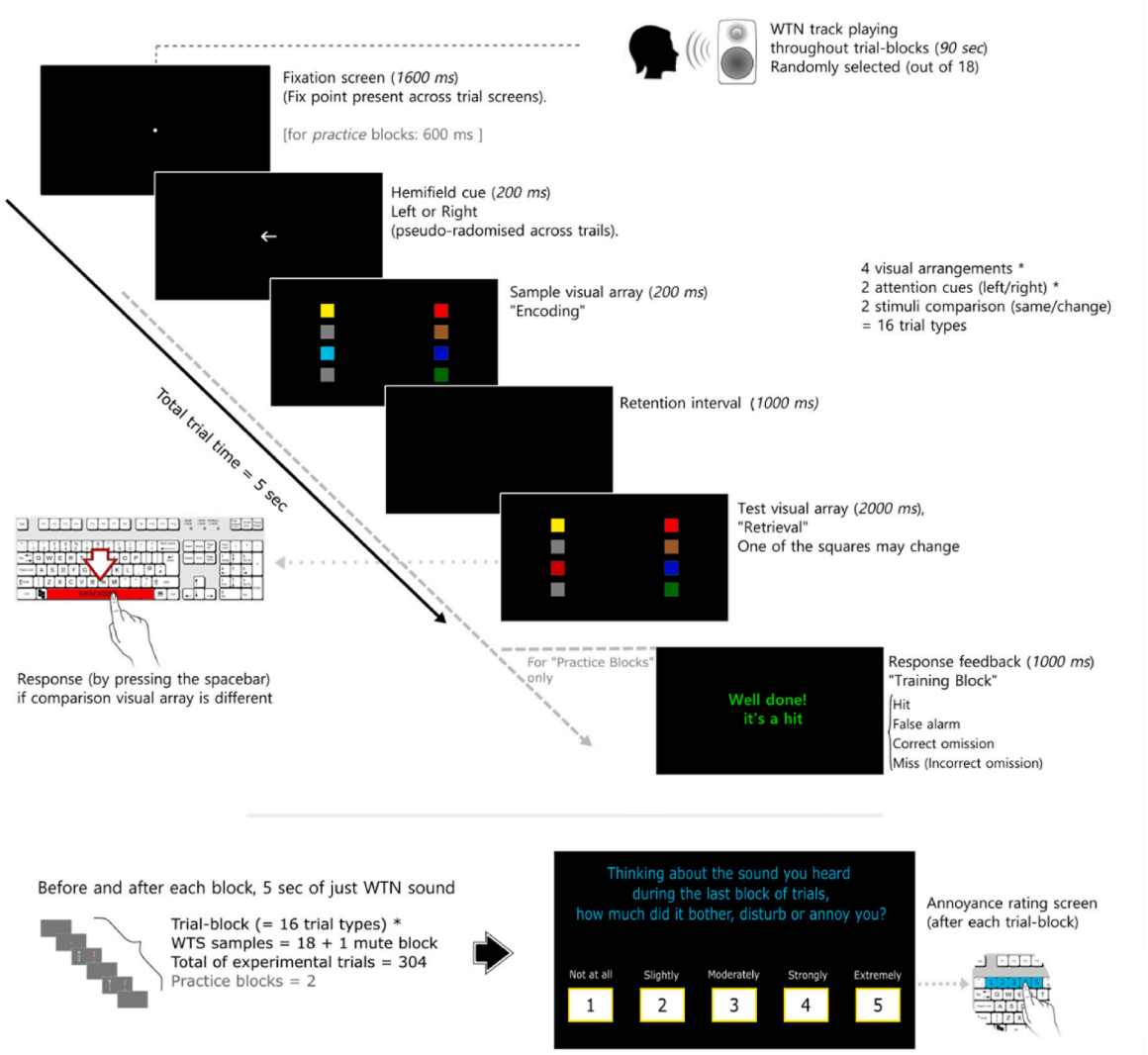

Fig. 2. Graphic representation of the trial structure of the Visuospatial Working-Memory Task (VSWMT), and various other features of the experimental design. The bottom illustrates the annoyance rating scale to the WTS stimuli (for each trial-block).

discussion). The Akaike Information Criteria (AIC) was used to judge the quality of the models; lower comparative AIC values reflecting better model fitness. Participant was specified as a random effect in all models to control for non-independence of repeated measures data. The predictor variables have also been transformed into z-scores to facilitate relative comparisons among the coefficients. Performance on the working-memory task was measured based on accuracy responses across trials (i.e., correct vs. incorrect responses).

3. Results

Participants completed a total of 304 trials each (13984 trials from all participants). Eighty-eight percent of the ratings about the wind turbine sound samples were rated as "not at all" annoying. The participants' sample was characterised by moderate-to-high levels of noise sensitivity ($M = 76.5/105$; $SD = 14.7$) and generally positive attitudes towards wind farms ($M = 40.2/50$; $SD = 6.2$); with no significant correlation between the two (Person's $r = -.25$, $CI_{95\ \%} = -.50, .04$, $p = .09$). See supplementary material S5 for more details on descriptive statistics.

Complementarily, Pearsons' correlation coefficients between noise sensitivity and annoyance, as well as between attitudes and annoyance were weak ($r = .23$ [$CI_{95\ \%} = .17, .30$], $p < .001$) and very weak ($r = .-18$ [$CI_{95\ \%} = -.24, -.11$], $p < .001$) respectively.[3]

3.1. To what extent do loudness, roughness, sharpness, and fluctuation strength contribute to perceived annoyance by wind turbine sound?

Overall, the auditory stimuli elicited minimal levels of perceived annoyance. The distribution of annoyance ratings was significantly skewed towards the lower end of the scale, with 58 % of stimuli rated as "not annoying", 25 % as "slightly annoying", and the remaining 17 % belonging to the three higher levels of annoyance. Thus—to facilitate a representative interpretation—, annoyance was dichotomized into two categories: "not annoying" and "slightly annoying". Fig. 3 depicts this

[3] However, these correlations should be read with caution as technical problems with the online server resulted in data loss for the attitudes' scale. Consequently, the attitude scale was not included in the mixed-effects models.

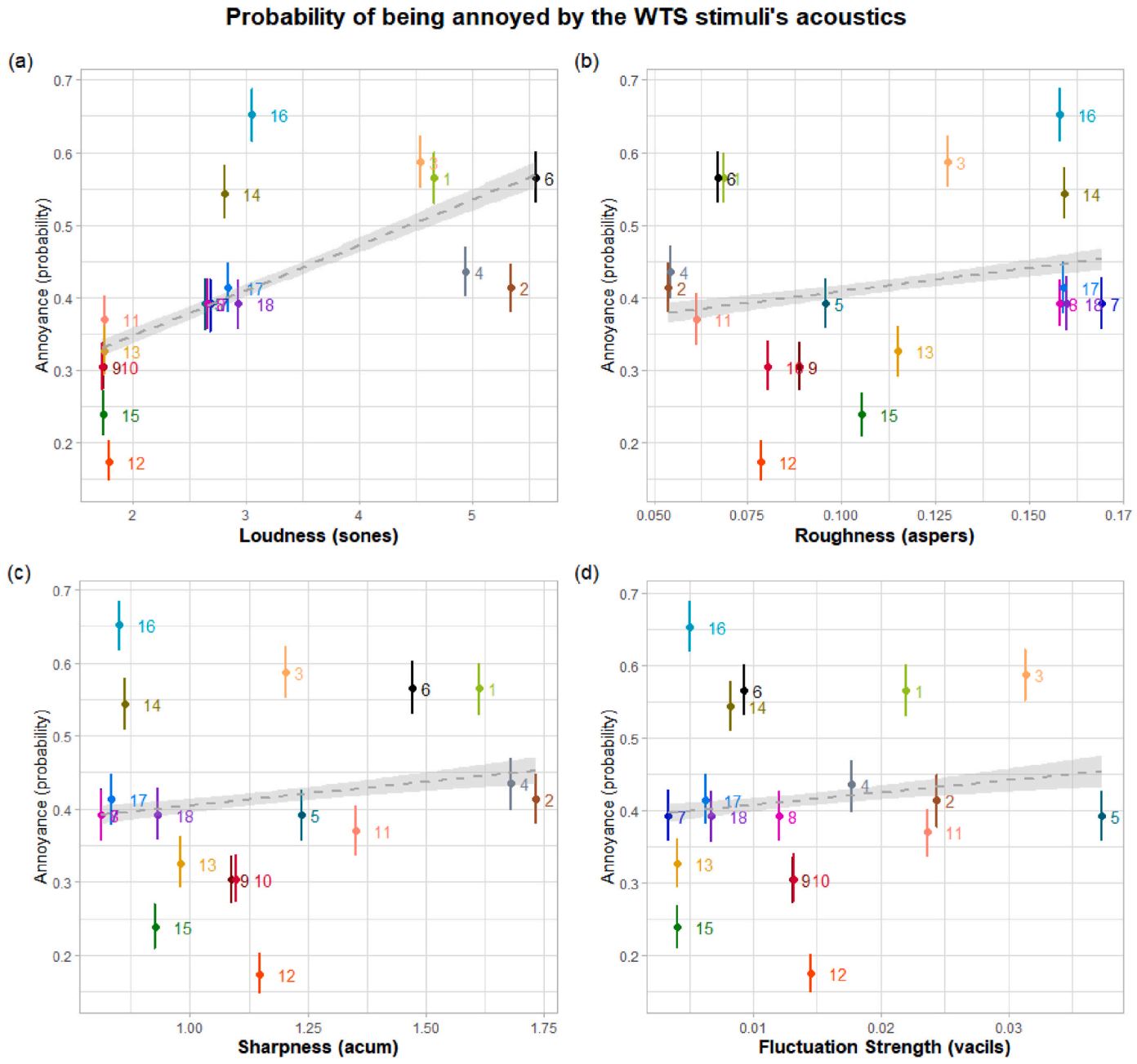

Fig. 3. Multiplot showing the values of the 18 auditory stimuli for each of the WTS acoustic parameters (abscissa): (a) loudness, (b) roughness, (c) sharpness, and (d) fluctuation strength; and the effect of these parameters on the 20–70 % probability (ordinate) of transitioning from "not at all annoyed" to "slightly annoyed". The vertical lines of each track represent their standard error bars (95 % confidence intervals). A linear function has been overlaid (dashed dark grey line) with its respective—residual—standard error (grey shade). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

relationship between loudness, roughness, sharpness and fluctuation strength and the probability of annoyance by the sound samples.

Worth noting is the differential distribution of annoyance ratings among the various auditory stimuli. This suggests inherent variability in the perceived aversiveness of the sounds' sample. For example, Track-12, -16, and −18 exhibit varying degrees of perceived annoyance, with annoyance probabilities of 18 %, 70 %, and 40 %, respectively. While track-12 is characterised by consistently low acoustic parameter values, tracks 16 and 18 demonstrate significant variability across all WTS acoustics, yet share certain similarities.

Similarly, track-1, with elevated loudness (4.66) and sharpness (1.61), is characterised by a probability of annoyance of .55. These results underscore the intricate relationship between WTS acoustics and perceived annoyance. Although our dataset revealed a high correlation between sound pressure (LAeq) and loudness (Pearson's $r = .90$ ($CI_{95\ \%} = .76; .96$), $p < .001$), including psychometrics that extend beyond traditional metrics allow a more nuanced understanding of WTS-induced annoyance.

To statistically estimate the effect of loudness (loud), sharpness (sharp), roughness (rough), and fluctuation strength (fStr) on annoyance, mixed-effects ordinal logistic regression models were employed; since annoyance was measured using a 5-point scale. Seven models were compared to assess whether the addition of explanatory variables improved the models. The simplest null-model only included intercept that varied randomly by participant, to account for inter-participant variability in sensitivity. The second model included noise sensitivity

(WNSS) as a linear predictor. The next model included these participant variables and added the acoustic variables of interest (loud, rough, sharp, fStr), as fixed effects. In the next model, amplitude modulation parameters (modulation frequency [MF] and modulation depth [MD]) were included. The next two iterations of the model included task characteristics, that affected cognitive load, and potential responses biases respectively (see supplementary material Table S6.1 for model fitness comparisons). The final model (see Table 1) included an interaction between noise sensitivity and the WTS acoustics.

As expected, the model with the random effects was better than the model with only fixed terms ($AIC = 27463$ to 20049, $df = 1$, $\chi^2 = 7078.9$, $p < .001$), indicating substantial variability in baseline annoyance levels across individuals. The statistical analyses indicated that WNSS affects annoyance levels ($b = .80$, $SE = .36$, $p = .02$), revealing that the more noise-sensitive people are, the more annoying they perceived the WTS audio samples to be. Moreover, the first model comparison favoured the model with the acoustic variables ($AIC = 20052$ to 18777, $df = 4$, $\chi^2 = 1282.9$, $p < .001$); further confirmed via likelihood ratio tests based on systematic removal of the predictors.

As shown in Table 1, the final model incorporating all acoustic predictors and their interactions confirms that core acoustic characteristics of WTS (loud, rough, sharp, fStr), significantly predict perceived annoyance. Higher values of these acoustic features are associated with increased odds of higher annoyance ratings. Roughness was the most influential acoustic characteristic of WTS and fluctuation strength was the least influential. However, the statistical interactions with WNSS suggest that the effect of the acoustic parameters over annoyance ratings was moderated by the participants' noise sensitivity levels ($AICs = 18701$ to 18693, $\chi^2 = 15.471$, $df = 4$, $p = .003$). That is, greater loudness and fluctuation strength predicted greater annoyance in individuals with high noise sensitivity, but a mitigating effect was found for roughness and sharpness.

Furthermore, we examined modulation frequency (MF) and modulation depth (MD) parameters. For these predictors, we chose range values between 200 and 800 Hz and dB respectively (averaged across WTS samples). These amplitude modulation parameters were also statistically significant, indicating that as modulation depth increases so do annoyance ratings; whereas an inversed relation was found for modulation frequency.

Lastly, we included characteristics related to the task (including task integrity checks) to control for factors such as task difficulty and response biases could have on the main effects of interest (e.g., indicating that there was a difference between the sample and comparison set of visual stimuli when there were in fact identical). These variables consisted of the number of relevant stimuli and distractors that were displayed, number of trials, and the number of times the participants pressed the spacebar or omitted their responses (Go/No Go). Only the number of trials had an influential effect, interpretable as people being likely to rate wind turbine sounds as more annoying the more they have been listening to them. Complementarily, in order to address gender biases in research, we included this factor ($b_{male} = -9.43$, $SD = 7.83$, $p = .22$) to the full model resulting in no improvement ($AICs = 18701$, $\chi^2 = 1.42$, $df = 1$, $p = .23$), suggesting no differences in performance between males and females.

3.2. Does exposure to wind turbine sound impair performance on a visual working-memory task?

Memory performance was characterised by a high proportion of accurate responses across the sample of participants, with 91 % of correct responses (hits = 6288; correct omissions = 6447) over the total number of trials.

To assess the effects of wind turbine noise on memory performance, we fitted binomial mixed-effects logistic regression models predicting accuracy on each trial (correct vs incorrect). We compared six models wherein the variables of interest were included with each iteration. The hierarchical structure followed the steps employed in the previous analysis, with the difference that this time the task-related characteristics known to affect memory performance were introduced earlier (see supplementary material Table S6.2 for model fitness comparisons). Consequently, after the null-model (with participants as random intercept), the second model contained the features related to cognitive load (i.e., number of distractors × relevant stimuli) as fixed terms. Controls for additional task features were introduced in third model. The four model introduced indices of annoyance (the noise sensitivity scale and subjective ratings). The last two models factored in the WTS acoustics and amplitude modulation variables respectively.Table 2.

The final model (see Table 2) revealed that visual working-memory is not affected by wind turbine sound features, despite the experimental task functioning as expected.

Model comparisons confirmed that the number of relevant and irrelevant stimuli significantly influenced memory performance (AIC = 7666.4 to 7495.7, $df = 3$, $\chi^2 = 176.73$, $p < .001$). Subsequent models including additional task-related features yielded expected results, further validating the task's integrity. Increasing the number of distractors or relevant stimuli independently impaired performance. However, the combined effect of increasing both distractors and relevant stimuli was less detrimental than their independent effects;

Table 1
Mixed-effects ordinal logistic regression models predicting annoyance based on WTS acoustics and memory-task features.

(*random intercept*)		σ^2	*SD*
subj		6.994	2.645
(*fixed terms*)	b_z	***b***	***SE***
WNSS	.885*	.178	.393
Loudness	.463***	.355	.056
Roughness	.773***	.187	.081
Sharpness	.635***	2.11	.118
Fluctuation strength	.109***	.112	.029
Mod. Depth (200–800 dB)	.184***	.171	.025
Mod. Frequency (200–800 Hz)	−.132***	−1.59	.023
4 Distractors	1.43*e-04*	1.43*e-04*	.057
4 Relevant	4.80*e-05*	5.07*e-05*	.057
n Trials	.101***	1.15*e-03*	.020
Go (/NoGo)	−1.12*e-05*	−1.47*e-05*	.040
WNSS * Loudness	.177***	9.38*e-03*	.049
‘’ * Roughness	−.271***	−.453	.072
‘’ * Sharpness	−.390***	−.008	.101
‘’ ***F.Strength**	.054*	.389	.024
Distractor*Relevant stim 4x4	6.66*e-05*	5.43*e-05*	.081

Note. Significance *p* levels at .05*, .01**, .001*** b_z: z-transformed coefficients.

Table 2
Mixed-effects binomial logistic regression models predicting memory performance based on memory-task features and WTS acoustics.

(*random intercept*)		σ^2	*SD*
subj		.358	.598
(*fixed terms*)	b_z	***b***	***SE***
(*intercept*)		4.327***	.919
4 Distractors		−.145*	.066
4 Relevant		−.799***	.066
Distractor*Relevant stim 4x4		.711***	.132
Go (NoGo)		−.287***	.062
hemicue (L)		−.117	.062
n Trials	.125	.001***	0.35*e-03*
WNSS	−.145	−.010	.006
Annoyance ratings	−.063	−.072	.051
Loudness	.097	.074	.068
Roughness	−.186	−4.527	3.105
Sharpness	−.238	−.795	.618
Fluctuation strength	.051	5.292	4.860
Mod. Depth (200–800 dBs)	−.012	−.011	.034
Mod. Frequency (200–800 Hz)	.003	.047	.431

Note. Significance *p* levels at .05*, .01**, .001*** b_z: z-transformed coefficients.

suggesting a non-additive relationship. Additionally, the stronger predictive power of relevant stimuli over distractors supports that participants were engaged and focused on the task.

As before, known inter-participant differences were controlled for. The data confirms that active response bias somewhat impacted performance negatively ($b = -.28$, $SE = .062$, $z = -4.58$, $p < .001$). Likewise, participants seem to have become better at the task—remembering more accurately—as a function of more trials being completed ($b = .12$, $SE = .00$, $z = 3.98$, $p < .001$). The model also indicates that there was no visual lateralization (left/right hemicue) effect influencing task performance ($b_{left} = -.117$ [$CI_{95\ \%} = -.237; .006$], $SE = .062$, $z = -1.890$, $p = .058$). Even though the effect of hemicue reached significance when specified as a random slope ($b_{left} = -.175$ [$CI_{95\ \%} = -.32; -.03$], $SE = .074$, $z = -2.364$, $p < .05$), judging by the difference in the variance between the random effects (i.e., subjects [intercept] = .37 and hemicue = .02; $r = -.77$), it is reasonable to conclude that there was consistent lateralization across subjects; with such an effect applying to only a few participants.

Nonetheless, variables related to subjective annoyance (WNSS and annoyance ratings to WTS) did not contribute to improving the model (AIC = 7463.4 to 7462.1, $df = 2$, $\chi^2 = 5.3127$, $p = .07$), nor did the inclusion of the variables related to WTS acoustics (AIC = 7474.3, $df = 11$, $\chi^2 = 11.063$, $p = .43$). Such results confirm that the WTS acoustics did not interfere with participants' performance in the working-memory task.

Gender did not affect memory performance ($b_{male} = -.069$, $SD = .189$, $p = .71$), nor did the addition of this factor improve the full model ($AICs = 7472.3$, $\chi^2 = .1318$, $df = 1$, $p = .71$).

3.3. Does the presence of certain acoustic characteristics in WTS, or the experience of annoyance, impair performance on a visual working-memory task?

A final line of inquiry of the preset study aimed to explore whether the influence of visual features on task performance was moderated by individual differences in noise sensitivity and perceived annoyance. However, since we did not observe any effects of wind turbine sound on visual working-memory, such effects were highly unlikely.

Nevertheless, for the sake of completeness, this question was statistically addressed by adding interactions to the previous full model predicting memory performance. This was done in two separate models: the first one included the effect of cognitive load variables (number of distract/relevant stimuli) in interaction with noise sensitivity (WNSS); in the second model cognitive load variables were specified in interaction with subjective ratings of annoyance.

Unsurprisingly, neither noise sensitivity ($b_{dis4} = -.006$, $SD = .062$, $p = .91$; $b_{rel4} = .034$, $SD = .062$, $p = .57$; $b_{dis4*rel4} = .076$, $SD = .125$, $p = .54$), nor annoyance ($b_{dis4} = .065$, $SD = .066$, $p = .32$; $b_{rel4} = -.027$, $SD = .066$, $p = .67$; $b_{dis4*rel4} = .094$, $SD = .133$, $p = .47$) stood as influential variables in these models; nor did they improve the former full model predicting memory performance ([$AICs = 7470.4$ to 7472.3, $\chi^2 = .7633$, $df = 3$, $p = .85$] and [$AICs = 7475.7$, $\chi^2 = .7633$, $df = 3$, $p = .85$] respectively).

4. Discussion

This study investigated the impact of wind turbine sound (WTS) on annoyance and memory. We found that loudness and fluctuation strength of WTS significantly contribute to perceived annoyance, especially for noise-sensitive individuals. Unexpectedly, WTS did not interfere with visual working memory.

In the literature, subjective annoyance is not reliably correlated with objective measures of sound (see McCunney et al., 2014 for a review). This may be partly due to the fact that traditional measures of sound pressure (e.g., dBA) are arguably inadequate for the subjective perception of sound (Jones, 1968; Olson, 1972; Rasch & Plomp, 1999). Thus, in the present study we measured loudness expressed in sones (instead of traditionally used units such as dBs), and found that other metrics, such as fluctuation strength, critically interact with psychological predispositions around noise sensitivity. Our results underscore the need for a comprehensive analysis of a broader range of acoustic parameters and their interactions to fully comprehend the complex interplay between WTS-acoustics and induced annoyance.

We argue that visualizations, such as the one employed in Fig. 3, can be instrumental in quantifying and understanding complex relationships between WTS-acoustics and psychological variables. By mapping WTS auditory based on their WTS characteristics and probability of being perceived as annoying, we can scrutinise some of the factors contributing to WTS-induced annoyance. For instance, in inspecting Fig. 3 it can be noted that track-16 is one of the most annoying of our tracks (annoy probability is approximately .70), but it is not consistently high across all acoustic measures. Relative to the other soundtrack stimuli, track-16 is low in sharpness (.849) and fluctuation strength (.005), moderate in loudness (3.05), and high in roughness (.158). Such patterns in acoustic parameters highlight the complexity of WTS in the natural environment and the additional insight that can be gained by incorporating this complexity into annoyance predictions. For instance, based on loudness (as the parameter closely associated with sound pressure level) alone, track-16 would not be identified as the stimulus with the highest probability to annoy; rather, track-6 would stand out.

To illustrate this point further, comparing track-6 against the confidence intervals of track-16, it can be seen that track-6 is above .55 probability of annoyance yet more comparable to track-14 which is below .55. Interestingly, track-6 is very low in roughness (.067), yet still quite likely annoying, whereas track-16 is quite high in roughness (.158). Likewise, compared to track-3 which has greater acoustic values than track-16 in loudness (4.54), sharpness (1.20) and fluctuation strength (.031), the former is still less likely perceived as annoying. Indeed, compared against track-15, it could be said that the roughness and loudness levels are the ones rendering track-16 high in probability of annoyance since the values of sharpness and fluctuation strength between these two tracks are low. Similarly, track-1, with elevated loudness (4.66) and sharpness (1.61), has a .55 probability of causing annoyance. This approach extends beyond traditional metrics like LAeq, offering a more nuanced understanding of the features driving people's tendency to report WTS sources as annoying.

Our results, thus, emphasise the inclusion of multiple acoustic metrics when establishing an association between WTS and annoyance. We chose four acoustic features based on previous research (e.g., Maffei et al., 2013; Waye & Öhrström, 2002), but there are many other acoustic features that may turn up to be of relevance if scrutinised in a similar interactive fashion. On this point, for example, Large and Stigwood (2014) found that while wind turbines complied with UK noise limits, the noise at one site was "highly tonal" when operating in higher gear mode. This suggests that tonal noise can still be a source of annoyance for nearby residents. However, amplitude modulation (AM) noise may exacerbate the annoyance of tonal noise by drawing attention back to it, questioning whether tonal noise *alone* would be less annoying (Large & Stigwood, 2014). In fact, from our visualization (Fig. 3) WTS tracks 1, 3, 6, 14, and 16 are more likely to elicit annoyance. Interestingly, while not the focus of this study, cluster 2 tracks (7–12) were less probable to be perceived as annoying and exhibited higher tonality and lower amplitude modulation values compared to the other clusters.

Our study provides statistical evidence for linking WTS acoustics to annoyance. However, it is unclear—from the limited available research to date—what is the contribution of the targeted psychoacoustics (loud, rough, sharp, fStr) in WTS-annoyance. This is worthy of mention, given the fact that our results stand in contrast to the findings of Waye and Öhrström (2002). In their study, different wind turbine sounds at the same loudness, evoked distinct annoyance levels. While their results also highlight the relevance of these psychoacoustics in shaping perception and annoyance, none of them explained the mentioned differences in

their data.

Although at face value both studies are comparable (targeting the same WTS acoustics), there are substantial methodological differences to consider. Namely, our study selected audio samples based on salient psychoacoustic characteristics as originally present, while Waye and Öhrström calculated and seem to have played the psychoacoustic parameters separately. The method for calculating loudness in Waye and Öhrström's (as per ISO 532-1975E) is based on physical measurements (i.e., spectrum analyses in octave and one-third octave bands). Ours instead, followed Zwicker's algorithm which estimates loudness as perceived by otologically normal persons under specific listening conditions (as per ISO 532–1:2017); expressed in sones. Our statistical analysis incorporated mixed-effects models to account for individual and experimental factors, while Waye and Öhrström used Pearson's correlations to analyse the relationships between annoyance and the psychoacoustic descriptors. Furthermore, our experimental setup differed in terms of speaker number, listeners' mobility, and other factors.

Unlike previous studies, our approach revealed that the relationship between the WTS acoustics and annoyance is moderated by individual differences, with higher loudness and fluctuation strength predicting higher annoyance as a function of individuals' noise sensitivity levels. The Noise Sensitivity Scale (Weinstein, 1978) stood as a useful proxy measure for WTS annoyance, aligning with previous research (Janssen et al., 2011; Knopper & Ollson, 2011; Michaud et al., 2016; Van Kamp & Van Den Berg, 2021). In hindsight, this is to be expected considering how a noise level difference of about 10 dB characteristically correlates with higher annoyance in noise-sensitive individuals compared to noise tolerant individuals (McCunney et al., 2014, see also Haac et al., 2019). Moreover, noise-sensitive people attend more to sounds, display lower noise discrimination thresholds and evaluate noises out of their control as more threatening, compared to noise-tolerant people (Stansfeld, 1992). Based on the accumulated evidence and our data, we advise social researchers working in the field of wind turbine acoustics to continue using the WNSS in conjunction to other assessments of subjective annoyance in their studies.

In accordance with previous research (e.g., Ioannidou et al., 2016; Lee et al., 2011; Maffei et al., 2013), amplitude modulation (AM) was found to also be positively associated with perceived annoyance. However, the relevance of amplitude modulation (and its role in annoyance) is highly contended since AM may be related to the distance from the sound source. To complicate things, there seems to be a lack of standardization in measuring and quantifying AM (Alamir et al., 2018; Larsson & Öhlund, 2014), and no universally accepted representative value for the strength of AM (Lee et al., 2011). Having said that, some evidence suggests AM to be more prominent closer to the wind turbine, as in the WTS recordings employed in our study, but less noticeable at greater distances where most residences would be located (Lee et al., 2011). The relevance of amplitude modulation in the context of how such a parameter may affect people who live nearby awaits further investigation (cf. Blumendeller et al., 2023).

We found no evidence that visual working-memory is affect by typical wind turbine sounds, nor did perceived annoyance reduce memory performance. Albeit unexpected, this finding resonates with a study conducted by Yu et al. (2017) which explored auditory working-memory through a virtual environment in which participants were exposed to wind farm recordings with the same acoustic parameters we used. In their experiment, one of their measurements consisted of a backward digit span (working-memory) task, wherein participants had to recall in reverse order a series of increasing digit sequences. The authors found no significant differences in memory recall scores across the experimental conditions.

Similarly, using immersive virtual scenarios, Ruotolo et al. (2012) investigated the effects of WTS on short-term verbal memory and semantic memory. For the former, fifteen written words where sequentially presented and then participants had to verbalise as many of those words as they could remember. Verbal fluency (viz. semantic memory) was tested by having participants generating as many words as possible based on a target letter shown to them. In line with our data, Ruotolo et al.'s results found short-term verbal memory not to be influenced by their experimental factors, such as distance to the noise source. Additionally, noise sensitivity was found to correlate positively with noise annoyance. Verbal fluency performance, on the other hand, improved as a function of the distance from the noise source. Comparable to our study, Ruotolo et al. included noise sensitivity as a covariate to account for individual differences. Their data revealed that noise sensitivity was indeed negatively correlated with semantic memory for the scenario corresponding to 600 m of distance from the noise source; but no interaction of noise sensitivity is reported for verbal memory.

For the present study we theorised that exposure to WTS could affect working-memory based on neural entrainment research (Henao et al., 2020; Herrmann et al., 2016; Ingendoh et al., 2023; Lakatos et al., 2008), in particular, given the fact that memory has been found to be sensitive to the neural entrainment phenomenon (Köster et al., 2019; Roberts et al., 2018). A theoretical reason for these results on memory performance may be due to the fact that, since working-memory is fundamental for many other perceptual and cognitive processes (Baddeley, 1992, 1996), survival would be minimised if such a process was easily compromised (Nairne et al., 2007; cf. Kroneisen et al., 2014). In fact, we experienced the "robustness" of working-memory in everyday situations where we handle interruptions to the flow of information being processed—and encoded into memory—without notable costs to performance (Oulasvirta & Saariluoma, 2006). Ruotolo et al.'s (2012) results could also be explained along this train of through since, while they did not find their performance on the short-term memory task to be affected, there was some effect on the—less cognitively robust—task of semantic verbal fluency.

The typical levels of wind farm sound that people (and experimental research participants) are exposed to may not be strong enough to alter psychological processes. Audiogenic stress has traditionally been studied with noise exposures to 80–100 dB for ≥60 min; Borg, 1981). Most people seem to find WTS acceptable at sound pressure levels below 40 dBA (Bakker et al., 2012; McCunney et al., 2014), which approximates the average sound pressure levels of the audio samples used in our study, and reproduced matching the distance from the noise source at approximately 500 m. Such a distance from wind turbine sounds and their typical noise levels are within general sensible ranges accepted in most countries embracing wind turbine energy technology (WHO, 2018).

The "immediate" annoyance induced under laboratory conditions does not directly reflect "chronic" annoyance reported in field studies. Even if a particular level of stimulation is not intense, prolonged exposure to such levels may render the stimulation aversive leading to annoyance and associated negative effects after prolonged exposure, or delayed reactions (Borg, 1981). Community studies of chronic exposure to WTS (i.e., Müller et al., 2023; Pohl et al., 2018) indicate that cognitive processes such as concentration can be affected when households report annoyance by wind turbines. Pohl et al. (2018) collected both qualitative and quantitative data for a 2-year monitoring period, and found that while the experience of annoyance may remain relatively stable, performance effects (e.g., due to lack of concentration) and emotional reactions (e.g., irritability) show a decrease over time (see also Müller et al., 2023). It has not been conclusively established whether these cognitive effects are due to WTS or constitute second-order effects of annoyance, but the balance of evidence suggests the latter. In addition, field studies typically record self-reported concentration and cognitive effects that are difficult to assess objectively. Further research with community samples incorporating more rigorous estimates of concentration and memory effects would enable greater insight into the effects of WTS on cognition.

In the current study, annoyance increased across trials. Such an effect comes as a surprise considering the brief duration of the experimental

task (with an average of 35 min), and that prolonged exposure to noise would be expected to give rise to habituation, reducing annoyance across exposure. That said, data from larger community-based research projects seems to suggest that sensitization—the opposite of habituation—may occur for characteristic wind farm sound (see Michaud et al., 2016; Müller et al., 2023). The interplay between acoustic characteristics, situational factors, individual sensitivities, and psychological factors makes it difficult to predict long-term effects to wind turbine noise. However, there could be features inherent to the nature of the WTS that undermine habituation. Specifically, habituation is inhibited when the stimulation is highly unpredictable, so features like amplitude modulation, characterised by fluctuating sound levels, may explain the lack of habituation (Large & Stigwood, 2014). In fact, the noise emitted by wind turbines can vary significantly depending on wind conditions, turbine operation, and gear changes (Saidur et al., 2011).

While research on long-term exposure to wind turbine noise is limited, Feder et al. (2015) provided an insight into potential adaptation or sensitization effects. They found that residents with less than a year of exposure exhibited slightly higher psychological distress scores compared to those with no exposure or longer exposure durations. In the same vein, Jalali's et al. (2016) collected community data prior and (one year) after wind turbine operation, on standardized questionnaires measuring psychical, mental and life satisfaction indicators. While the results showed no significant pre-post mean differences on the physical component score, there were indeed statistical differences in both the mental and life quality components, with 41.9 % feeling worried after the installation of turbines (albeit negative attitude anticipation was high in their sample). While the present study offers insights into short-term annoyance to WTS exposure, the connection between this and long-term annoyance requires further investigation.

There are psychological reasons to hypothesise that a relatively low probability of annoyance in the moment—as induced in many experimental studies or intermittently experienced in nearby residents of wind farms—might contribute to a relatively high probability of annoyance in the long run. Such a hypothetical transition from "temporary annoyance" to annoyance as a "state" could depend on how repeated instances of a particular experience may amount to a more permanent or latent psychological disposition, and once "permanent annoyance" has set in, it may be difficult to ignore such a state. For example, it is well established in evolutionary and social psychology that our social-emotional processes are negatively biased (Aloise, 1993; Ito et al., 1998; Kahneman & Tversky, 1984; Kanouse & Hanson, 1972; Peeters & Czapinski, 1990). That is, negative events carry more weight than positive events (Kahneman & Tversky, 1984); so moments of annoyance, for example, could be evaluated more heavily than annoyance-free moments. Understanding how emotionally-laden evaluations of temporary annoyance can lead to chronic annoyance requires further work.

Acknowledging that wind farms may constitute a trigger for emotional reactions such as irritability, and half of the wind farm residents may experience WTS-related annoyance at least once a week (see Pohl et al., 2018), the health effects of long-term annoyance and its association with stress-related problems (e.g., Bakker et al., 2012; Fritschi et al., 2011; Hübner et al., 2019; Jalali's et al., 2016; Michaud et al., 2016; Pohl et al., 2018; Stallen, 1999) warrant just as much attention (Fritschi et al., 2011; McCunney et al., 2014; Niemann et al., 2006; Palmer, 2017).

Lastly, a notable discrepancy emerged: 58 % of wind turbine sound samples were rated "not at all" annoying, while 87 % of respondents expressed annoyance in the attitude questionnaires. This disparity likely reflects biases in evaluating wind farms as complex environmental stimuli (Karasmanaki, 2022; Knopper & Ollson, 2011; Schäffer et al., 2019; Schmidt & Klokker, 2014; Van Kamp & Van Den Berg, 2018, 2021). Thus, questionnaire responses may better indicate attitudes toward wind turbines than specific noise annoyance (Karasmanaki, 2022; but see Blanes-Vidal & Schwartz, 2016). Our study's approach, evaluating individual responses to specific sound samples, allowed us to link annoyance to acoustic features—as opposed to relying on generic questions about WTS. Further research could inform conceptual distinctions between noise sensitivity and annoyance susceptibility (Job, 1999).

Our ability as researchers to identify nuances in how people respond to environmental stimuli can only come from specialized and comprehensive measures; single-item scales for whole sets of stimuli simply fall short in capturing complexity (cf. Hübner et al., 2019) and—as demonstrated in this paper—nuanced data interactions can reveal complex relationships underlying how we perceive sound stimuli. This is of particular importance when we broaden the scope and recognise the percentage of annoyance that has been attributed to factors other than sound pressure levels (e.g., Michaud et al., 2016; Müller et al., 2023; Gaβner et al., 2022).

Additional limitations of the present work and recommendations for future research ought to be mentioned. Our sample of participants was characterised by a lack of strong annoyance reactions towards WTS, potentially underestimating the reported percentage of WTS annoyance. Since opposition to wind farm developments is likely to come from noise sensitive individuals, studies seeking to identify and mitigate the acoustic features that give rise to WTS-annoyance could maximise their efforts by recruiting individuals that are noise-sensitive and/or adhere to wind-turbine opposition groups.

Future research could benefit from employing methodologies that assess the input interferences. For instance, a phonological competition approach (e.g., Brière, 1966; Calabria et al., 2020; Martin, 2006) may offer more sensitive measures to study the impact of WTS over cognitive processes. The development of standardized testing protocols for assessing cognitive performance in relation to WTS is crucial for generating reliable and comparable data across studies. Future work could compile and justify candidate cognitive processes and the most appropriate experimental tasks to study them in the context to WTS exposure. Experimental research that deconstructs wind turbine sound acoustics and that tackles basic psychological processes—thus generalizable across contexts—can provide invaluable insights for social domains (Lunn & Ní Choisdealbha, 2018).

As a final remark, permit us rethink an old philosophical question in the context of wind turbines: "If a tree falls in a forest and no one is around to hear it, does it make a sound?" Although it is common in the field of wind turbine acoustics to use objective measures of sound loudness (e.g., based on sound pressure levels expressed in dBA or Leq), the subjective perception of sound is both frequency and level dependent (and human perception threshold varies at different frequencies). This means that the loudness perception of dB values at different frequencies can be perceived very differently—or not at all. Sones maybe a suitable psycho-acoustic metric as it takes into account the frequency and level dependent nature of human hearing (e.g., see Olson, 1972). We encourage researchers in the field to include and report sones in their analyses, especially in cases where the impact of wind turbine sound/noise is interpreted in the context of human reactions.

5. Conclusions

The current interdisciplinary study contributed to the body of research that seeks to identify psychoacoustic characteristics that may play a significant role in perceived levels of WTS annoyance. Our results identified loudness and fluctuation strength of WTS to be a crucial predictor of perceived annoyance for noise-sensitive individuals; suggesting that such a population is particularly prone to be disturbed by nearby wind farms with these sound features. Our results highlight the perils of just focusing on one parameter (e.g., loudness) to estimate a subjective experience such as annoyance.

In addition, the present study is among the few experimental studies looking at the potential effect of WTS over psychological processes, and the first to specifically measure visual working-memory. The data indicate that temporary exposure to WTS does not affect working-

memory. However, as the popular words of caution go: "absence of evidence is not evidence of absence". Our experimental paradigm targeted a specific cognitive process, known to be sensitive to neural synchronization with external signals. This is not to say that a greater range of auditory stimuli or a different cognitive process could indeed be shown to be negatively affected by WTS stimulation. More studies are needed to address the knowledge gap around WTS and their effect—or lack thereof—on psychological processes.

CRediT authorship contribution statement

Santiago Garcia-Guerrero: Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Manish Manohare:** Writing – review & editing, Validation, Resources, Investigation, Data curation, Conceptualization. **Denis O'Hora:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Eoin A. King:** Writing – review & editing, Supervision, Resources, Investigation, Funding acquisition.

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Conflict of interest

The authors declare no known conflict of interest to disclose.

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Appendix A. Supplementary data

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