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Cognitive neuroscience approach to explore the impact of wind turbine noise on various mental functions

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Despite their alignment with sustainable development principles, wind farms often provoke controversy and misinformation, particularly regarding the noise they produce and their potential impact on human functioning. Concerns have been raised about the possible effects of this noise on irritation levels, psychological well-being, and cognitive functioning. Yet, there is still a lack of controlled, comprehensive studies that could substantiate these concerns. Here, a cognitive neuroscience approach is proposed to experimentally and multifactorial explore wind turbine noise's impact on various mental functions. We used recordings from an actual wind turbine to investigate its effects on the dynamics of brain waves crucial for complex cognitive tasks, as well as on sustained attention and inductive reasoning in healthy adult volunteers. We also tested the subjective evaluation of the stress induced by wind turbine noise and the annoyance it causes. Control conditions included silence and road traffic noise (participants were blind to the nature of acoustic variables). The findings of this pilot study reveal that short-term exposure to wind turbine noise with a sound pressure level corresponding to the real-world situation (i.e., 65 dB SPL) does not adversely affect any of the examined cognitive functions and is not perceived as more stressful or bothersome than road traffic noise. Furthermore, we utilized various psychological scales and found that even tendencies towards rumination or reduced capacity for reflection and ambiguity tolerance did not lead to maladaptive perceptions of wind turbine noise and, therefore, to a state that might indirectly influence mental functioning. Although these results cannot be generalized, they support the concept that the interlinkage between exposure to wind turbine noise and human cognitive functioning is not a cause-and-effect relationship. We discuss the mediating role of socially constructed beliefs about wind farms in this interrelation. We also indicate how important the use of a cognitive neuroscience approach in future research may be for an objective assessment of the impact of wind farms on human cognition.

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Introduction

Noise, a pervasive environmental stressor, has been demonstrated to adversely affect human functioning, encompassing physiological and psychological processes, as well as the neuronal mechanisms underpinning behavior and the execution of cognitive tasks. Consequently, noise has emerged as a significant public health concern worldwide, with its influence on human functioning, particularly mental functioning, becoming a focal point of rigorous scientific investigation (Jafari et al., 2019; Liang et al., 2024). A synthesis of these studies reveals that individuals exposed to elevated noise levels undergo adverse psychophysiological changes (primarily felt as an increase in annoyance), often culminating in disturbances in cognitive functioning. These disturbances may manifest as diminished effectiveness in performing tasks requiring concentrated attention, storing information in working memory, or problem-solving within the reasoning process (Astuti et al., 2023; Muller et al., 2023; Pieper et al., 2021). In other words, such mechanisms as subjective noise annoyance assessment controls, in a way, the impact of noise on mental processes. A prevalent source of noise capable of influencing cognitive abilities in this manner is, for example, the noise generated by air conditioners. Research indicates that impulsive sounds produced by air conditioners can elicit physiological responses, subsequently impacting cognition (Soeta and Onogawa, 2023). In recent years, novel noise sources have emerged, and their impact on diverse cognitive functions remains largely uncharted. Nonetheless, systematic research suggests that certain new noises can be highly disruptive. An example of this is the noise generated by drones, which research suggests is considerably more annoying than other typical environmental noise sources and is poorly masked by ambient noise (Alkmim et al., 2022; Schaffer et al., 2021; Torija and Nicholls, 2022).

In the context of some new noises, various misleading or fake information have surfaced, insinuating that such noises may possess a certain uniqueness that impairs cognition. A case in point is the noise from wind turbines. Despite the development of wind farms being a pivotal element of the global energy transformation and numerous countries investing in this technology to increase the share of renewable energy sources in their energy mix and reduce greenhouse gas emissions, the social perception of wind farms is markedly diverse (Davy et al., 2020; Hanning and Evans, 2012). They are often negatively evaluated, for instance, as overly intrusive in the landscape, insufficiently contributing to the development of the local community residing near the farm, and as a source of noise that is purported to affect life detrimentally, including impairing cognitive functioning, particularly concentration efficiency (Hansen and Hansen, 2020; Lundheim et al., 2022; Takeuchi, 2023). This phenomenon has been informally termed *wind turbine syndrome* (Pierpont, 2009), yet its actual etiology has never been described. As a result, conspiracy slogans or internet posts are often disseminated suggesting that, for example, wind turbine noise could limit learning effectiveness in nearby schools or constrain mental processes conducted in local homes or workplaces. Since there are no controlled and comprehensive studies on these issues (Clark and Paunovic, 2018; van Kamp and van den Berg, 2021; cf. Pleban et al., 2024), the degree to which these claims reflect reality remains a matter for further investigation (Marshall et al., 2023).

Prior studies into the influence of wind turbine noise on the comprehensive spectrum of human functionality have yielded diverse outcomes, some of which remain equivocal, contributing to a non-comprehensive or inconsistent body of evidence. This is particularly relevant to health issues, where numerous investigations have examined the impact of wind turbine noise on various aspects of health-related quality of life (Shepherd et al., 2011), such as cardiovascular functioning or sleep efficiency (Ageborg Morsing et al., 2018; Michaud et al., 2025; Smith et al., 2020). The only relatively consistent research results pertain to the increase in annoyance levels among people living near wind farms and the generally high annoyance ratings attributed to wind turbine noise (Ramalho et al., 2025; van Kamp and van den Berg, 2021). For instance, for equivalent day-evening-night noise levels, wind turbine noise is rated as the most annoying, followed by aircraft noise, then road noise, with railroad noise being the least annoying (Janssen et al., 2011). Consequently, it is often posited that annoyance (which has negative consequences for cognitive functioning) is the sole health risk factor associated with wind turbine noise (Radun et al., 2022). Nonetheless, the reasons for this increase in annoyance remain unclear.

One of the common hypothetical explanations of annoyance caused by wind turbine noise may be related to acoustic characteristics. This noise differs from other environmental noises (e.g., traffic, trains, air traffic), particularly in terms of sound level changes over time and spectral structure. A distinguishing feature of wind turbine noise is the periodicity of level changes, known as amplitude modulation. The noise level of a wind turbine periodically decreases and increases within a range of about 4 dB. This change occurs at an average frequency of about 0.5 Hz to 2 Hz, although it can sometimes reach up to 4 Hz (Ioannidou et al., 2016). It is argued that the amplitude modulation of wind turbine noise is the most significant factor determining the detection of this sound against other noises and the effect on the degree of annoyance (Hafke-Dys et al., 2016). The greater the change in sound level over time (modulation depth), the greater the annoyance caused by wind turbine noise. In terms of spectral structure, when comparing the sound spectra of road traffic noise and wind turbine noise expressed in dB SPL, in both cases, there is a large proportion of acoustic energy in the low-frequency range (<200 Hz) (see Fig. 2a in "Methods"). However, despite the high sound pressure levels in the low-frequency range, especially in the infrasound range (up to 20 Hz), this band does not play a significant role in the perception of wind turbine and road traffic noise sounds (van Kamp and van den Berg, 2021; Yokoyama et al., 2014). On the other hand, when analyzing the spectra of wind turbine and road noise, taking into account the correction curve A (dBA), it can be seen that for road traffic noise, the energy maximum clearly falls in the 1 kHz frequency band (Okada et al., 2020). In contrast, a clear maximum does not occur for wind turbine noise, but the band's energy from 400 to about 1600 Hz is dominant (Fig. 2a). The amplitude modulation is likely the largest contributor to the annoyance rating of wind turbine noise, the occurrence of which causes an unmasking effect compared to other types of environmental noise (Hafke-Dys et al., 2016).

However, a growing body of literature suggests that the assessed annoyance is less strongly linked to the acoustic characteristics of wind turbine noise than previously believed. This has led to the formulation of an alternative hypothesis, proposing that the source of annoyance is rooted in non-acoustic variables (McCunney et al., 2014; Schmidt and Klokker, 2014), or, as a very recent questionnaire-based study suggests (Ata Teneler and Hassoy, 2024), in the interaction of acoustic factors with non-acoustic variables. These variables may be associated with visual phenomena, such as the visibility of wind turbines or shadow flicker (Hubner et al., 2019; Knopper and Ollson, 2011; Szychowska et al., 2018; van Kamp and van den Berg, 2021; Voicescu et al., 2016), but primarily with socially constructed attitudes and expectations or certain psychological conditions (Miedema and Vos, 2003; Pohl et al., 2018; Schaffer et al., 2016). As shown by the latest systematic review (Obuseh et al., 2025), social contexts, such as misinformation about the impact of wind turbines on human functioning, may play a major role here. It is also postulated that potential adverse physical and mental responses emerge solely among individuals with a negatively oriented personality, exhibiting, for instance, high levels of neuroticism, negative affect, and intolerance to frustration (Taylor et al., 2013). The importance of such personality characteristics for wind turbine noise perception was demonstrated in a rapid evidence review covering 2020–2024 (Woodland et al., 2024). Moreover, a systematic literature review including publications from 1998–2022 (Ramalho et al., 2025) shows no empirical evidence proving a cause-and-effect relationship between wind turbine noise and health, suggesting the presence of moderating social and psychological factors. Thus, within the framework of this hypothesis, it is conjectured that wind turbine noise does not exert a genuine (direct) negative impact on human functioning in a broad sense (Michaud et al., 2016). This could be, in essence, a nocebo effect, where the dissemination of inaccurate information through social conversations and media reports can build artificial adverse symptoms, especially in psychologically sensitive people (Clark et al., 2020; Crichton and Petrie, 2015; Schaffer et al., 2016; Smith et al., 2020). However, recent discussions (e.g., Michaud et al., 2025; Woodland et al., 2024) have noted that due to the non-interventional and opinion-based nature of most studies to date, as well as inconsistent and poor-quality evidence, it is impossible to conclude whether the impact of wind turbine noise on physical-mental health is objective or merely a socioculturally constructed stressor.

In light of the literature reviewed above, and bearing in mind the importance of renewable energy and the development of wind farms (Brouwer et al., 2025; le Maitre et al., 2024; Martinez and Iglesias, 2024), it seems that a new approach is needed in research on the impact of wind turbine noise on human functioning (Michaud et al., 2025; Rabbani et al., 2025). Such an approach should allow for a more objective and comprehensive assessment of this impact. It may limit the role of misinformation in decision-making or opinion-forming and increase the share of evidence in discussions among stakeholder groups, such as residents, policymakers, and energy developers (Brouwer et al., 2025; Tsionas et al., 2025). Against this background, this work proposes a novel approach to explore the impact of wind turbine noise on various mental functions by applying cognitive neuroscience techniques and tenets that current traditional approaches have missed (Boone and Piccinini, 2016; Ilardi and Feldman, 2001). Apart from describing the assumptions of such a unique approach, we attempted to apply it in a pilot study with three research questions. The first question is whether exposure to wind turbine noise significantly changes mental functioning when tested by recording brain activity and objective measurements of cognitive processes. The second question explores whether wind turbine noise is perceived as bothersome and stressful when highly ecologically valid conditions and blinding procedures are used. The last question is whether noise-induced annoyance levels are proportional to the participants' personality traits measured by valid psychological tools. Based on the results, we scrutinize the interlinkage between exposure to wind turbine noise and human cognitive functioning. We also discuss how to further develop a proposed cognitive neuroscience approach to advance research on the wind industry's impact on human cognition.

Methods

Approach and hypotheses. The proposed approach includes several minimum criteria for the research procedure. These guidelines are derived from methodological assumptions in the interdisciplinary field of cognitive neuroscience and the literature review on the psychophysical consequences of exposure to wind turbine noise. Firstly, the study should be highly controlled and allow for manipulation of the independent variable (noise exposure). Therefore, it should take the form of laboratory-based experiments. Additionally, such an experiment should explore both behavioral effects (using recognized and standardized psychological methods) and directly record responses from the nervous system, e.g., through electroencephalography or other brain activity imaging techniques (Basner et al., 2014). Secondly, such a study must also demonstrate high ecological validity (Klichowski and Kroliczak, 2020), i.e., resemble real-world scenarios of wind turbine noise exposure (Alamir et al., 2019). Using a somewhat artificial model, i.e., laboratory-based experiments, this would be evident in the use of actual recordings of wind turbine noise at volumes characteristic of natural situations as acoustic stimuli, unlike the majority of past research where synthetic sounds were used (Maijala et al., 2021). Simultaneously, the recordings must be clean in that they are not contaminated by other noises, such as sounds from a nearby highway, which often occurred in previous studies (McKenna et al., 2025). Furthermore, ecological validity should be ensured by measuring cognitive components associated with everyday mental tasks (e.g., fluid intelligence, problem-solving) rather than tasks abstracted from daily life (Malecki et al., 2023). Thirdly, it is crucial to consider the psychological conditions (characteristics) that render wind turbine noise more bothersome and stressful using standardized psychological tests. The study should also be organized so that the examinee is unaware of the nature of the sound (i.e., blinding) and non-focused listening is employed (Alamir et al., 2019; Szychowska et al., 2018; Turi et al., 2019). Finally, it is imperative to confirm that all participants exhibit standard auditory perception across an extensive frequency spectrum, noting that traditional audiological examinations rarely assess hearing sensitivity below 250 Hz, thereby overlooking a significant frequency domain when evaluating the impact of wind turbine noise (Alamir et al., 2019; Yonemura and Sakamoto, 2025).

Here, we conducted a pilot study for such a complex cognitive neuroscience experiment. Employing a baseline-intervention design and recordings from an actual wind turbine (with the sound pressure levels corresponding to the real situation in which a person residing at a distance of several hundred meters from sources), we compared how the dynamics of brain waves crucial for complex cognitive tasks and the effectiveness of sustained attention and inductive reasoning change under short-term exposure to wind turbine noise. Note that sustained attention plays a crucial role in everyday learning and working, and that in everyday life most reasoning is inductive (Cowley, 2018; Hayes and Heit, 2017). We also examined the level of such changes when exposed to road traffic noise and in the absence of any noise. Additionally, we tested the subjective evaluation of noise-induced annoyance and stress while controlling the participants' hearing. We correlated these results with the diagnosed levels of such psychological characteristics in the participants as ambiguity tolerance, rumination, and reflection, i.e., variables moderating the adaptation process (or lack thereof) to new, atypical conditions (Thalbourne and Houran, 2000; Thomsen et al., 2013). Importantly, we only revealed the nature of sounds during debriefing. Thus, participants did not know what they heard, i.e., the procedure was blind.

We defined three hypotheses to predict the potential answers to the three research questions mentioned in the introduction: (i) The exposure to wind turbine and road traffic noise would elicit significant changes in cognitive functioning, both at behavioral and neuronal levels, compared to a control group operating in silence. Specifically, the noise-exposed groups would deteriorate in cognitive performance, while the control group might exhibit stability or even improvement. Hypothesis 1 thus refers to the theoretical assumption described earlier that individuals exposed to noise undergo adverse psychophysiological changes (primarily felt as an increase in annoyance), often culminating in diminished effectiveness in performing tasks requiring concentrated attention or problem-solving within the reasoning process (Astuti et al., 2023; Muller et al., 2023; Pieper et al., 2021). (ii) Wind turbine noise would be perceived as more bothersome and stressful than road traffic noise, thereby inducing more pronounced negative changes. Hypothesis 2 is based on research findings indicating the generally high annoyance ratings attributed to wind turbine noise (Ramalho et al., 2025; Radun et al., 2022; van Kamp and van den Berg, 2021), and that for equivalent noise levels, wind turbine noise is rated as more annoying than road noise (Janssen et al., 2011). (iii) The perceived annoyance and stress from wind turbine noise would be inversely proportional to the participant's tolerance for ambiguity and reflectiveness and directly proportional to their tendency for rumination. In other words, individuals with less adaptive strategies for perceiving new situations and a higher propensity for neurotic self-focused thoughts would be expected to find wind turbine noise more annoying and stressful. Hypothesis 3 thus relates to the concept that non-acoustic variables, such as psychological traits stimulating negative responses to unusual stimuli, like intolerance to frustration or epistemic self-focused thoughts, cause maladaptive perceptions of wind turbine noise (Obuseh et al., 2025; Pohl et al., 2018; Schaffer et al., 2016; Taylor et al., 2013; Woodland et al., 2024).

Participants. In order to determine the minimum sample size necessary for this pilot study, an a priori power analysis was conducted for a mixed-model 2 × 3 ANOVA. This analysis included the within-subject factor of time (comprising the baseline/initial phase of the study and the intervention/second phase) and the between-subject factor of the group (encompassing wind turbine noise, road traffic noise, and silence). The investigation was performed using *G*Power* for Mac (Version 3.1.9.6). The results indicated that a total of 42 participants are needed to demonstrate a medium effect size (f) of 0.25, with a Type I error (α) of 0.05 and a Type II error (β) of 0.20 ($1-\beta$/power = 0.80), and, therefore, to achieve the power of 80%, typically sought in behavioral sciences (Cohen, 1988; Tomczak et al., 2014). Consequently, 45 volunteers were recruited.

As is typical for basic laboratory cognitive neuroscience experiments (particularly those beginning a broader research program or a cycle of full-scale studies), the participants were healthy university students (30 females, 15 males, recruited *via* university website, email, and snowball sampling), aged between 18 and 25 years (mean=22.47, SD = 1.63). Thus, they were mature individuals who were not yet subject to aging processes and had a lengthy educational background. It is important to note that a previous study (Miedema and Vos, 1999) indicated that age is a factor that modifies the evaluation of noise annoyance. However, there is no linear relationship; instead, it has a curvilinear shape, meaning that relatively young (<20) and relatively old (>60) individuals report less annoyance than people between 20 and 60 years old. Moreover, a recent literature review (Ni and Huang, 2022) showed that noise-induced annoyance increases with age, peaking at around 18 years and then declining until approximately 30 years, after which it stabilizes, albeit with a continued gradual decline. Consequently, the participants in our study belong to the age group that is typically the most sensitive to noise compared to other age groups. Regarding education, individuals with higher education levels feel relatively more annoyed. Therefore, our group should be characterized by a sensitivity to noise annoyance (although we had a few people just starting their university studies). As such, similar exposure to wind turbine noise as in our experiment would not cause higher annoyance in younger or older individuals and those with lower education levels. In other studies on the impact of noise on human functioning, an analogous selection of the research sample was used, both in the decision on the size and in the recruitment of volunteers from the university student population (for a recent example, see Yonemura and Sakamoto, 2025 and Zhang et al., 2024).

Eligibility was determined using a brief questionnaire to ensure that they met the inclusion criteria (e.g., being of legal age, having university student status) and did not meet any of the exclusion criteria (e.g., having severe head injuries or undergone ear surgery, experiencing dizziness or tinnitus). All participants reported having normal or corrected-to-normal vision abilities and no history of neurological disorders or severe head injuries. Additionally, they declared not to use any medication that could affect the functioning of the nervous system, not to have used psychoactive substances within 24 h prior to the experiment, and not to have consumed caffeine on the day of the examination. Furthermore, all individuals have self-declared normal hearing abilities, which were corroborated by three auditory assessments: audiometry, otoacoustic emissions, and tympanometry. Audiometric measurements of participants' hearing thresholds were performed for frequencies in the 0.125–8 kHz range using an AC40 Interacoustics audiometer. The measurement frequencies were 0.125, 0.25, 0.5, 1, 2, 4, 6 and 8 kHz. The study participants' mean hearing thresholds in the 0.125–8 kHz frequency range were 3 dB HL and did not exceed 25 dB HL for each frequency. The measured SNR (signal-to-noise ratio) values of DP (distortion product) otoacoustic emission were 21 dB SPL. Tympanometry results showed Type A tympanograms in all participants. Before the study, participants were assured of anonymity and provided written informed consent. All 45 volunteers completed the study.

Procedure. Before the experiment commenced, all volunteers were required to complete a digital questionnaire at home, which included a demographic survey, the Tolerance of Ambiguity Scale, and the Rumination-Reflection Questionnaire. Then, irrespective of their responses, they were randomly allocated to one of the groups: (1) exposed to the noise of road traffic, (2) subjected to the wind turbines noise, or (3) a group in which participants performed all tasks in silence. We used a gender-balanced approach – the same number of females ($n = 10$) and males ($n = 5$) were in each group. The groups did not differ in mean age ($F_{2,42} = 0.897$, $p = 0.416$). We used a between-groups study design to prevent carryover effects of the preceding sound to the following procedure, which can occur in a within-subjects study design.

The laboratory part of the study procedure (implemented in our Cognitive Neuroscience Center) was divided into two nearly identical phases, i.e., baseline/first section of the study and intervention/second section. Each section was initiated with a 10-min task involving reading a text on a tablet. More precisely, participants were asked to sit comfortably in an armchair and provided with a tablet (Galaxy Tab 4 10.1 LTE, SM-T535) displaying a popular science article in their native language. They were instructed to relax and read silently at their own pace until they were informed that the time was up. Subsequently, participants moved to a computer station (located in another laboratory room) where an EEG measurement was conducted, followed by two cognitive ability assessments: the Sustained

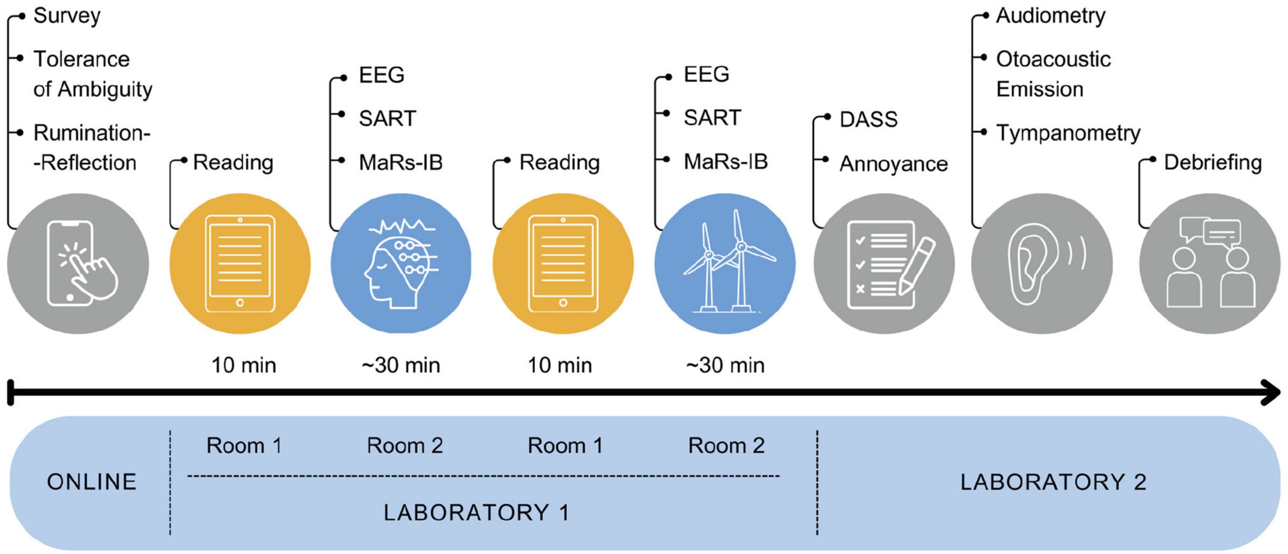

Fig. 1 Schematic overview of the study design. The experimental protocol commenced with participants completing an online demographic survey on the preceding days. This survey also included the Tolerance of Ambiguity Scale and the Rumination-Reflection Questionnaire. The study was initiated in the first room of the laboratory. Here, participants engaged in a 10-min reading session on a tablet device. Subsequently, they were relocated to an alternate (acoustically isolated) room. In this chamber, electroencephalogram (EEG) measurements were taken. This was followed by completing the Sustained Attention to Response Task (SART) and the Matrix Reasoning Item Bank test (MaRs-IB). EEG and both tests were conducted in silence. Participants then returned to the initial room and took a 10-min reading break. Following this, the EEG, SART, and MaRs-IB were conducted again. However, this time, some participants (randomly selected) did this with exposure to wind turbine noise ($n = 15$) and others with exposure to road traffic noise ($n = 15$) or in silence ($n = 15$). Participants in the wind turbine and road traffic noise conditions were required to complete two supplementary questionnaires on the subjective assessment of the auditory stimuli: the Depression, Anxiety and Stress Scale (DASS) and the Noise Annoyance Questionnaire. The final phase of the experiment took place in a psychoacoustic laboratory, where participants' auditory capabilities were assessed using audiometry, otoacoustic emission testing, and tympanometry. The experimental procedure concluded with a debriefing session, during which the nature of the auditory stimuli was disclosed to the participants in the noise-exposed conditions.

Attention to Response Task and the Matrix Reasoning Item Bank test. After completing all tasks in the first section, they returned to the first room with an armchair to continue reading the article for another 10 min. Further, based on the assigned condition, they completed the remaining measurements and tasks from the second part of the study either in silence or while exposed to wind turbines or road traffic noise. Afterward, participants from the road traffic and wind turbine noise groups completed two additional pen-and-paper questionnaires related to the subjective assessment of the auditory stimuli used in the study: Depression, Anxiety and Stress Scale and Noise Annoyance Questionnaire. Finally, their hearing was evaluated using audiometry (Interacoustics AC40), otoacoustic emission testing, and tympanometry (Interacoustics Titan) in the psychoacoustic laboratory in our center's third room. The last element was a debriefing, during which we revealed the nature of sounds to participants from the noise-exposed groups.

It must be strongly emphasized that participants were not informed about the purpose of the noise exposure either before or during the experiment. They were only told that there might be some sound during the study. The participants did not know if or when the sound would occur, nor did they know what the sound would be (blinding). After the study, we asked the group exposed to wind turbine noise to name the sound. None identified it as wind turbine noise. Most provided general descriptions indicating it was some noise, and some participants specified that the sound reminded them of a noise generated by ocean waves or an airplane.

The research procedure was approved by The Ethics Committee of the Faculty of Educational Studies at Adam Mickiewicz University, Poznan, on December 12, 2022 (Ethical Approval No. WSE-KEdsPB-03/2022/2023) and adhered to the principles of the Declaration of Helsinki. The overall workflow of our experimental design is visualized in Fig. 1, and all its relevant elements are described in the following subsections.

Tolerance of Ambiguity Scale. The Tolerance of Ambiguity Scale is comprised of 12 items, each presented as a statement. Respondents must indicate their level of agreement with each statement on a scale ranging from 1 (completely disagree) to 7 (completely agree). The instrument presupposes a unifactorial structure for ambiguity tolerance. Hence, the scoring is conducted by summing the points assigned to individual responses (note that seven items are reverse scored). A higher overall score on the scale (ranging from a minimum of 12 to a maximum of 84) indicates a greater tolerance of ambiguity (McQuarrie and Mick, 1992). Herein, ambiguity tolerance is conceptualized as the capacity to manage ambiguous situations, i.e., ones that cannot be adequately categorized. The scale thus gauges the degree to which an individual perceives ambiguous situations as desirable and their typical reactions to such situations. Individuals with low ambiguity tolerance typically exhibit aversion to undefined stimuli, whereas those with high ambiguity tolerance often respond to such stimuli with curiosity. Low ambiguity tolerance may elicit a sense of threat and limit engagement in atypical experiences, whereas high ambiguity tolerance may stimulate satisfaction and enhance activity (Thalbourne and Houran, 2000). Given that our study involved participants who are native speakers of Polish, we utilized the Polish adaptation of the Tolerance of Ambiguity Scale (Czajeczny, 2016).

Rumination-Reflection Questionnaire. The Rumination-Reflection Questionnaire is made up of 13 items. Individuals rate each item on a scale from 1 (completely disagree) to 5 (completely agree).

These 13 statements comprise six items diagnosing rumination (one item is reverse scored) and seven for reflectiveness (two are reverse-scored). The score is calculated by summing the points for each part. For rumination, one can receive from 6 to 30 points, and for reflectiveness, from 7 to 35 points. The higher the sum score, the more pronounced the characteristic (Trapnell and Campbell, 1999). These scales measure two types of thoughts that arise, for example, in new situations. Ruminations are maladaptive thoughts that unnecessarily consume a large part of cognitive resources and consequently hinder the performance of new tasks (they, of course, also have many other consequences). They are, therefore, a type of neurotic self-focused thoughts. On the other hand, reflectiveness refers to adaptive thoughts that open the mind to new experiences and facilitate the performance of cognitive tasks (and improve functioning in several other areas). Thus, these are epistemic self-focused thoughts (Thomsen et al., 2013). In our study, we used the Polish version of the Rumination-Reflection Questionnaire (Radon, 2014).

EEG. The power ratio of theta to beta frequencies (Theta/Beta Ratio, TBR) in spontaneous EEG is a widely recognized biomarker for cognitive control, where lower TBR indicates a higher level of attentional (Angelidis et al., 2016) and executive control (van Son et al., 2019), and cognitive processing (Clarke et al., 2019). Therefore, a decrease in TBR is indicative of an enhancement in cognitive functioning, whereas an increase in TBR suggests a decline in cognitive performance. To determine TBR, we collected the EEG signals using an amplifier (ProComp 2, Thought Technology) connected to a gold-plated active FCz electrode, adhering to the international standard 10-10 electrode placement system. Reference and ground electrodes were attached to the left and right earlobes, respectively. During the measurement, the impedance was kept below 5 kΩ for each channel, and the sampling frequency of the EEG signal was set at 256 Hz. We used the diagnostic protocol (built into BioGraph Infiniti Software, Thought Technology), which consisted of three parts, each lasting 60 s. The first two parts were conducted in the resting state with the participant's eyes open and then closed. The last part involved the cognitive state, during which the participant was asked to silently read text displayed on the screen of a 21.5-in. Apple iMac computer, which was positioned ~57 cm away from the participant. Following the collection, the EEG signal was preserved for subsequent offline analysis. After removing eye and muscle artifacts, the signal was segmented into frequency bands based on the Fourier Transform with the range designated as 4–8 Hz for theta and 13–30 Hz for beta waves. Based on this, the TBR was computed individually for each segment and finally for the entire measurement duration.

Sustained Attention to Response Task. The Sustained Attention to Response Task (SART) was employed to measure participants' ability to sustain attention. This Go/No-Go task requires participants to react to and inhibit reactions to specific stimuli across 225 trials. During the initial 250 ms of each trial, either a Go stimulus, represented by digits from 1 to 9 excluding 3, or a No-Go stimulus, represented by the digit 3, is presented, followed by a mask (a diagonal cross inscribed in a ring) for 900 ms. The presentation of numbers is pseudo-randomized, with each digit appearing 25 times and never consecutively. The size of the white font displayed on a black screen is also randomized (48, 72, 94, 100, and 120 points). Participants are instructed to respond to Go stimuli by pressing the keyboard's spacebar and withhold their reaction when the digit 3 appears on the screen, emphasizing both accuracy and speed of responses equally. The test is preceded by a training session of 18 trials, including two No-Go trials. We used the online SART test on the Psytoolkit platform (version 3.4.4) for non-commercial research purposes (Stoet, 2010, 2017). One of its advantages is the ability to edit the code provided on the website freely. Since the Psytoolkit's SART slightly differs from the original version, we made minor modifications to the code (removed the error message; the modified code is available in the Open Science Framework database: https://osf.io/wpk4c) to align it with the version developed by Robertson et al.1997). We tested using the Firefox browser on an Apple iMac 21.5-in. computer. Participants performed the task seated ~57 cm away from the screen, using a wired Apple keyboard (they pressed the spacebar with both index fingers). Psytoolkit recorded data for the SART test, including reaction time and response accuracy for each stimulus. Based on these data, we calculated the percentage correctness of the reaction for all Go stimuli and separately for No-Go stimuli, as well as the average reaction time for Go stimuli. Additionally, we calculated a skill index by dividing the correct response to No-Go stimuli by the average reaction time to Go stimuli and multiplying the result by 1000. This index better reflects the efficiency of task performance (Jonker et al., 2013) and thus better represents the general ability to sustain attention, with higher scores indicating better test performance. Responses to Go stimuli with reaction times more than two standard deviations above or below the mean were excluded from all analyses.

Matrix Reasoning Item Bank test. The Matrix Reasoning Item Bank (MaRs-IB) test assesses individuals' inductive reasoning. This test is considered a good indicator of fluid intelligence correlated with reasoning, problem-solving, and learning abilities. Therefore, MaRs-IB is used to assess the efficiency of complex cognitive processes. It is also a good indicator of working memory capacity, which is the aspect of cognition most often affected by noise (Chierchia et al., 2019; Klichowski, 2024). It does not require a psychology degree for administration and is freely available for research (https://osf.io/g96f4/). Moreover, it can be simply implemented in computer-based experiments. The design of MaRs-IB is similar to Raven's Progressive Matrices (Raven, 2009). It consists of three-by-three matrices filled with abstract shapes, with the bottom right-hand side cell always empty. The participant's task is to analyze the relationships between the shapes in the cells (which could vary across color, size, position, and shape) and select the missing shape from a set of four possible answers (an example matrix is shown in Fig. 5a). (Chierchia et al., 2019) developed three counterbalanced test forms, each with 80 matrices differing only in the exact shape. Thanks to this, it is possible to implement selected test forms in procedures with a pre-test or baseline and a post-test or intervention without repeating the same trials. Additionally, items can be freely adapted and selected for tasks of different duration and difficulty levels. Therefore, following the approach of Jaeggi et al. (2014), who divided the 36 matrices from the advanced version of Raven's Progressive Matrices into pre-test/baseline and post-test/intervention, we prepared similar (modeled on the Raven's Progressive Matrices test) sets based on MaRs-IB matrices. We have already used them in our recent study, and the detailed description and the adjustment procedure are shown in our paper (Klichowski et al., 2023). Briefly, we selected the 18 most difficult matrices from two test forms, arranged by the number of transformations, and we verified the reliability of this test for baseline-intervention comparisons (selected matrices are available in the Open Science Framework database: https://osf.io/kp48h). In the current study, participants had 60 s to solve one matrix, with a clock symbol appearing on the screen after 50 s to indicate the remaining 10 s. If no response was given within 1 min, the software automatically moved to the next trial. At the same time, the participants were informed that the tasks should be completed as correctly and quickly as possible, so as soon as they knew the answer, they should provide it and continue to the following matrix. Participants were required to complete two training trials before taking the test. They performed the task on an Apple iMac 21.5-in. computer, using a certified pad (Cedrus RB-730) to provide answers and SuperLab 6.1.2 software, which ran tests and recorded data for analysis. Based on these data, we calculated the accuracy as a percentage of correct responses to all trials, the total test completion time, and the average response time for only correctly answered matrices in both study phases. Since the matrices in parts one and two were analogously related pairs of the same difficulty level and type, we could compare them. So, for this last analysis, we matched them together and removed reaction time from any matrices that were only solved correctly in the first or second section of the study. Subsequently, we separately calculated the average reaction time for the remaining responses in baseline and intervention. Trials with response times under 250 ms were not included in the analyses.

Depression, Anxiety and Stress Scale. The Depression, Anxiety, and Stress Scale (DASS) is a self-report instrument developed to assess an individual's emotional states over a specific period of time (Lovibond and Lovibond, 1995). The DASS questionnaire is open-access, and its administration does not necessitate any particular qualifications or skills. It can be downloaded from the official website and copied without restriction. The scale is available in several versions: the original DASS-42 and two shorter versions, DASS-12, as well as DASS-21, which we used in this study. Owing to its ability to reduce response time while preserving high reliability, DASS-21 is recommended for research applications. It includes 21 items divided into three subscales, each corresponding to a negative emotional state: depression, anxiety, and tension/stress. Participants are asked to select a number from 0 to 3 that best represents the extent to which the statement applies to them over a specified period, which in our study was the duration of experimental noise exposure. Scores are calculated for each subscale separately and for the entire test, then multiplied by 2 to enable comparison with results from the DASS-42, with higher scores (range for a single scale 0–42 points and the entire test 0–126 points) indicating greater severity of negative emotional symptoms. While our primary objective was to examine stress, necessitating the use of the corresponding subscale, the authors of the tool note that this subscale pertains to a narrow understanding of stress. Given the close interrelation of the emotional states investigated in the questionnaire, a broader understanding of stress can be achieved by using all three subscales together. Consequently, we administered the entire DASS-21 questionnaire. However, we focused our analysis solely on the stress subscale results and the overall test outcome, omitting the results of the depression and anxiety scales themselves. We used the Polish translation of the DASS form, the factorial validity of which has been confirmed (Makara-Studzinska et al., 2022).

Noise annoyance. Annoyance caused by noise was evaluated using a modified 11-point scale from the International Commission on Biological Effects of Noise (ICBEN) (Fields et al., 2001). This scale is a standardized way of assessing noise annoyance and is part of the procedure for assessing noise annoyance contained in the ISO/TS 15666:2021 standard; therefore, it is widely used in noise research (Clark et al., 2021). Participants were instructed to select a number that most accurately represented the level of disturbance, irritation, or annoyance they experienced from the sounds while conducting the experimental task. The ICBEN scale extends from 0 to 10, where 0 signifies a situation where the sounds were not annoying, and 10 denotes extreme annoyance induced by the sounds. If a noise source is rated 7 points or higher, then this indicates a high level of annoyance with the noise source being evaluated.

Acoustic conditions. In the study conducted, our focus was on two distinct types of noise. The first type was road traffic noise, predominantly generated by vehicles in transit on the highway. The second type of stimulus was the noise produced by an operational wind turbine.

It should be noted that in practically all cases of the most used 2 MW wind turbines, the distance between the wind turbines and residential areas is no less than 500 m. For this reason, in the study setting, we assumed exactly this least favorable case of wind turbine location concerning areas people use. The sound pressure levels of wind turbine noise (as well as road traffic noise) were at 65.4 dB SPL. This sound pressure level corresponds to the actual average noise level of a wind turbine at 500 m. Thus, the study's conditions should be considered boundary conditions under which wind turbine noise may be generated soon. However, wind turbine and road traffic noise levels used in the study were not hazardous to health, as levels of 65 dB SPL correspond to the average level of speech during conversation.

To ensure a high degree of ecological validity, we utilized recordings of real-world noises and implemented them in an experimental setup using acoustically sophisticated procedures for playback. The subsequent sections provide a detailed account of the approach to obtaining these recordings and the procedure adopted for their experimental playback.

Road traffic noise. Road traffic noise, characterized by the sounds of cars and trucks moving on the highway during peak traffic, was recorded outdoor at a distance of 500 m from the A2 highway near Poznan, a large city in Poland. The recording was facilitated using a RODE NTSF1 ambisonic microphone, positioned at a height of 1.5 m relative to the ground level and connected to a SQuadriga II digital recording device. A Svantek SVAN 979 1. class sound level meter microphone was also deployed adjacent to the ambisonic microphone to measure the sound levels. From the recorded road traffic noise, a 15-min signal was selected. This signal was then duplicated three times to prepare a one-hour recording, which was subsequently presented to the participants during the experiment. Due to the continuous flow of vehicles on the highway, individual passes cannot be distinguished from the noise of road traffic. During the tests, the equivalent level of road traffic noise was set at $L^{RTN}{}_{eq} = 65.4$ dB SPL (56.8 dBA).

Wind turbine noise. The noise emitted by a single operational wind turbine was recorded outdoor at one of the wind farms located near Poznan. The recording was facilitated using a RODE NTSF1 ambisonic microphone, which was connected to a SQuadriga II digital recorder. A Svantek SVAN 979 first-class sound level meter microphone was used to control the sound levels. Both microphones were positioned at a height of 1.5 m relative to the ground level and were distanced 500 m from the wind turbine. The recordings were made for a typical 2 MW wind turbine commonly used in the country's wind farms, with a nacelle at 105 m and a rotor diameter of 90 m. During the recording session, the wind speed at the wind turbine hub height (105 m) was 8.2 m per second; at 10 m above the ground, it was ~4.5 m per second; and at the height of 1.5 m, the wind speed was less than 1 meter per second. The wind did not compromise the quality of the sound recordings. A seven-minute segment of the wind turbine noise signal was selected from the collected recordings and looped to generate one-hour sound material for the experiments. The wind turbine noise was characterized by periodic fluctuations in the sound level, known as amplitude modulation. The average modulation rate was 0.8–1 Hz, while the modulation depth, on average, stood around 6.9 dB. During the experiment, the equivalent noise level of the wind turbine was $LW^{TN}{}_{eq} = 65.4$ dB SPL (38.5 dBA). This level was equal to the

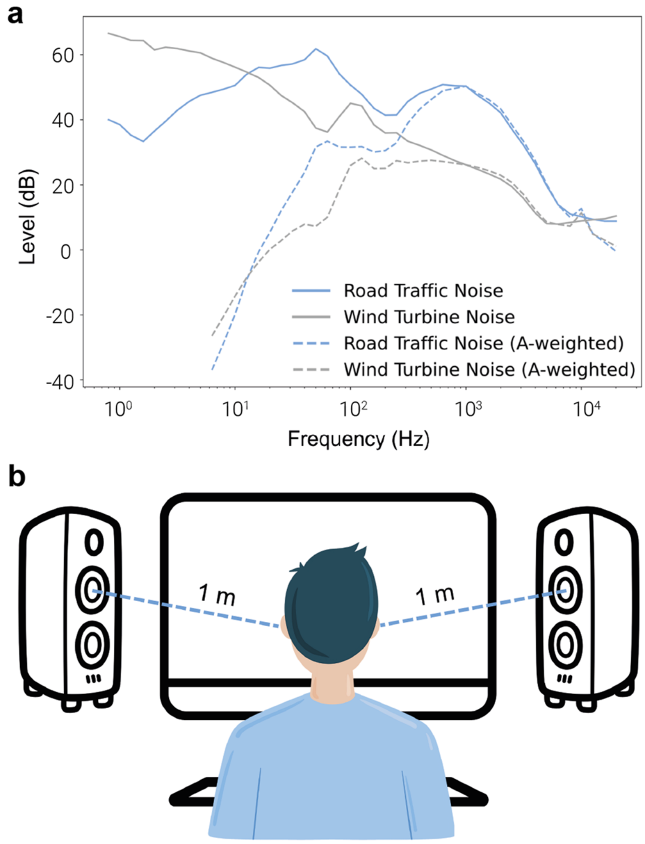

Fig. 2 Noise playback. a 1/3 octave frequency spectra of test signals used in the study. Solid lines show spectra without frequency correction and dashed lines with A-weighting. The A-weighted curve is derived from the 40-phon equal-loudness contour, which reflects the perception of loudness across the entire range of human hearing (note that A-weighting is used for environmental or workplace noise measurements, and based on A-weighted noise levels, the risk of hearing loss is evaluated). The frequency range for the uncorrected spectrum is 0.8 Hz–20 kHz, and for the A-weighted spectrum, 20 Hz–20 kHz. **b** Arrangement of sound sources in an acoustically isolated room. The speakers were symmetrically positioned on the left and right sides of the participant, each maintaining a distance of 1 meter. They were aligned to match the height of the listener's head. A subwoofer was placed on the floor.

equivalent level of road traffic noise. Both recordings (road traffic and wind turbine noise) which have been developed are available in the Open Science Framework database: https://osf.io/wpk4c.

Road traffic noise and wind turbine noise playback. Participants were presented with the original wind turbine/road traffic noise sounds as they were recorded in the environment, also keeping the sound pressure level of the sounds presented. The sounds were not filtered. The road traffic and wind turbine noise recordings were played back in an acoustically isolated room. The playback was facilitated using an Apple iMac 21.5-in. computer, which was connected to two Yamaha HS5 speakers and a Velodyne EQ-Max 15 subwoofer. Both the road traffic and wind turbine noise had equivalent levels of 65.4 dB SPL. The 1/3 octave spectra of the road traffic and wind turbine noise are depicted in Fig. 2a. The speakers were symmetrically positioned on the left and right sides relative to the participant, maintaining a distance of 1 m, and were aligned with the height of the listener's head. Figure 2b shows an arrangement of the locations of the sound sources. The sounds were calibrated using a Class 1 SVANTEK SVAN 979 sound level meter in the test room. The calibration microphone, connected to the sound level meter, was located where the test subject's head was during listening. Equivalent sound levels were measured during calibration. The gain was selected to obtain equivalent sound levels of 65.4 dB SPL for both wind turbine and road traffic noise. This test set replicates the situation where a person is exposed to a wind turbine or road traffic noise outside their property or inside a room with a window open (i.e., without the noise reduction provided by a closed window).

Data analysis. Initially, we employed a repeated measures ANOVA for each dependent variable with time (baseline/first section of the study, intervention/second section) as the repeated measure factors and group (wind turbine noise, road traffic noise, silence) as between-subject factors. The Greenhouse-Geisser correction was applied where appropriate. We utilized partial eta squared (η^2p) to gauge the effect size. Subsequently, we computed the changes/delta (Δ) between intervention and baseline measurements by subtracting the baseline value from the second measurement result. Then, using a one-way ANOVA with group as a grouping variable, we compared the differences in mean Δ between groups, as well as in the assessment of stress and annoyance levels. All necessary post hoc tests for pairwise comparisons were conducted with an additional Tukey's correction. Finally, we performed a Pearson's correlation analysis between the assessed levels of stress and annoyance and the values obtained from the scales of ambiguity tolerance, rumination, and reflection. All statistical analyses were executed using *jamovi* (Version 2.3.18.0) for Mac (Lenth, 2020; R Core Team, 2021; Singmann, 2018; The jamovi project, 2022), and the *jamovi* file with anonymized data is available in the Open Science Framework database: https://osf.io/wpk4c. Prior to any analyses, a combination of visual methods using Q-Q (quantile-quantile) plots and assessment using skewness and kurtosis was employed to examine indicators related to the shape of the distribution (Ghasemi and Zahediasl, 2012; Kim, 2013). The level of significance adopted was $\alpha = 0.05$.

Results

Alterations in neural dynamics. In our pilot study, we found no significant main effect of time on neural dynamics during the resting state (Fig. 3a, b), irrespective of whether the eyes were open ($F_{1,42} = 0.270$, $p = 0.606$, $\eta^2p = 0.006$) or closed ($F_{1,42} = 2.806$, $p = 0.101$, $\eta^2p = 0.063$). A similar observation was made for the main effect of group, which remained non-significant in both phases ($F_{2,42} = 0.636$, $p = 0.534$, $\eta^2p = 0.029$ and $F_{2,42} = 0.927$, $p = 0.404$, $\eta^2p = 0.042$, respectively). However, an effect of time was noted for the cognitive state ($F_{1,42} = 5.168$, $p = 0.028$, $\eta^2p = 0.110$), as indicated by a deterioration in TBR by 0.04 (from 1.15 to 1.19, $t = 2.273$, $df = 42$, Tukey's $p = 0.028$). Despite this observation, the main effect of group did not reach significance ($F_{2,42} = 1.451$, $p = 0.246$, $\eta^2p = 0.065$). Moreover, the time × group interaction was also non-significant ($F_{2,42} = 1.049$, $p = 0.359$, $\eta^2p = 0.048$; Fig. 3c). Consequently, the change in TBR over the entire measurement duration merely showed a trend ($F_{1,42} = 3.296$, $p = 0.077$, $\eta^2p = 0.073$) toward worsening (by 0.03, from 1.15) without reaching statistical significance ($t = 1.815$, $df = 42$, Tukey's $p = 0.077$). Furthermore, neither the effect of group ($F_{2,42} = 1.096$, $p = 0.343$, $\eta^2p = 0.050$) nor the time × group interaction ($F_{2,42} = 0.562$, $p = 0.574$, $\eta^2p = 0.026$) were significant for overall TBR (Fig. 3d).

Ultimately, the group variable did not manifest as a distinguishing factor for the average Δ derived from the EEG recordings. No significant differences were detected in TBR during various states when comparing the groups. This includes

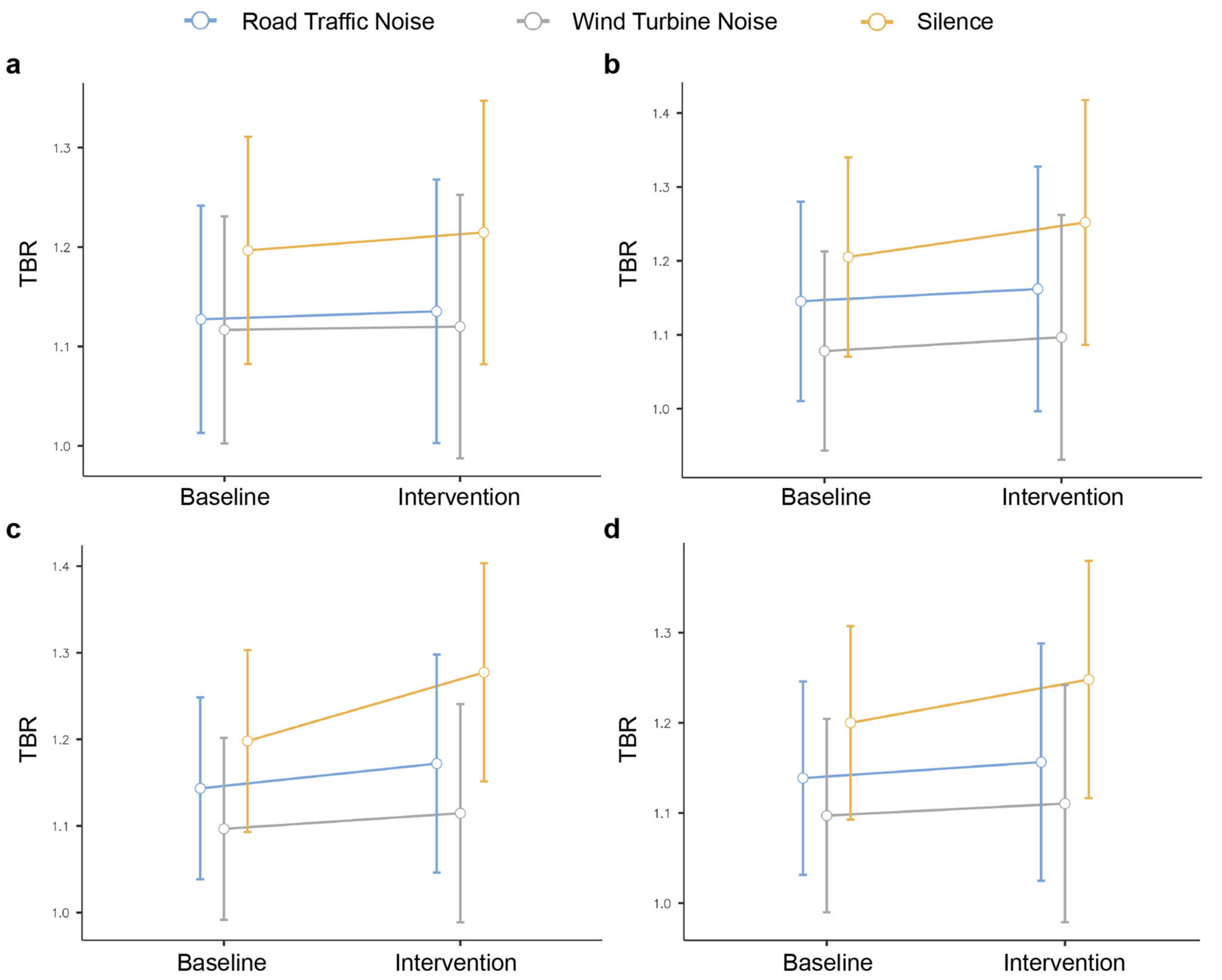

Fig. 3 Effects of wind turbine noise on alterations in neural dynamics compared to two other acoustic conditions. a The estimated marginal means plot shows no change in the Theta/Beta Ratio (TBR) measured during the resting state with open eyes across all groups ($n = 45$). **b** The estimated marginal means plot shows no change in the TBR measured during the resting state with closed eyes across all groups ($n = 45$). **c** The estimated marginal means plot shows a significant decrease in the TBR measured during the cognitive state across all groups ($n = 45$). **d** The estimated marginal means plot shows a decreasing trend in the TBR measured throughout the entire duration of the measurement across all groups ($n = 45$). Error bars represent standard errors of the means.

the resting state with the participant's eyes open ($F_{2,42} = 0.053$, $p = 0.949$), the resting state with the participant's eyes closed ($F_{2,42} = 0.352$, $p = 0.705$), the cognitive state ($F_{2,42} = 1.049$, $p = 0.359$), and throughout the entire duration of the measurement ($F_{2,42} = 0.562$, $p = 0.574$). In other words, the observed deterioration in neural dynamics in the cognitive state and the negative trend in global TBR were not attributable to exposure to wind turbine (or control) noise. Instead, these effects were likely due to cognitive fatigue resulting from participation in a relatively long experiment or other factors.

Effects on cognitive behaviors. Although we observed a main effect of time in some instances involving improved cognitive functioning as a specific manifestation of gaining skills and learning, we did not detect a group effect anywhere. Moreover, none of the interactions of time and group were significant.

For sustained attention, an improvement occurred in the accuracy of responses to Go stimuli ($F_{1,42} = 5.377$, $p = 0.025$, $\eta^2p = 0.113$) as such that the participants improved their score by an average 0.57% (from 98.41% to 98.98%, $t = 2.319$, $df = 42$, Tukey's $p = 0.025$). However, the group effect was not significant here ($F_{2,42} = 1.481$, $p = 0.239$, $\eta^2p = 0.066$). Also, the time × group interaction was not significant ($F_{2,42} = 0.267$, $p = 0.767$, $\eta^2p = 0.013$; Fig. 4a). The mean reaction time to Go stimuli (Fig. 4b) did not improve in terms of speed ($F_{1,42} = 0.171$, $p = 0.682$, $\eta^2p = 0.004$), and this was a finding that did not differ between groups ($F_{2,42} = 0.681$, $p = 0.512$, $\eta^2p = 0.031$). The same was observed for the accuracy of responses to No-Go stimuli (Fig. 4c). There was neither a time effect ($F_{1,42} = 0.537$, $p = 0.468$, $\eta^2p = 0.013$) nor a group effect ($F_{2,42} = 0.712$, $p = 0.193$, $\eta^2p = 0.075$). Ultimately, the analysis for the skill index (Fig. 4d) did not show a global change (improvement or deterioration) in sustained attention ($F_{1,42} = 0.146$, $p = 0.705$, $\eta^2p = 0.003$) and no differences in this respect between groups ($F_{2,42} = 1.480$, $p = 0.239$, $\eta^2p = 0.066$).

Concerning inductive reasoning, improvement occurred in all of the three contexts analyzed (Fig. 5b–d). Regarding the accuracy of responses, the main effect of time was significant ($F_{1,42} = 9.311$, $p = 0.004$, $\eta^2p = 0.181$), leading to an average improvement of 7.65% in participants' performance during the second part of the test (from 60.74% to 68.39%, $t = 3.051$, $df = 42$, Tukey's $p = 0.004$). This effect was also apparent in the execution speed

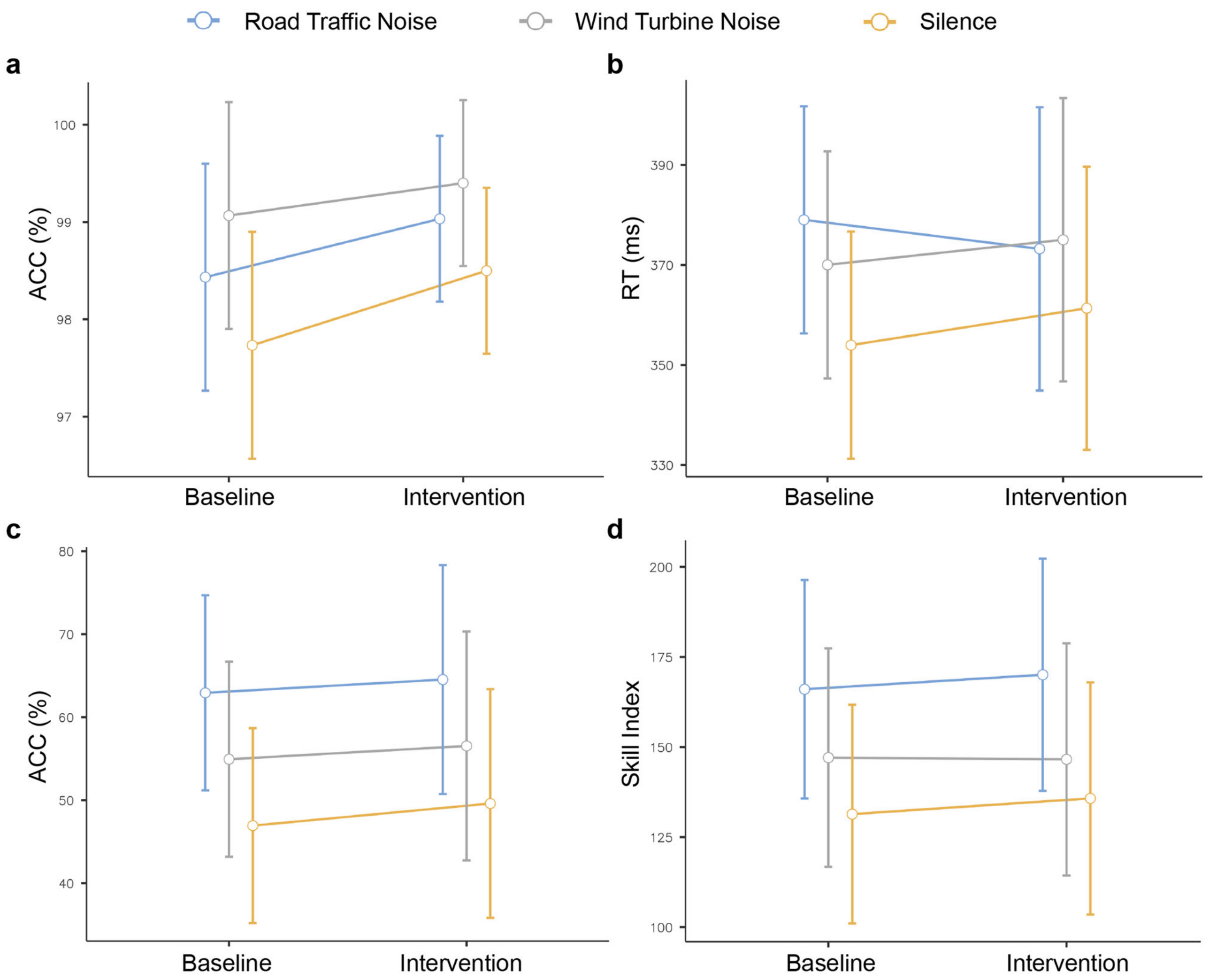

Fig. 4 Effects of wind turbine noise on sustained attention compared to two other acoustic conditions. a The estimated marginal means plot shows a significant improvement in the accuracy of responses to Go stimuli across all groups ($n = 45$). **b** The estimated marginal means plot shows no change in the average reaction time to Go stimuli across all groups ($n = 45$). **c** The estimated marginal means plot shows no change in the ACC of responses to No-Go stimuli across all groups ($n = 45$). **d** The estimated marginal means plot shows no change in the overall ability to maintain attention across all groups ($n = 45$). ACC is an abbreviation for accuracy, while RT is for reaction time. Error bars represent standard errors of the means.

of the test section ($F_{1,42} = 16.293$, $p = 0.00023$, $\eta^2 p = 0.280$), with participants completing the second part, on average, 1 min and 42 s faster (from the initial 10 min and 37 s to 8 min and 55 s, $t = 4.036$, $df = 42$, Tukey's $p = 0.00023$). Moreover, the influence of time extended to the average response time ($F_{1,42} = 37.926$, $p < 0.00001$, $\eta^2 p = 0.475$), which was reduced by an average of 6 s in the second part (from 35 s to 29 s, $t = 6.158$, df = 42, Tukey's $p < 0.00001$). Despite these observations, no group effect was detected (all $F_{2,42} < 2.304$, all $p > 0.112$, all $\eta^2 p < 0.099$), and the interaction between time and group remained consistently non-significant (all $F_{2,42} < 1.179$, all $p > 0.318$, all $\eta^2 p < 0.053$).

Moreover, the group variable did not emerge as a differentiating factor for the mean Δ calculated from the behavioral measurements. Consequently, no differences were observed between groups in terms of the change in response accuracy to Go stimuli ($F_{2,42} = 0.267$, $p = 0.767$), the average reaction time to Go stimuli ($F_{2,42} = 0.589$, $p = 0.560$), the response accuracy to No-Go stimuli ($F_{2,42} = 0.018$, $p = 0.982$), and the sustained attention skill index ($F_{2,42} = 0.051$, $p = 0.950$). Similarly, no disparities were found between groups when it comes to change in the response accuracy during inductive reasoning ($F_{2,42} = 0.395$, $p = 0.676$) and the total test completion time ($F_{2,42} = 0.305$, $p = 0.739$), including the average response time ($F_{2,42} = 1.179$, $p = 0.318$).

Assessment of stress and annoyance levels, and their psychological underpinnings. Participants evaluated the stress induced by the acoustic conditions of the experiment as extremely low, both in terms of the stress subscale (mean=9.27 points, $SD = 7.06$ points) and the overall emotional score (mean=19.47 points, $SD = 14.63$ points). In both instances (Fig. 6a, b), no significant differences were detected between the groups ($F_{1,28} = 0.023$, $p = 0.880$ and $F_{1,28} = 0.002$, $p = 0.961$, respectively). A similar pattern was observed in the context of noise annoyance. Participants rated it as minimal (mean=2.00 points, $SD = 2.03$ points). Moreover, as Fig. 6c and Table 1 show, although wind turbine noise was reported as marginally more annoying than road traffic noise (the mean difference=0.80), this disparity was not significant ($F_{1,28} = 1.167$, $p = 0.289$).

Furthermore, the distributions of these three variables in response to wind turbine noise did not correlate with the values obtained from the scales of ambiguity tolerance (for the stress subscale $r = -0.423$ and $p = 0.116$, for the overall emotional score $r = -0.243$ and $p = 0.382$, for the noise annoyance

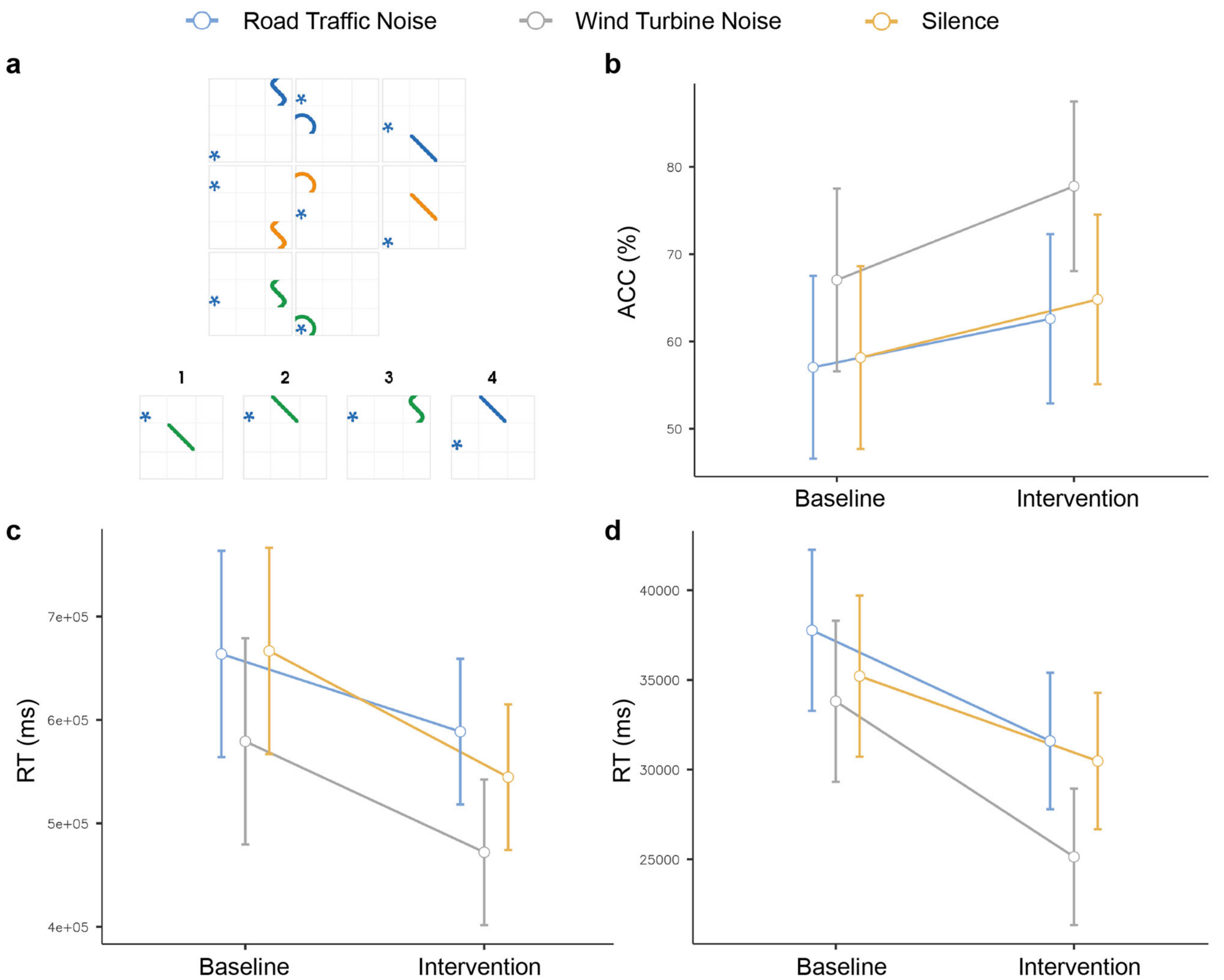

Fig. 5 Effects of wind turbine noise on inductive reasoning compared to two other acoustic conditions. a An example matrix of Matrix Reasoning Item Bank Test (the participant's task is to select the missing shape from a set of four possible options; the correct answer, in this case, is "2"). **b** The estimated marginal means plot shows a significant improvement in the accuracy of responses across all groups ($n = 45$). **c** The estimated marginal means plot shows a significant enhancement in the execution speed of the test part across all groups ($n = 45$). **d** The estimated marginal means plot showing a significant reduction in the average response time across all groups ($n = 45$). ACC is an abbreviation for accuracy, while RT is for reaction time. Error bars represent standard errors of the means.

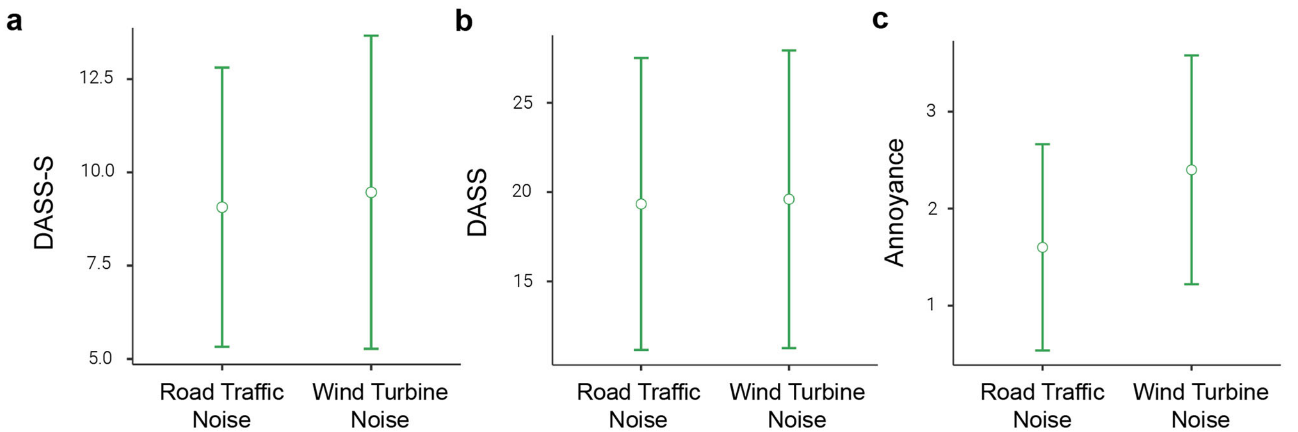

Fig. 6 Assessment of noise-induced stress and annoyance. a A one-way ANOVA shows no significant differences between groups concerning noise-induced stress ($n = 30$). **b** A one-way ANOVA shows no significant differences between groups concerning noise-induced overall emotional state ($n = 30$). **c** A one-way ANOVA shows no significant differences between groups concerning noise annoyance assessment ($n = 30$). DASS is an abbreviation for Depression, Anxiety, and Stress Scale, while DASS-S for its stress subscale. Error bars represent standard errors of the means.

Table 1 Assessment of noise-induced stress and annoyance, and the results of pairwise comparisons.

Scale	Group				Mean difference	*t*	*df*	Tukey's *p*
	Road Traffic Noise		Wind Turbine Noise					
	Mean	*SD*	Mean	*SD*				
DASS	19.33	14.75	19.60	15.03	0.27	0.049	28	0.961
DASS-S	9.07	6.76	9.47	7.58	0.40	0.153	28	0.880
Annoyance	1.60	1.92	2.40	2.13	0.80	1.080	28	0.289

DASS Depression, Anxiety, and Stress Scale, *DASS-S* stress subscale of Depression, Anxiety, and Stress Scale.

$r = -0.397$ and $p = 0.142$; Fig. 7a), rumination ($r = 0.252$, $p = 0.364$, $r = 0.317$, $p = 0.249$, and $r = -0.358$, $p = 0.191$, respectively; Fig. 7b), and reflection ($r = -0.265$, $p = 0.340$, $r = -0.061$, $p = 0.829$, and $r = -0.207$, $p = 0.460$; Fig. 7c). Therefore, even a low tolerance for ambiguity or tendencies towards neurotic self-focused thoughts, as well as a diminished capacity for epistemic self-reflection, did not result in maladaptive perceptions of wind turbine noise, which could have an indirect impact on cognitive functioning.

Discussion

The limitations of previous research approaches leave open the question of whether wind turbine noise directly affects human functioning or if its possible negative impact results from non-acoustic variables, such as socio-culturally constructed beliefs (Michaud et al., 2016; Michaud et al., 2025; Ramalho et al., 2025; Tsionas et al., 2025; Woodland et al., 2024). Considering the social importance of this unresolved issue (Brouwer et al., 2025; le Maitre et al., 2024; Martinez and Iglesias, 2024), we described in this work how cognitive neuroscience techniques and tenets can be applied for a more objective and comprehensive assessment of the impact of wind turbine noise on various mental functions. Apart from outlining the assumptions of such a unique approach, we attempted to apply it in a pilot study. Overall, in line with the proposed approach, we conducted the study under highly controlled conditions (i.e., in a laboratory) while ensuring high ecological validity. Additionally, the primary dependent variable was measured not only at the behavioral level (using recognized psychological tests) but also at the neuronal level (via EEG). The dependent variable itself was cognitive processes associated with everyday mental tasks. The study was also blind regarding the independent variable (acoustic conditions). This was accompanied by controlling psychological and auditory factors, as well as measuring annoyance and stress levels.

Our results did not show a negative impact of short-term exposure to wind turbine noise on cognitive functions when tested at the neuronal and behavioral levels. Wind turbine noise neither lowered cognitive efficiency nor interfered with learning mechanisms (Figs. 4 and 5), nor changed the natural dynamics of brain waves for a given state (cognitive or rest, Fig. 3). Furthermore, this noise was not perceived as significantly more annoying or stressful than road traffic noise (Fig. 6 and Table 1), even when individuals exhibited maladaptive traits, such as low ambiguity tolerance (Fig. 7a), decreased reflection/epistemic self-focused thoughts (Fig. 7c), and high rumination/neurotic self-focused thoughts (Fig. 7b). Therefore, our initial hypothesis that exposure to wind turbine noise would detrimentally affect cognitive functioning was not validated. The other two hypotheses, namely that wind turbine noise would be perceived as more bothersome and stressful than road traffic noise and that psychological traits moderate its perception, were also not supported.

However, these null results do not negate the potential adverse influence of such noise on human brain processes or the fact that psychological diversity plays no role here. Instead, they indicate that under the conditions proposed in our approach, which are blind to the nature of the acoustic variable and thus detached from the social meanings attributed to wind turbine noise, such effects do not occur. It should be noted that, based on the ICBEN scale results, 14 out of 15 participants exposed to wind turbine noise rated their annoyance as either 0 ($n = 4$), 1 ($n = 3$), 3 ($n = 2$), or 4 ($n = 5$), indicating minimal disturbance, even in the presence of maladaptive or neurotic psychological traits. Only one individual rated their annoyance as high (at 7), despite a low score for rumination, but with low ambiguity tolerance and reflectivity. This implies that 93% of participants did not find wind turbine noise intrusive (Clark et al., 2021; Fields et al., 2001). As per previous studies, noise would negatively impact the neural dynamics of complex cognitive processes, sustained attention, and inductive reasoning only in case of high annoyance (Astuti et al., 2023; Muller et al., 2023; Pieper et al., 2021). The low annoyance (as well as stress) ratings observed in our exploration would be attributed to the fact that participants were unaware of the nature of the sounds they were exposed to (the procedure was blind, and no volunteers identified experimental sounds as wind turbine noise). Thus, they did not evaluate the noise from the perspective of socially constructed assertions or as a consequence of wind turbine syndrome mechanisms (Clark et al., 2020; Pierpont, 2009; Schaffer et al., 2016; Smith et al., 2020). As a result, they did not experience the nocebo effect (Crichton and Petrie, 2015), and we did not observe any impact of wind turbine noise on their cognitive functioning. This suggests that the sound pressure level of the wind turbine noise used in our study, i.e., 65 dB SPL, which mirrors real-world conditions and has no effect on the onset of hearing loss (Natarajan et al., 2023), does not directly threaten also human cognitive functioning. The real threat likely stems from socially constructed beliefs (Davy et al., 2020; Hanning and Evans, 2012; Hansen and Hansen, 2020; Lundheim et al., 2022; Takeuchi, 2023).

This interpretation is compatible with previous findings showing social contexts, such as socialization and misinformation, as a moderator of the interlinkage between wind turbine noise and human functioning (Miedema and Vos, 2003; Obuseh et al., 2025; Pohl et al., 2018; Ramalho et al., 2025; Schaffer et al., 2016). More broadly, it is consistent with approaches emphasizing that concerning wind turbines, the source of annoyance is rooted in non-acoustic variables (Ata Teneler and Hassoy, 2024; McCunney et al., 2014; Schmidt and Klokker, 2014). Nevertheless, further research is needed to confirm the proposed interpretation. For instance, our experiment could be replicated with a placebo-controlled condition, where beliefs are induced. Participants would be informed in one group that they would perform tasks amidst wind turbine noise. In another group, individuals would receive the same instruction but would not be exposed to wind turbine noise. Instead, they would listen to a non-annoying control sound (Klichowski et al., 2023). The results, correlated with psychological scales, could reveal the

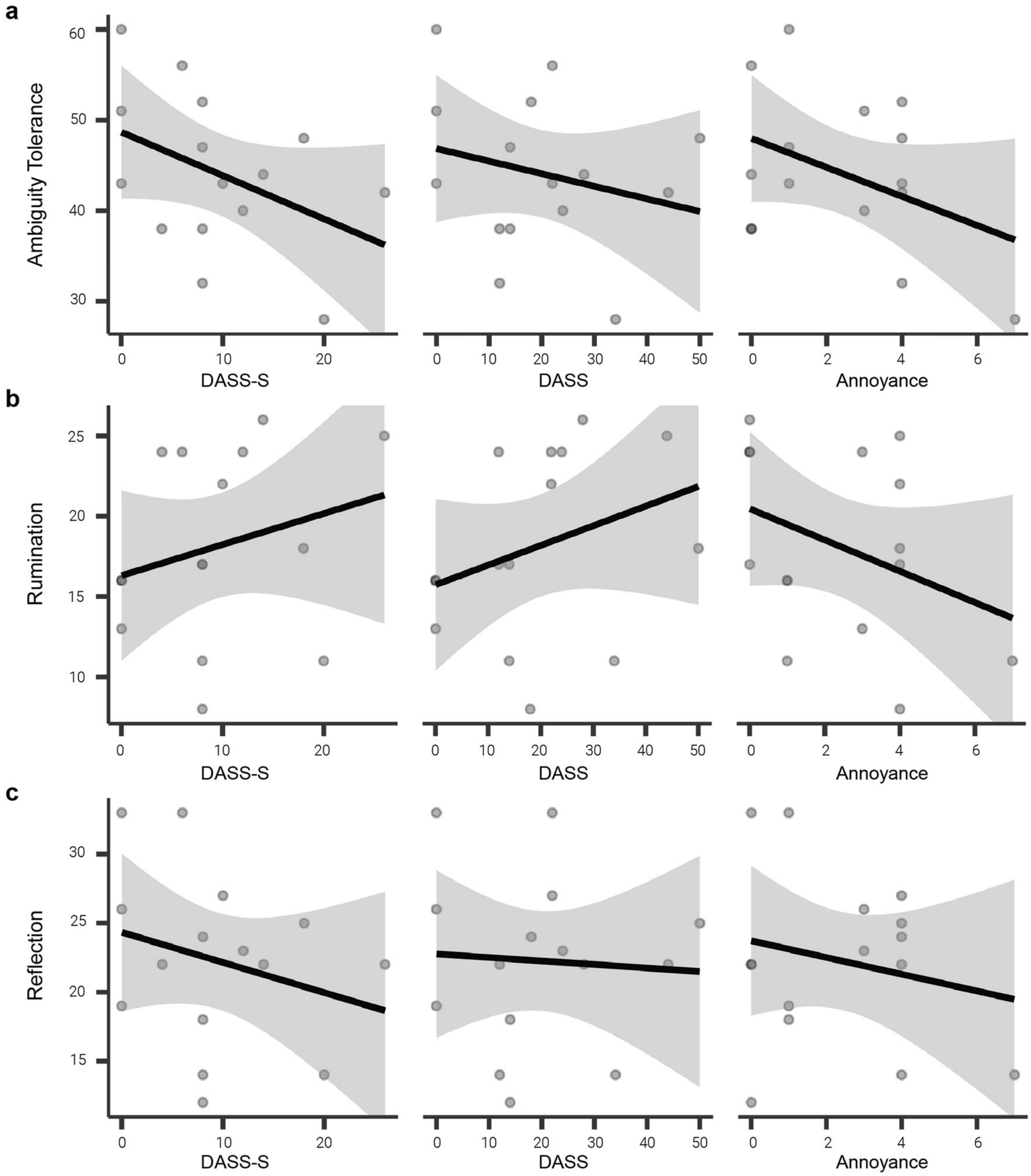

Fig. 7 Psychological underpinnings of wind-turbine-noise-induced stress and annoyance. a Pearson's correlation analyses show no relation between the level of ambiguity tolerance and wind-turbine-noise-induced stress and annoyance ($n = 15$). **b** Pearson's correlation analyses show no relation between the level of rumination and wind-turbine-noise-induced stress and annoyance ($n = 15$). **c** Pearson's correlation analyses show no relation between the level of reflection and wind-turbine-noise-induced stress and annoyance ($n = 15$). DASS is an abbreviation for Depression, Anxiety, and Stress Scale, while DASS-S for its stress subscale. The dark line represents regression of two variables, and shaded area shows standard error of the regression line.

personality profile of individuals susceptible to wind turbine syndrome; however, it would be necessary to ensure a more diverse and extensive sample than in our experiment (Clark et al., 2020; Crichton and Petrie, 2015; Schaffer et al., 2016; Smith et al., 2020; Taylor et al., 2013; Woodland et al., 2024).

Future research should also address the problem of the duration of noise exposure (Alamir et al., 2019; Merino-Martinez et al., 2021). We are uncertain whether we would observe no adverse effects if participants were exposed to noise longer, for example, for several hours. Yet, it is essential to emphasize that our goal was to investigate the direct impact of wind turbine noise on the dynamics of mechanisms controlling cognitive processes. Therefore, short-term exposure to wind turbine noise was appropriate here. Moreover, it was ecologically valid, as people sometimes find themselves where they need to perform short cognitive tasks near wind farms (not while living next to them). However, the results of our study cannot be extrapolated to more frequent situations where exposure to wind turbine noise is much longer (such as for individuals who work or live close to wind farms). Thus, it remains an open question whether prolonged exposure would lead to annoyance and, as a consequence, impair cognitive functions; alternatively, whether or not some habituation may occur in a long-exposure situation and minimize the annoyance (Mutschler et al., 2010). New studies are needed to answer these questions. Duration of exposure should be manipulated in them. Such experiments may take into account, for example, conditions with short exposure (as in our experiment), more prolonged exposure (e.g., 3–5 h), and extremely long exposure (e.g., 24 h). To objectively evaluate the impact of different exposure durations to wind turbine noise on various cognitive functions, a between-group study design should be chosen, and the measurement of cognitive process efficiency should be run at the end of each exposure type.

Some technical and operational contexts should also be considered in further experiments. The wind turbine noise used in the study was recorded during operation at a hub wind speed above 8 m per second. At wind speeds of 8 m per second and above, the turbine generates maximum noise levels, and the sound power level, which uniquely characterizes any sound/noise source, including wind turbines, ranges from 104 to 108 dBA (Hoen et al., 2023). Since the sound power level of any wind turbine reaches its maximum value at a wind speed of 8 m per second, measurements are made at this wind speed (Keith et al., 2016). Additionally, the 2 MW wind turbine is now widely used in wind farms, including in Poland (Talarek et al., 2022), and (Hoen et al., 2023) show that the difference in sound power level between a 2 MW turbine and a larger turbine (up to 5 MW) is at most 4 dB. Thus, it can be assumed that the wind turbine noise recording used in our study represents the situation when the turbine is 500 m away from the observer, reflecting maximum noise levels for such a distance (importantly, without the noise reduction provided by the building facade, Hu et al., 2022). Future studies should use recordings from different wind turbine models or those prepared under different operational conditions, such as starting multiple turbines or varying weather conditions, as additional conditions.

Conclusions

In this work, we proposed a cognitive neuroscience approach to experimentally and multifactorially explore the impact of wind turbine noise on various mental functions. The uniqueness of this approach lies in adopting multiple assumptions inspired by cognitive neuroscience methodologies while simultaneously adhering to psychoacoustic research standards previously used in wind energy development studies. In summary, this approach involves conducting highly controlled laboratory experiments using recognized tests and techniques to measure cognitive components associated with everyday mental tasks at both the behavioral and neuronal levels. Additionally, it requires constructing high ecological validity conditions, for example, by using actual recordings of wind turbine noise at volumes characteristic of natural situations as an experimental factor. The approach assumes that participants are blind to the nature and manipulation of acoustic variables and that all participants exhibit standard auditory perception across an extensive frequency spectrum. Furthermore, it includes the control of psychological variables (using reliable and standardized psychological tests) that could render wind turbine noise more annoying and stressful.

Using this approach, we conducted a pilot study, the results of which indicate that when participants are exposed to wind turbine noise with a sound pressure level corresponding to real-world situations (i.e., 65 dB SPL) without knowing that it is the sound of an operating wind farm, the noise does not adversely affect brain functions and is not perceived maladaptively, even when individuals have tendencies towards maladaptive thoughts. These results cannot be generalized; however, they support the concept that the interlinkage between exposure to wind turbine noise and human cognitive functioning is not a cause-and-effect relationship but is mediated by socially constructed beliefs about wind farms. Further development of this promising approach could advance research on the wind industry's impact on human cognition. Undoubtedly, subsequent studies must consider additional elements such as placebo-controlled conditions, manipulation of exposure duration, recordings from different wind turbine models prepared under various operational conditions, and diverse and extensive samples. The results of the studies using our approach extended with the above-mentioned additional procedure criteria could limit misinformation's role in decision-making or opinion-forming and increase the share of evidence in discussions among stakeholder groups, such as residents, policymakers, and energy developers. Additionally, they could help formulate reliable recommendations regarding wind energy policy.

Data availability

The anonymized data generated in the current study is available in the Open Science Framework database: https://osf.io/wpk4c.

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Author contributions

MK and AR conceived the study. AR, MK, AW, and MB designed the experiment. AR, AK, TP, GD-K, and MK performed the experiment. AR and MK analyzed the data, with GD-K and BBN aiding in data preparation. MK and AR wrote the manuscript with input from AW and MB, while AK prepared the figures. MK supervised the project's development at all stages and revised the manuscript.

Competing interests
The authors declare no competing interests. However, MK was a Collection Guest Editor for this journal at the time of acceptance for publication. The manuscript was assessed in line with the journal's standard editorial processes, including its policy on competing interests.

Ethical approval
This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Ethics Committee of the Faculty of Educational Studies at Adam Mickiewicz University, Poznan, on December 12, 2022 (Ethical Approval No. WSE-KEdsPB-03/2022/2023).

Informed consent
All participants provided written informed consent prior to the experiment.

Additional information
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