# THE SOUND OF THE ENVIRONMENT: EFFECTS ON BRAIN, COGNITIVE PERFORMANCE AND AFFECT

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by
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I hereby declare in lieu of oath

- that I have written this dissertation independently and without unauthorized assistance,
- that I have not submitted this dissertation to any other university and that I do not hold a doctoral degree in the subject pf psychology, and
- that I am aware of the doctoral regulations for the degree of Dr. rer. nat./Ph. D. in the Department of Education and Psychology at the Freie Universität Berlin dated August 8th, 2016 (official gazette of the Freie Universität Berlin 35/2016).

Hiermit erkläre ich an Eides statt,

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Emil Stobbe

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# List of included works

This doctoral dissertation is based on the following original works:

1. **Stobbe, E**., Lorenz, R. C., & Kühn, S. (2023). On how natural and urban soundscapes alter brain activity during cognitive performance. *Journal of Environmental Psychology, 91*, 102141.

2. **Stobbe, E**., Forlim, C. G., & Kühn, S. (2024). Impact of exposure to natural versus urban soundscapes on brain functional connectivity, BOLD entropy and behavior. *Environmental Research, 244*, 117788.

3. **Stobbe, E**., Sundermann, J., Ascone, L., & Kühn, S. (2022). Birdsongs alleviate anxiety and paranoia in healthy participants. *Scientific Reports*, *12*(1), 16414.

# List of abbreviations

| | |
|---|---|
| AFNI | Analysis of functional neuroimages |
| ANOVA | Analysis of variance |
| ART | Attention restoration theory |
| BEN | Brain entropy |
| BDS | Backward digit span |
| BOLD | Blood oxygen level dependent |
| CAPE | Community Assessment of Psychic Experiences |
| CRT | Conditioned restoration theory |
| DAN | Dorsal attention network |
| DMN | Default mode network |
| DNB | Dual n-back |
| FD | Framewise displacement |
| FC | Functional connectivity |
| FEW | Family-wise-error |
| FMRI | Functional magnetic resonance imaging |
| FOV | Field of view |
| IPL | Inferior parietal lobule |
| ISI | Inter-stimulus interval |
| MNI | Montreal neurological institute |
| MANOVA | Multivariate analysis of variance |
| MPFC | Medial prefrontal cortex |
| MPRAGE | Magnetization prepared gradient echo |
| MRI | Magnetic resonance imaging |
| NBS | Network based statistics |
| PANAS | Positive and negative affective scale |
| PCC | Posterior cingulate cortex |
| PAC | Primary auditory cortex |
| ROI | Region of interest |
| SART | Sustained attention to response task |

| | |
|---|---|
| SCL | Skin conductance level |
| SPM | Statistical parametric mapping |
| SPSS | Statistical Package for the Social Sciences |
| SRT | Stress reduction theory |
| STADI | State trait anxiety depression inventory |
| STG | Superior temporal gyrus |
| TE | Echo time |
| TE_ML | Two-error maximum length |
| TR | Repetition time |

# Summary

The steady increase in urbanization presents several challenges for humans, as they are forced to adapt to an environment that differs from the natural habitats in which they evolved. Consequently, studying the effects of this environmental shift on psychological well-being has become increasingly important. Especially the influences of environmental sounds seem understudied. Previous research has demonstrated that exposure to natural sounds can improve cognitive performance and positive affect while exposure to urban sounds was found to be detrimental. In order to facilitate the benefits of natural sound exposure, a deeper understanding of the underlying psychological and neural mechanisms is essential. The current dissertation sought to provide insights into these mechanisms by investigating the brain's response to environmental sounds via magnetic resonance imaging (MRI) and sub-clinical assessment of mental well-being.

In Paper I (Stobbe et al., 2023), the impact of exposure to natural versus urban soundscapes on brain activity during cognitive performance was assessed. It was found that performance gains in a working memory task were associated with a reduction of activity in the medial prefrontal cortex (mPFC) proposing facilitated information processing in a subregion of the frontal executive network following exposure to a natural soundscape. Moreover, the reduction of negative emotions was linked to reduced activity in the inferior parietal lobule (IPL), a region that is part of the cognitive control network, suggesting that cognitive processes required less effort and elicited fewer negative emotions following the exposure to the natural soundscape condition.

In Paper II (Stobbe et al., 2024), the effects of natural versus urban sounds on brain entropy (BEN) and functional connectivity (FC) during the sound exposure was examined. It was demonstrated, that the brain's signal complexity, or BEN, in the posterior cingulate cortex (PCC) was significantly higher while participants listened to the urban soundscape. The increased BEN was found to be associated with a reduction of positive emotions in the urban soundscape condition, suggesting that the dislike of urban sounds might be represented by high signal complexity within the PCC. Additionally, it was discovered that FC in the auditory brain network was greater during exposure to natural soundscape compared to urban soundscape. This increment of FC was found to be associated with a performance gain on two working memory tasks, indicating that exposure to natural sounds could facilitate the brain's processing efficiency via increased FC within a task relevant network.

In Paper III (Stobbe et al., 2022), the influence of birdsongs versus traffic noise on depressive, anxious and paranoid states was investigated. It was found that while traffic noise exposure heightened the depressive states of healthy participants, exposure to birdsongs alleviated anxious and paranoid states in the same sample. These results suggest a possible explanation for the high prevalence of mental illness in urban areas while they simultaneously provide insights into how natural sounds such as birdsong could potentially be utilized to prevent the emergence mental illness.

In conclusion, the present dissertation complements the debate on whether exposure to natural sounds can lead to improvements with respect to cognition and mental well-being and provides insights into possible mechanisms that underlie these benefits. These insights could contribute to more effective natural sound interventions and highlight the potential hazards of urban noise pollution.

# Zusammenfassung

Die stetige Zunahme der Urbanisierung stellt für Menschen mehrere Herausforderungen dar, da sie sich an eine Umgebung anpassen müssen, die sich von den natürlichen Lebensräumen unterscheidet, in denen sie sich entwickelt haben. Folglich ist die Erforschung der Auswirkungen dieses Umweltwandels auf das psychische Wohlbefinden zunehmend wichtiger geworden. Insbesondere die Einflüsse von Umgebungsgeräuschen scheinen wenig untersucht zu sein. Frühere Untersuchungen haben gezeigt, dass die Exposition gegenüber natürlichen Geräuschen die kognitive Leistungsfähigkeit und das positive Befinden verbessern kann, während die Exposition gegenüber städtischen Geräuschen nachteilig war. Um die Vorteile der Exposition gegenüber natürlichen Geräuschen zu fördern, ist ein tieferes Verständnis der zugrunde liegenden psychologischen und neuronalen Mechanismen unerlässlich. Die vorliegende Dissertation hatte zum Ziel, Einblicke in diese Mechanismen zu liefern, indem sie die Reaktion des Gehirns auf Umgebungsgeräusche mittels Magnetresonanztomographie (MRT) und der subklinischen Bewertung des psychischen Wohlbefindens untersuchte.

In Paper I (Stobbe et al., 2023) wurde der Einfluss der Exposition gegenüber natürlichen versus städtischen Klanglandschaften auf die Hirnaktivität während kognitiver Leistungsfähigkeit untersucht. Es wurde festgestellt, dass Leistungsgewinne bei einer Arbeitsgedächtnisaufgabe mit einer Reduktion der Aktivität im medialen präfrontalen Kortex (mPFC) verbunden waren, was auf eine erleichterte Informationsverarbeitung in einem Teilbereich des frontalen exekutiven Netzwerks nach Exposition gegenüber einer natürlichen Klanglandschaft hinweist. Darüber hinaus wurde die Reduktion negativer Emotionen mit einer verminderten Aktivität im unteren Parietallappen (IPL), einer Region, die Teil des kognitiven Kontrollnetzwerks ist, in Verbindung gebracht, was darauf hindeutet, dass kognitive Prozesse nach Exposition gegenüber der natürlichen Klanglandschaft weniger Anstrengung erforderten und weniger negative Emotionen hervorriefen.

In Paper II (Stobbe et al., 2024) wurden die Auswirkungen von natürlichen versus städtischen Geräuschen auf die Gehirnentropie (BEN) und die funktionelle Konnektivität (FC) während der Schallexposition untersucht. Es wurde gezeigt, dass die Signal-Komplexität des Gehirns, oder BEN, im hinteren cingulären Kortex (PCC) signifikant höher war, während die Teilnehmer der städtischen Klanglandschaft zuhörten. Die erhöhte BEN wurde mit einer Reduktion positiver Emotionen in der städtischen Klanglandschaft in Verbindung gebracht, was darauf hindeutet, dass die Abneigung gegenüber städtischen Geräuschen durch hohe

Signal-Komplexität im PCC repräsentiert sein könnte. Darüber hinaus wurde entdeckt, dass die funktionelle Konnektivität im auditiven Gehirnnetzwerk während der Exposition gegenüber natürlichen Klanglandschaften im Vergleich zu städtischen Klanglandschaften größer war. Dieser Anstieg der funktionellen Konnektivität wurde mit einem Leistungsgewinn bei zwei Arbeitsgedächtnisaufgaben in Verbindung gebracht, was darauf hinweist, dass die Exposition gegenüber natürlichen Geräuschen die Verarbeitungseffizienz des Gehirns durch eine erhöhte funktionelle Konnektivität innerhalb eines für die Aufgabe relevanten Netzwerks erleichtern könnte.

In Paper III (Stobbe et al., 2022) wurde der Einfluss von Vogelgesängen im Vergleich zu Verkehrslärm auf depressive, ängstliche und paranoide Zustände untersucht. Es wurde festgestellt, dass während die Exposition gegenüber Verkehrslärm die depressiven Zustände gesunder Teilnehmer verstärkte, die Exposition gegenüber Vogelgesängen ängstliche und paranoide Zustände in derselben Stichprobe milderte. Diese Ergebnisse legen eine mögliche Erklärung für die hohe Prävalenz von psychischen Erkrankungen in städtischen Gebieten nahe, während sie gleichzeitig Einblicke geben, wie natürliche Geräusche wie Vogelgesang möglicherweise genutzt werden könnten, um das Auftreten psychischer Erkrankungen zu verhindern.

Zusammenfassend ergänzt die vorliegende Dissertation die Debatte darüber, ob die Exposition gegenüber natürlichen Geräuschen Verbesserungen hinsichtlich der kognitiven Leistungsfähigkeit und des psychischen Wohlbefindens bewirken kann, und liefert Einblicke in mögliche Mechanismen, die diesen Vorteilen zugrunde liegen. Diese Erkenntnisse könnten zu effektiveren Interventionen mit natürlichen Geräuschen beitragen und die potenziellen Gefahren durch städtische Lärmbelastung verdeutlichen.

# Contents

*Chapter 1.*

# GENERAL THEORETICAL AND EMPIRICAL BACKGROUND

The human species evolved in a rural environment. In just a fraction of its existence, small towns evolved into cities. Within the next 30 years, it is expected that this percentage will increase to as much as 70% (Gross, 2016). This shift in habitat, which occurs at an unprecedented pace in the context of human history, presents various challenges. Therefore, studying the effects of urbanization is more important than ever. To investigate the effects of urbanization on humans systematically, it is necessary to conduct research that illuminates the impact of experiencing natural versus urban environments.

## 1.1 Studying the effects of urbanization

One of the first concepts regarding the psychological impact of urbanization is called the biophilia hypothesis in which American ecologist E. O. Wilson defines biophilia as the innate tendency of humans to center on and connect to life-forms and like-like processes. He further claims that this connection is the outcome of a long history of human evolution in a natural environment where contact with, and reliance on life-forms was essential for survival and reproduction. Wilson consequently argues, that the human brain requires contact with natural environments in order to develop normally (Wilson, 1984). In the field of environmental psychology other theoretical accounts emerged, focusing on explanations for the effects that exposure to nature elicited. The hospital window-view experiment is a well-known example that demonstrated that surgical patients had shorter postoperative hospital stays when they had a window-view of a natural scenery compared to those whose window faced a brick wall (Ulrich, 1984). Ulrich's explanation for this effect is related along the lines of the biophilia hypothesis. He claims that contact with nature has been evolutionarily associated with reduced stress and arousal due to survival-signaling cues that natural environments possess, such as food, shelter and other resources. Based on this concept, stress reduction theory (SRT) was formulated. Research investigating the recovery effects of environments distinguishes between natural and urban environments (Ulrich et al., 1991). This represents the physical settings to which individuals are exposed. Both settings have been shown to possess different visual properties eliciting distinct affective and perceptual responses (Kaplan et al., 1972).

Ulrich and colleagues (1991) present studies that focus on the recovery effects of outdoor environments by distinguishing between natural and urban environments. Their evidence demonstrates how differences in visual properties of these environments can elicit different patterns of affective responses and play a crucial role in their perception.

It is now understood that differences in auditory properties of environments can elicit similar changes in affective and cognitive responses. However, in comparison to the visual domain, the auditory domain remains understudied (Ratcliffe, 2021), despite the existence of various known health hazards from urban noise pollution.

## 1.2 Effects of urban noise on health

When humans are born, they are very sensitive. While they will close their eyes in reaction to light, they cannot close their ears in reaction to loud noise. The abrupt change of the auditory environment from silence in the womb to the extreme noisy hospital raises a growing concern of interference with the development of prematurely born infants in terms of cognitive abilities (McMahon et al., 2012). Even when growing up humans have limited capacities to block out surrounding noise completely. Considering the aforementioned example of babies, urbanization could be seen as a similar transition from living in a mostly quiet natural environment to life in a noise-polluted urban world, which has been demonstrated to elicit detrimental effects on health-related factors. Exposure to urban noise interferes with the restorative function of sleep and relaxation even on a subconscious level (Muzet, 2007), resulting in associated health impairment (Raschke, 2004) and increased risks of injury and accident (Babisch, 2005). Urban noise exposure has also been shown to cause increases in heart rate and blood pressure (Stansfeld et al., 2000).

Regarding mental health, urban noise pollution has been shown to be detrimental as well. Noise annoyance at work is linked to depressive symptoms and suicidal thinking (Yoon et al., 2014) and a meta-analysis of residential traffic noise and mental health revealed that aircraft noise increases depression risk by 12% per 10dB (Hegewald et al., 2020).

In addition to general and mental health, urban noise exposure is also known to disrupt attentional performance in direct comparison with natural sounds (Van Hedger et al., 2019). On top of that it has been demonstrated that urban noise pollution can cause decreased learning ability, concentration deficits (Hammer et al., 2014; Stansfeld et al., 2005) and working memory problems from a neurological perspective (Cheng et al., 2019). Lastly, urban noise was found to be associated with psychosocial (Leather et al., 2003), physiological stress (Daiber et al., 2019; Hahad et al., 2019) and mood (Correia et al., 2013). The numerous disadvantages of engaging with urban noise highlight the need for humans to seek exposure to alternative soundscapes to counteract these negative effects. In the common sense this can be seen as taking a break from the sound of rushing cars while strolling through the park accompanied by the song of birds and the subtle sound of wind rattling through the leaves of a tree.

## 1.3 Effects of natural sounds on health

Exposure to natural sounds such as water, bird song, insects or wind has been established to elicit positive health related effects in various domains. In a study on stress recovery, natural sounds of a water fountain and singing birds facilitated recovery of the skin conductance level (SCL) during the sound exposure compared to the noisy traffic sounds, following induced stress in the participants. These effects were found after participants had performed a stressful mental arithmetic task and the authors suggest that natural sounds seem to foster the recovery of sympathetic nervous system activation after a stressful experience (Alvarsson et al., 2010). Birdsongs have also been reported to be perceived as the natural sound that is most commonly related to stress recovery and attention restoration (Ratcliffe et al., 2013). Several factors were found to influence the perceived restorative value of bird sounds. Bird sounds associated with joyful events increased the perceived restorative value, while negative affect appraisals of certain bird species decreased the perceived restorative value of this listening experience. Furthermore, reports on the perception of bird sounds in terms of restorative value indicate that cognitive appraisals may also be a factor. Participants described the sound of a bird as “a source of alternative focus”. Additionally, bird sounds were perceived as easily attenable and novel, providing a restorative value in the sense of being distant from everyday environments (Ratcliffe et al., 2013). The perceived pleasantness of natural sound elements such as water sound and bird sounds were revealed to increase self-reported restoration from tiredness and to reduce annoyance in an open-plan office environment. Taking into account the comparison between visual and auditory elements in this simulated environment, it has been shown that sound elements have a greater impact on psychological restoration (Ma & Shu, 2018). The idea that subjectively pleasant sound stimuli can mask the negative effects of a noisy environment was supported by a study showing a significant increase of self-reported pleasantness of a traffic noise environment masked by the occurrence of birdsong elements within the noisy environment (Hao et al., 2016). Moreover, the physiological effect of natural sound exposure at rest was demonstrated to be influenced by the subjective perception of that sound.

Subjectively pleasant sounds were proven to decrease skin conductance levels in contrast to subjectively unpleasant sounds (Medvedev et al., 2015).

Considering the effect of natural sound in other psychological domains, it has been indicated that mood recovers to a greater extent when participants are exposed to a brief period of natural sounds after watching a disturbing video compared to the same natural audio that also contains human voices and traffic sounds (Benfield et al., 2014). Buxton and colleagues' meta-analysis supports the previously described health benefits of exposure to natural sounds. The meta-analysis findings indicate that exposure to natural sounds can lead to improved health, positive affect and reduced stress and annoyance. Water sounds were found to have the greatest impact on health and positive affect, while birdsong was found to be most effective in alleviating stress and annoyance (Buxton et al., 2021).

With regard to changes in cognitive performance following natural sound exposure, the current literature reveals ambiguous results. Despite showing that natural sounds were rated as more relaxing compared to their urban counterparts, Emfield & Neider (2014) found no significant differences in cognitive performance following exposure to natural or urban sounds. The cognitive battery used in their study comprised several attention and working memory tasks, none of which revealed any effect related to the natural or urban sound category. In another study however, natural sound exposure did lead to greater performance in a working memory task. Importantly this performance gain only approached statistical significance and should be treated with caution (Abbott et al., 2016). In yet another investigation on the cognitive effects of listening to natural versus urban soundscapes, van Hedger and colleagues (2019) found a significant performance improvement after subjects listened to natural soundscapes (13 minutes). Furthermore, research has shown that exposure to natural sounds, such as water and bird songs, can improve cognitive performance in school children. Specifically, listening to these sounds has been linked to faster responses in the sustained attention to response task (SART) and better working memory performance, as assessed by the digit span task (Shu & Ma, 2019). The SART requires participants to refrain from making behavioral responses to an infrequent and unpredictable target while engaging in a phase of prompt and rhythmic responses to frequent nontargets (Shu & Ma, 2019). In an experiment by Zhang and colleagues (Zhang et al., 2017) Chinese university students were exposed to a restoration experience by spending 40 minutes in one of three zones outdoors. The zones were categorized as containing natural sound, machinery sound and traffic sound. After performing an attentional fatigue inducing reasoning test participants' attentional capacity was measured via a complement test in which subjects needed to identify pairs of adjacent numbers adding up to 10. The more pairs identified, the higher the attention level was graded. The results reveal that participants who spent their time in the natural sounds zone had significantly higher attentional restoration levels than those spending the same time in the machinery or traffic sound zones (Zhang et al., 2017).

## 1.4 Natural sounds and the brain

In order to facilitate research on the health-related effects of exposure to natural versus urban sounds it is essential to engage in a neuroscientific approach. Understanding the neural mechanisms underlying the benefits associated with natural sound exposure can lead the way towards tailored interventions and experiences with nature that maximize these benefits. The lack of research on these neural mechanisms emphasizes the need for further studies to investigate them. One approach is focusing on the brain's default mode network (DMN). The default mode network is a large-scale brain network mainly comprised of two frontal brain regions (medial prefrontal cortex (mPFC) and posterior cingulate cortex (PCC)) the precuneus and the angular gyrus. The DMN is activated during periods of wakeful rest, commonly termed mind-wandering and deactivated during task performance (Gould Van Praag et al., 2017). A study by Gould Van Praag and colleagues (2017) investigated the activity and functional connectivity (FC) of the DMN during natural versus urban sound exposure. FC refers to the coherence between brain regions that share functional properties. The results reveal a shift from anterior to posterior FC during exposure to naturalistic sounds. This change was accompanied by an increase in heart rate variability signaling heightened parasympathetic activation. The authors argue that based on the balanced relationship between parasympathetic and sympathetic nervous system activations that an increase in the former suggest a decrease in the latter showing that natural sound exposure causes changes in the DMN connectivity in addition to a reduction in autonomic activity. In line with that a recent study on visually presented natural versus urban stimuli revealed differences in FC between the default mode network and the dorsal attention network (DAN). While subjects were viewing photos of natural environments FC was shown to be significantly higher between these two networks compared to the urban photo condition (Kühn et al., 2021). In another study, it was shown that sounds originating from a living vs a man-made source elicit connectivity differences in various brain regions (prefrontal cortex, anterior-superior temporal gyrus, posterior cingulate cortex and supramarginal gyrus) shortly after the sound onset. The authors suggests that these types of sounds are processed in distinct cortical networks, creating the opportunity to illuminate the functional mechanisms behind these networks in future studies (Salvari et al., 2019). The current lack of such studies complicates the formulation of concrete hypotheses and theories that aim to explain the neural mechanisms behind the positive effects of exposure to natural sounds compared to urban sounds. Current theoretical accounts rather focus on the psychological mechanisms behind these effects and will be reviewed in the next section.

## 1.5 Current theories and implications

In the history of environmental psychology two theories have been prominent since the 1980's. While one theory suggests an affective mechanism for the beneficial effects of exposure to nature (SRT) the other theory claims the mechanism to be cognitive (Attention restoration theory). Currently, yet another account has been established trying to explain the positive effects of nature exposure via a different route. In the following section these theories will be introduced in detail.

Ulrich's (1991) stress reduction theory (SRT) proposes an evolutionary perspective to explain the positive effects of nature. Central in his view resides the fact, that humans evolved in natural environments over a long period of time becoming physiologically and psychologically adapted to this type of environment. Ulrich claims that the human initial reaction towards natural environments is affective which resides in the fact that affective responses have evolved to be fast and quick in guiding survival-oriented decisions in new environments. Support for this comes from the fact that evaluations of liking or disliking a stimulus are independent of its recognition (Zajonc, 1980). In terms of natural environments, Ulrich proposes that natural stimuli such as water or vegetation can produce visual ambiances eliciting affective responses prior to identification (Ulrich, 1983). Moreover, he highlights a combination of two mechanisms to explain the differential reactions to natural and urban stimuli. Individuals often make more positive experiences in natural settings compared to urban environments, particularly during leisure time or vacations. In addition he states that reactions to environments are affected by instincts which evolved in order to guide survival-oriented behavior (Ulrich, 1983). In the theoretical account on stress reduction following exposure to natural environments, a fundamental proposition is that the preconscious process of responding to an environment has evolved to be adaptative, such that it motivates the appropriate behavior to facilitate ongoing well-being and survival. Such adaptive responses can range from stress and avoidance behavior to restoration and approach behavior, states Ulrich (1991). Natural settings that signal the existence of elements favorable for survival such as nutrition or shelter elicit a restorative response leading to a reduction in physiological arousal. According to Ulrich, acquiring the capacity to have a restorative response to low-risk natural environments provided a major evolutionary advantage for survival. Consequently, humans possess an instinctive response to many unthreatening natural environments while there is no such response to most of the built and urban settings (Ulrich et al., 1991).

Attention restoration theory (ART), as posited by Kaplan (1992), is grounded in the distinction between two attentional mechanisms: involuntary attention and directed attention. William James (1892) defined involuntary attention as the form of attention elicited by stimuli that provoke excitement, rendering the utilization of this capacity effortless. Directed attention on the other hand does require effort in order to selectively focus on or guide higher order information processing such as planning or problem solving (Kaplan, 1992). In contrast to involuntary attention, directed attention is under voluntary control. In the field of environmental psychology, involuntary attention has previously been referred to as undirected attention (Stevenson et al., 2018), highlighting the difference between the two mechanisms. Kaplan argues that the modern world imposes a high pressure on attentional demands. This represents a significant departure from the demands of rural environments, where humans evolved. "The emphasis on efficiency and productivity, coupled with recent technological advancements, has tended to reduced or eliminate the moments of rest that were at one time a natural part of everyday life" (Kaplan, 1992). According to Kaplan, as a consequence of urbanization humans are forced to exert more effort employing directed attention with a higher frequency resulting in mental fatigue. This mental fatigue can be counteracted by a restorative experience helping to recover from the fatigue. The recovery process relies on the "model" (Kaplan, 1992) of the current situation and how easily it can be processed. The degree to which the existing model can be executed without effort depends on the environment's "cooperation" (Kaplan, 1992). In ART the environmental cooperation depends on four main aspects. These aspects encompass "being away", "extent", "fascination" and "compatibility". Being away refers to the opportunity to rest the mind from daily life which is supported by settings that provide distance to the everyday environment. The extent of an environment needs to be perceived as large enough while still belonging to a larger whole providing a model to effortlessly process the current situation. Fascination within an environment allows the individual to restore directed attention because contents are attended to involuntarily due to their fascinating properties. Environments are perceived as compatible when their requirements align with the individuals' goals and aims, e.g., concentrating on one's thoughts during a tranquil walk through the forest. Kaplan suggests that an environment providing these aspects is most efficient in restoring directed attention and thereby counteracting mental fatigue (Kaplan, 1992). According to ART, natural environments tend to provide these aspects inherently, giving rise to the restorative experience and resulting in the well-known positive effects of interacting with nature.

Recently, a critical statement regarding ART was published. Results obtained from studies centered around testing ART are frequently interpreted within the framework of an attentional recovery process suggesting that improved performance, following attentional fatigue, is directly related to attentional recovery. Because most of these studies are lacking a non-fatigue control group it becomes impossible to attribute nature's positive effects to an entirely distinct and unrelated process. Critics suggest that natural environments could have an energizing potential (Ryan et al., 2010) that can enhance individuals' performance beyond a baseline level (Joye & Dewitte, 2018). This is supported by a study that demonstrates a nature-related benefit in self-regulation, regardless of whether subjects were ego-depleted or not (Beute & de Kort, 2014). Following up on this, another theory trying to explain nature-related benefits was developed. Conditioned restoration theory (CRT) proposes that the restorative effects of natural environments can be explained by conditioning and associative learning (Egner et al., 2020). Initially, individuals undergo a process of conditioning that establishes an association between nature and a sense of relaxation. Consequently, when exposed to nature thereafter, the conditioned response prompts a state of relaxation. Within this framework, interactions with nature produce relaxation through the type of activity commonly carried out in that environment. Activities such as hiking, exploring or experiencing wildlife are disconnected from the typical everyday life and social constructs. Egner and colleagues posit a mechanism behind their theory which is well known in behavioral psychology. This mechanism is similar to classical conditioning but focuses more on the conditioning of emotions and less on behavior. The process that they refer to is called evaluative conditioning. In the context of leisure activities in nature, the positive emotions resulting from these activities are conditioned to the environment in which they were elicited (Egner et al., 2020). Alluding from this, if positive emotions have been conditioned to natural environments throughout childhood, this conditioning will remain positive until multiple negative experiences are conditioned to the same environment. Importantly, in the field evaluative conditioning it has been shown that some stimuli are faster to condition than others (Egner et al., 2020). These preexisting conditions, or instincts in Ulrich's (1983) words, are also demonstrated by prospect-refuge theory (Appleton, 1996) which suggests that humans have an innate liking for places providing an overview of the scenery while being hidden to some degree. Such preexisting conditions imply a process where the described conditioning can be actively fine-tuned by these instincts (Egner et al., 2020). Within CRT these preexisting conditions are treated as additional reinforcers of the conditioning process fostering the conditioning. However, such conditions can still be overwritten by new experiences. Egner and colleagues (2020) give the example of a field of flowers where someone gets bitten by a snake and dies. It would be naturally very ineffective to not be able to overwrite that this environment has previously been conditioned to be safe and restorative. Referring back to the theories mentioned above (ART & SRT), which state that nature inherits sensory characteristics that should elicit restoration regardless of prior experiences or beliefs towards nature, it is worth noting that restorative effects have been demonstrated to a lesser degree in people who are in contact with nature during non-leisure purposes, such as occupational engagement (Egner et al., 2020). This evidence contradicts ART & SRT and is rather in line with CRT. However, CRT acknowledges the environmental qualities mentioned by ART (“being away”, “extent”, “fascination” and “compatibility”) as these are strongly associated with how core affect is linked to exposure to natural environments. Egner and colleagues (2020) conclude that CRT does not compete with ART & SRT but merely offers to explore a previously unexplained mechanism behind the restorative effects of nature.

### 1.6 Objectives and scope of the dissertation

The presented dissertation aims to fill a research gap by exploring the psychological and neural mechanisms that underlie the positive effects of exposure to natural versus urban soundscapes. Because there is currently limited understanding of the neural mechanisms underlying the effects of natural versus urban soundscapes on the brain, the first paper aims to replicate a previously demonstrated cognitive performance improvement following exposure to natural soundscapes (Van Hedger et al., 2019). Additionally, the paper seeks to complement existing research by investigating neural activity, by means of functional magnetic resonance imaging (fMRI), before and after exposure to these soundscapes. This approach addresses the question whether brain activity during an attention-demanding task, following exposure to natural versus urban soundscapes, manifests in brain activation differences. Additionally, it seeks to provide information to evaluate the current theoretical debate about the psychological mechanisms involved in nature-related restoration effects. The first paper was designed to answer the question whether nature-related benefits can be explained by variations in neural information processing. To investigate this from a neuroscientific perspective, the study examined whether there were differences in neural activity following exposure to natural versus urban soundscapes and, more specifically where those differences were located in the brain. Anticipated disparities in brain activity arising from attention-associated neural regions are hypothesized in accordance with ART, while affective or stress-processing-related brain regions are posited to exhibit conditional differences following SRT.

The second paper aims to enlighten this question through the investigation of differences in brain FC and brain entropy (BEN) during the exposure to the soundscape types (natural versus urban). BEN is a quantification of the brain's signal variability interpreted as its information processing capacity (Keshmiri, 2020). In this second paper it was hypothesized that exposure to natural versus urban soundscapes will result in different levels of FC and BEN during the exposure. Concerning the anticipated alterations in FC or BEN associated with soundscape exposure, a more exploratory and data-centric methodology was adopted. This approach refrained from formulating a directional hypothesis due to the limited extent of prior literature in this research domain. Furthermore, the aim of this study was to investigate whether there is a relationship between the expected differences in FC or BEN and changes in the behavioral variables of cognitive performance and affect, as assessed in the first paper.

To summarize, this series of studies aimed at unraveling the impact of natural versus urban soundscape exposure on the human mind, the focus now shifts to the effects of these soundscapes on psychological well-being. The third paper presented in this dissertation centers on the general question whether exposure to natural (birdsong) versus urban (traffic noise) soundscapes affect mental health related tendencies. The paper aimed to investigate the effect of listening to birdsong versus traffic noise soundscapes on paranoid, depressive and anxious mental states in healthy subjects. Due to the higher prevalence of schizophrenic, depressive and anxious symptoms of people living in urban areas (Penkalla & Kohler, 2014; Sampson, L., Ettman, C. K., & Galea, 2020; Vassos et al., 2012) and the known positive effects of natural sounds, especially birdsongs on human well-being (Methorst et al., 2021; Murgui & Hedblom, 2017; Ratcliffe, 2021) it was hypothesized that exposure to a birdsong (vs. traffic noise) soundscape has a beneficial effect on mood and paranoia. Based on the behavioral experiment by van Hedger and colleagues (2019), it was also hypothesized that listening to the birdsong (vs. traffic noise) soundscape would enhance cognitive performance in the backward digit span and the dual n-back task. Furthermore, the paper sought to ascertain whether the variation in the diversity of bird species or traffic noise sources within the soundscapes, particularly in the context of greater as opposed to lower diversity, would constitute a significant factor in relation to the dependent variables.

*Chapter 2.*

# SNYOPSIS OF RESULTS

## 2.1 Paper I

**Stobbe, E**., Lorenz, R. C., & Kühn, S. (2023). On how natural and urban soundscapes alter brain activity during cognitive performance. *Journal of Environmental Psychology, 91*, 102141.

### *2.1.1 Summary*

The primary focus of Paper I was the exploration of neural mechanisms underlying enhanced cognitive performance following exposure to natural soundscapes in contrasts to urban soundscapes. To achieve this, the investigation sought to reproduce the behavioral effect observed in van Hedger et al.'s (2019) research, while acquiring brain imaging data during task execution. In their experiment, participants showed significantly improved performance in a composite score of the backward digit span and the dual n-back task after exposure to natural soundscapes compared to their performance after exposure to urban soundscapes (Van Hedger et al., 2019). Consequently, in Paper I participants performed both of the mentioned tasks within the fMRI scanner after exposure to the natural, urban or no sound intervention. Additional behavioral variables assessed participant's positive and negative emotions (PANAS), stress reactivity (PSS) and their aesthetic judgment of the soundscape intervention. Analysis of the cognitive performance revealed no significant differences between the sound conditions, when both tasks were examined separately. When both tasks' performances were combined into a composite score, as done in the study presented by van Hedger et al. (2019), natural soundscapes did lead to a better performance compared to the urban or no sound conditions, however the interaction effect did not reach significance. Concerning participants affect before and after the soundscape interventions, Paper I revealed a significant reduction of negative emotions following the exposure to the natural soundscape. Moreover, participants evaluated the natural soundscape significantly more aesthetic compared to the urban or no sound condition. For the purpose of fMRI analysis, the DNB task comprised single-modality blocks presenting either visual or auditory information, as well as dual-modality blocks presenting both information at the same time. Analysis of the BOLD signal during the execution of the dual modality blocks of the DNB task, indicated an interaction effect within an uncorrected cluster in the superior temporal gyrus (STG) (nature vs urban comparison). While activity in that region was shown to increase following the urban soundscape exposure activity in the nature condition decreased after the sound intervention. The uncorrected cluster was shown to be located within the auditory processing stream. As part of a follow-up analysis the behavioral data from the DNB task's dual modality blocks was analyzed separately unveiling a significant interaction effect. Pairwise comparisons between the sound conditions demonstrated a significant performance increase after exposure to the natural sound condition in this sub-part of the task. Intending to examine the relationship between subject's behavior and the changes in neural activity two whole brain regression analyses considering the behavioral change as a covariate were performed. A negative correlation was observed between cognitive performance gain (post-pre) in the natural soundscape condition from the DNB task and brain activity changes in the medial prefrontal cortex (mPFC) during the same task and condition. Furthermore, it was unveiled that the reduction of negative emotions (post-pre, PANAS) in the natural soundscape condition was positively correlated with brain activity changes (DNB task, natural sound condition) in the inferior parietal lobule (IPL) region.

## 2.2 Paper II

**Stobbe, E**., Forlim, C. G., & Kühn, S. (2024). Impact of exposure to natural versus urban soundscapes on brain functional connectivity, BOLD entropy and behavior. *Environmental Research, 244*, 117788.

### *2.2.1 Summary*

This data analysis was conducted on the same study as the previous one, but with a focus on brain connectivity measures during exposure to natural and urban soundscapes. Specifically, BEN and FC were examined. Subsequently, the observed differences were correlated with relevant behavioral variables, providing an integrated examination of the interplay between auditory environments and neural and behavioral responses. A significant difference in brain entropy was observed among the three experimental conditions (nature sound, urban sound, and no sound) in a cluster spanning the posterior cingulate gyrus, cuneus, precuneus, and occipital lobe/calcarine. More specifically, this cluster exhibited higher BOLD signal complexity (brain entropy) when subjects were exposed to the urban soundscape condition. With respect to brain FC, the analysis revealed lower FC between areas in the auditory, cinguloopercular, and somatomotor hand and mouth networks while subjects were exposed to the urban sound condition. A subsequent analysis, examined the relationship between the conditional differences in brain entropy and brain FC and relevant behavioral variables including cognitive performance (DNB & BDS task) and positive as well as negative affect (PANAS). The results revealed a negative correlation between the subject's brain entropy levels and the change in positive emotions before and after exposure to urban sounds. This demonstrates that higher levels of brain entropy might be associated with a greater decrease in positive emotions when exposed to urban sounds. Pertaining to the correlation between the mean FC during exposure to the natural sounds and the performance gain of the DNB and BDS task composite score, a positive relationship was established. Thus, greater FC in the aforementioned networks during natural sound exposure correlates with an increased cognitive composite score following exposure to natural sounds.

## 2.3 Paper III

**Stobbe, E**., Sundermann, J., Ascone, L., & Kühn, S. (2022). Birdsongs alleviate anxiety and paranoia in healthy participants. *Scientific Reports*, *12*(1), 16414.

### *2.3.1 Summary*

Paper III investigated the effect of exposure to birdsong versus traffic noise on states of depression, anxiety, and paranoia, alongside cognitive performance. Additionally, in order to explore the role of content diversity within a soundscape, both types of sounds (birdsong vs. traffic noise) were administered with different levels of diversity. The diversity of both soundscapes was modulated by the number of sound sources present in each soundscape. The diverse traffic soundscape included not only cars but also other vehicles and traffic related noises. Similarly, the diverse birdsong soundscape consisted of eight different birds instead of only two. The experiment utilized state versions of mood (anxiety & depression) and paranoia scales in order to inspect the tendencies of healthy subjects towards these outcomes. With regard to the assessment of cognitive performance the BDS and DNB task were employed. Moreover, the participants' evaluation of the soundscape was measured in terms of its diversity/monotony, aesthetic appeal, and pleasantness. Although the high diversity traffic soundscape was not perceived as monotonous as the low diversity traffic soundscape, no significant difference was observed between the low and high diversity birdsong soundscapes. Both types of birdsong soundscapes (low vs. high diversity) were perceived as significantly more pleasant and beautiful compared to both traffic noise conditions. Concerning the depression measure, participants reported a significant increase in depressive states after listening to the high and low diversity traffic noise soundscapes. Regarding the exposure to the two types of birdsong soundscapes only the high diversity birdsong condition significantly lowered participant’s reported depressive states. With respect to changes in anxious states both traffic soundscapes yielded no significant difference. Listening to the birdsong soundscapes however, alleviated anxious states in subjects irrespective of diversity (low vs. high). Similarly, there was no effect of traffic noise exposure on paranoid states while both birdsong conditions significantly decreased those states in the current sample. In the context of cognitive performance as measured by the DNB and BDS task, no significant differences were observed for any of the natural or urban soundscape conditions. The aggregation of task scores into a composite score did not elicit a statistically significant result either.

## *Chapter 3.*

# DISCUSSION

The present dissertation set out to investigate how natural versus urban sounds impact the brain, cognitive performance, affect and mental well-being. Concerning the brain, a particular emphasis was placed on discerning how it differentially processes natural versus urban sounds both during and after the exposure. Further, the purpose of this dissertation is to enhance our understanding of the mechanisms by which natural sounds, as opposed to urban sounds, provide psychological benefits in terms of cognition, affect and mental well-being.

Paper I examined the effects of natural and urban soundscapes on cognitive performance, aesthetic judgments, affect, and changes in brain activity during task performance following exposure to the sounds.

The approach to replicate the beneficial effect of natural sound exposure on cognitive performance in the DNB and BDS task (Van Hedger et al., 2019) was, similar to the original study, an attempt to provide evidence for an attentional restoration effect in line with ART. One striking difference between Paper I and the study by Van Hedger is the setting in which the tasks were performed. While participants in the Van Hedger study performed the tasks in a quiet experimental room on a computer, participants in Paper I did so inside the fMRI scanner. Performing cognitive tasks inside the scanner may have made participants more nervous due to the unfamiliar setting including the scanner noise and the tightly constrained space. This could have resulted in a noisier performance, distorting the statistical significance of the behavioral phenomenon. Despite the insignificance of the effect that we intended to replicate, a speculative interpretation can be drawn, proposing that natural sound exposure might positively affect cognitive performance. Research on attentional restoration through nature experiences, in line with ART, implies that directed attention is restored through interactions with nature, as this type of attention is rarely required in natural environments. Consequently, experimental tasks assumed to be tapping into the domain of directed attention are chosen to reveal nature-related attentional restoration. More specifically, Berman and colleagues (Berman et al., 2008) provide evidence for this idea showing that nature-related benefits in an attention network task are only present for the executive portions of this task. Directed attention is closely related to this ability and is suggested to play a vital role in executive functioning

(Kaplan & Berman, 2010). Interestingly, when the behavioral data in this study was re-analyzed for the blocks of the DNB task that required the subject to attend to both modalities (dual modality blocks), increasing the executive load, a significant gain in performance was demonstrated for the natural sound condition. The fact that, focusing on the higher load condition led to a significant restoration of attentional resources after exposure to the natural soundscape is in line with ART, however alternative explanations for such effects exist. Joye et al., (Joye et al., 2022) found that subjects were more motivated to complete a task after viewing aesthetically pleasing nature images as compared to unattractive pixelated nature images. The author proposes that motivation might be the underlying mechanism that improves cognitive performance on the task. Alluding to this, in a study about the recognition of natural versus urban sounds it was revealed, that natural sounds were aesthetically preferred over urban sounds if they were easily recognizable as natural sounds (Van Hedger et al., 2019). In line with that, the current study shows that participants perceived beauty and pleasantness to be significantly higher for the natural sound condition, with the soundscapes distinctly recognized as belonging to their respective categories (nature or urban). Therefore, the question remains whether natural sounds possess attention-restoring characteristics, in line with ART, or can be recognized, resulting in top-down effects of motivation that boost participants' cognitive performance. While both explanations seem plausible, it is yet to be discovered what truly underlies the cognitive benefit of interacting with natural sounds. Brain signal changes following the exposure to both sound conditions, offer insights into this phenomenon. Although the whole brain analysis in Study I did not reveal any significant activity difference between the three experimental conditions (nature sound, urban sound, no sound), an exploratory approach suggested an increase in neural activity during certain blocks of the DNB task within a region of the early auditory processing stream (STG) after subjects were exposed to the urban soundscape. Considering that the DNB task, involves attending to both visual and auditory information, the question arises why conditional changes in brain activity became apparent in a region responsible for processing early auditory information. It is possible that subjects had to exert more attentional effort to process the auditory information, resulting in changes in brain activity within a region that overlaps with the primary auditory cortex (PAC). Although the STG result does not survive conventional multiple comparison correction in fMRI analysis, a speculative interpretation may provide insights into a possible neural mechanism that explains the increase in STG activity following exposure to the urban soundscape. The present result suggests, that the attentional mechanisms at hand might be affected by the soundscape exposure as early as the initial processing stage in primary auditory cortex. This may be viewed as supported by a study demonstrating that attention is able to selectively modulate activity in the PAC (Jäncke et al., 1999). The increase in STG activity while subjects performed the DNB task after being exposed to the urban soundscape, could be explained in light of another study that showed reduced PAC activity following the recruitment of attention (Hugdahl et al., 2000). Potentially, and according to the mechanisms outlined by ART, directed attention has been resorted after subjects had been exposed to the natural soundscape, resulting in more attentional capacity and thus reduced PAC activity according to Hugdahl (2000). Under the assumption that PAC activity is modulated by attention in a balanced way, depletion of attention through the urban soundscape would result in an activity increase in PAC. Regardless, this interpretation remains highly speculative and should be backed up by future research specifically investigating physical environments and their effects on early attentional mechanisms.

Examining the neural signatures associated with behavior, data from the current study reveals a negative correlation between the cognitive performance gain following natural sound exposure and activity in the mPFC. This suggests that performing better in DNB task was associated with less medial prefrontal activity. When this region was overlapped with a contrast representing general task activation a minor overlap was displayed, indicating that a subregion of the frontal executive network potentially benefits from the restorative experience with natural sound, resulting in more efficient information processing. The observation in Gould van Praag et al. (2017) that exposure to natural soundscapes modulated connectivity within the DMN, including the mPFC, proposes a potential benefit to the mPFC resulting from this exposure. With relevance to the reduction of negative affect following natural sound exposure, a positive correlation with brain activity, during the DNB task, in the IPL region was found. This points to the fact that experiencing fewer negative emotions after nature exposure might be associated with decreased activity in the IPL, a region that is part of the cognitive control network (Fassbender et al., 2006; Westerhausen et al., 2010). It is possible that processing task-related information required less cognitive effort after exposure to natural sounds. Additionally, the decrease in effort may have resulted in a reduction of negative emotions reported by the participants.

Paper II extended the results of Paper I by examining brain responses to the same natural and urban sounds during the exposure of these sounds. Understanding the effects of natural versus urban sound exposure on the brain is essential to explain why urban exposure may be detrimental while natural sound exposure appears to be beneficial in various ways. With regard to the signal complexity, or entropy, in the brain this study demonstrated a more complex

BOLD signal in the PCC, precuneus and the calcarine during the period when subjects were listening to the urban soundscapes. Putting this result into context, it seems important to mention that noise pollution is known to cause a decline of cognitive abilities (Cheng et al., 2019). Additionally, Drachman (2006) suggested a link between cognitive decline and increased levels of brain signal complexity. In light of the elevated levels of BEN during urban noise exposure found in the current study, it is possible that the brain's response to this noise exposure is being reflected by the high levels of BEN. The complexity of brain signals, as indicated by high levels of BEN, may be attributed to either the acoustic features of the urban sound or the contextual knowledge of the listener. One would suggest that urban sounds contain a lot of uncertainty possibly eliciting a more complex processing of information. Previous research has shown that more entropic sounds tend to be less preferred, but only when the sounds cannot be identified as belonging to either an urban or natural category. In contrast, when sounds can be recognized as having an urban or natural origin, more entropic sounds are actually preferred (Van Hedger et al., 2019). Thus, it seems plausible that the increase in BEN after urban sound exposure is elicited by contextual information rather than the acoustic properties of the sound, due to the top-down effect of evaluating a sound preference based on the context of its source. To establish a direct relationship between urban sounds and brain signaling complexity, further experiments are needed that systematically examine different levels of sound entropy while measuring brain activity.

Moreover, FC between the brain’s sub-networks was investigated during the exposure of natural and urban soundscapes. Paper II reveals lower FC during exposure to the urban soundscape compared to the natural soundscape exposure. Interestingly, the symptom of low FC is recognized in individuals with schizophrenia (Friston, 1998), and there is an established association between residing in urbanized areas and an increased risk of developing schizophrenia (Krabbendam & Van Os, 2005; Vassos et al., 2012). Future research should explore whether the mechanism that links urban living to an increased risk of schizophrenia is similar to the one linking schizophrenia to low FC. Decreased FC between cognitively relevant brain regions (parietal cortex, temporal lobe and default mode network regions) as observed in schizophrenic patients has been linked to cognitive impairments regarding for example the working memory ability (Zhou et al., 2015). Working memory decline is also shown to be a consequence of artificial noise pollution. Therefore, it seems plausible that the impairments in working memory and the risk for schizophrenia in cities are both driven by chronic exposure to noise. Further validation and an exploration of the role of brain FC in this link are essential.

To establish a connection between brain responses and behavior, this study investigates the correlation between reported affect before and after the soundscape intervention and changes in BEN, which reflects the brain's response during the intervention. The results illustrate that a reduction of positive emotions was associated with increased levels of BEN after the urban sound exposure. Taking into account the fact that urban, as compared to natural sounds, are usually less preferred (Stobbe et al., 2023; Van Hedger et al., 2019), the present correlation suggests that the increase in BEN might be a negative consequence following from the exposure to noise pollution. However, it remains to be noted, that this correlation does not survive multiple comparison correction and should be treated with caution. Further research is necessary to confirm a causal relationship between affect, levels of BEN, and exposure to environmental sound.

Another brain-behavior link that was examined in the present study revealed an association between cognitive performance gain and the brain's FC during the natural sound exposure. Cognitive performance as measured by two working memory tasks (BDS and DNB) increased after listening to the natural soundscape. This performance gain positively correlated with FC within, among others, the brain's auditory network. Despite the fact that this correlation did not survive multiple comparison correction it is worthwhile to note that FC was previously reported to be a strong predictor for cognitive performance (van den Heuvel & Hulshoff Pol, 2010). The relationship between greater FC and improved cognitive performance advocates that natural sound exposure could enhance the brain's processing efficiency. The performance gain did not reach significance, however the data pattern suggested an increase in the natural sound condition, while the urban and control condition showed a decrease. The mechanism by which exposure to natural sounds increases the brain's FC are not yet fully understood. The study on the brain's default mode network (DMN) connectivity, mentioned earlier, demonstrated that exposure to natural sounds significantly enhances connectivity in the default mode network (DMN). This enhancement correlates with an increase in parasympathetic nervous system activity, which in turn represents a reduction in stress. Consequently, the authors propose a potential role of environments in regulating physiological, neural and psychological activity in line with SRT (Gould Van Praag et al., 2017). While the brain's FC has previously been shown to increase through in-situ nature experiences (Chen et al., 2016), the study at hand demonstrates this effect during the mere exposure to natural soundscapes. This indicates, the brain's ability to extract environmental benefits from cues of an environment. Interventions, that aim to elicit these benefits could profit from this by eliminating the need for real, in-situ nature experiences.

In order gain a better understanding of how environmental exposure affects BEN and FC, it is important to address a fundamental question: Are the observed effects driven by auditory stimulus features (bottom-up) or a knowledge-based (top-down) construction by the listener? One potential approach to resolve this issue has been presented in a study that used a source-attribution manipulation. In this study, participants were presented with an ambiguous sound (pink noise) and were told that it originated from either a natural or urban sound source (Haga et al., 2016). If this design is able to demonstrate conditional differences in brain activity, it would support the notion that the environmental benefits may have been driven by the knowledge-based construction of the listener (Stobbe et al., in preparation). Conversely, in order to test the hypotheses if environmental benefits are driven by mere stimulus features an approach from visual brain science theory seems appropriate. There it is claimed that the brain is able to process visual natural stimuli more efficiently than urban stimuli because of the coherent structure of these stimuli (Chen et al., 2016; Valtchanov, 2013). Future research could investigate whether the coherence-based efficient processing of visual stimuli is also evident in the environmental sound domain. Additionally, future research could enhance our understanding of the relationship between the entropy of brain signals and the entropy of environmental sounds (Beltrán-Márquez et al., 2012; Devos, 2016; Van Hedger et al., 2019) by systematically studying soundscapes with varying levels of stimulus entropy and relating them to the BOLD signal entropy they elicit. Ultimately, these approaches will help to unravel the fundamental question whether the positive effects of natural sounds are driven by perceptual features or associations residing in the knowledge of the listener.

Paper III sought to inquire the effects of listening to birdsongs versus traffic noises on mental health and cognitive performance. In contrast to Van Hedger et al.'s (2019) study, which found that exposure to natural soundscapes improved cognitive performance on two working memory tasks (BDS and DNB) without affecting mood, the current study showed effects on mood (specifically depression, anxiety) and paranoia, but not on cognitive performance. Additionally, the current study explored whether the diversity of the sound sources within a soundscape differently affects the outcome variables by separating each condition (birdsong, traffic noise) into a low and high diversity group.

Listening to traffic noise generally aggravated depressive states, whereas the more diverse traffic noise soundscape did so to a greater extent. In line with this, participants also rated the two traffic noise conditions (low vs high) as significantly different in terms of perceived diversity, suggesting that the recognition of multiple noise sources resulted in a more negative experience for the listener. In line with that, participants rated the more diverse traffic sound as less pleasant than the monotone traffic sound. This suggests that the negative effects on depressive states may be attributed, at least in part, to the accumulation of various unpleasant traffic noise sources present in the sound intervention. This is supported by acoustic research showing that multiple sound sources cause more annoyance than single sources (Marquis-Favre et al., 2021) and the fact that the loudness of a soundscape containing multiple sources is perceived higher despite no variation of loudness within the single sound sources (Yost, 2018). Conversely, the high and low diversity birdsong audio were not rated as significantly different in terms of diversity/monotony. Regarding the subject's depressive states, only the highly diverse birdsong soundscape resulted in a reported decrease. Concerning the effects on state anxiety and state paranoia, the study found that exposure to birdsong soundscapes significantly alleviated these states. There was no difference between the high and low diversity soundscapes concerning the effect on anxious and paranoid states. In a study on life-satisfaction and bird species diversity in a given region, it was demonstrated that people reported higher life-satisfaction in relation to more bird species diversity present in their home region. The authors put forth that, a multisensory experience of birds is essential in order to affect life-satisfaction, and that species diversity is central to such a multisensory experience (Methorst et al., 2021). With relevance to the current study, it is possible, that the virtual experience of the low and high diversity birdsong audio did not fully replicate the immersion present in a real-life multisensory experience, thus eliminating the diversity effect. It is clear that acknowledging diversity within a soundscape depends heavily on the ability to differentiate between various sound sources. Due to urbanization, humans may be accustomed to various traffic sounds, which provides them with the necessary knowledge to recognize their diversity. However, inexperienced bird listeners are less likely to be able to differentiate between multiple bird calls. Alluding from this, it may be beneficial to practice recognizing bird sounds that are otherwise unconsciously perceived to improve mental health outcomes such as anxiety and paranoia. Pertaining to the positive effects on mood after listening to natural sounds (Benfield et al., 2014; Jiang et al., 2021), the present study is able to affirm these findings. According to current knowledge, natural sounds have been shown to have a positive effect on state paranoia for the first time. Theoretical background in the field suggests that SRT may provide a reasonable explanation for the beneficial effects of birdsong exposure on state paranoia. The song of birds could be inherently associated with a vital natural environment, deviating the focus away from internal and external stressors. Moreover, it might provide information about the absence of threats. Dealing with less stressors and threats might decrease paranoid states by means of feeling of control. Furthermore, natural environments are typically more associated with the absence of other humans and their voices which when present trigger interpersonal sensitivity playing a crucial role in the emergence of paranoia (Meisel et al., 2018). Future experiments should investigate this in more detail by examining the effects of urban soundscapes containing human voices on paranoid states.

In contradiction to the study by Van Hedger and colleagues (2019), neither of the four sound conditions (high/low, bird/traffic) significantly affected cognitive performance measured by the DNB and BDS task. One possible reason for that was the lack of control when these tasks were administered in the online study environment. The DNB and BDS task require a thorough understanding in order to produce a valid score. Although the raw cognitive data did not show any significant deviations from the expected results, the lack of control over participants' situation during task performance and understanding of the task could be problematic. To support the ongoing debate on whether such a cognitive effect exists on a population level, future studies could repeat the experiment in a more controlled laboratory setting.

Overall, this dissertation set out to inquire how sounds of natural and urban environments impact neural and psychological responses in humans. With respect to the influence of environmental sound on the brain the current dissertation illuminated several aspects demonstrating that the brain responds differently during and following the exposure to natural versus urban soundscapes. In order to link the results from Paper I and Paper II, the question arises whether changes in brain FC and BEN during sound exposure actively influences brain activity during a post-exposure cognitive task. FC within, among others, the auditory functional brain network was lower when subjects experienced the urban soundscape. When participants performed the DNB task after being exposed to urban sounds, there was an increase in activity in the STG, which is part of the PAC. While it has previously been demonstrated that FC differences can predict task-induced BOLD activity (Mennes et al., 2010), it would be valuable for future research to investigate if such a relationship exists for the results described above. If this would be the case it could suggest that the STG region may have increased its activity to compensate for the lower FC state compared to the natural sound exposure. Contrary, increased FC has been associated with higher information processing efficiency (Achard & Bullmore, 2007; Sepulcre et al., 2010) potentially explaining the result from Paper II demonstrating an association between the cognitive performance gain and increased FC within the auditory functional brain network after exposure to the natural soundscape. Demonstrating a link between FC in Paper II and the BOLD signal activity in the STG from Paper I, would suggest that the lower STG activity after nature exposure could be the result of higher processing efficiency elicited by the increase in FC during the natural sound exposure. However, this interpretation remains speculative as the activity increase in the STG region did not survive a conventional multiple comparison correction in fMRI analysis.

Pertaining to the impact of environmental sound on cognitive performance, as examined in Paper I and III, the results are mixed. While Paper I was not able to replicate the behavioral findings by Van Hedger et al., (2019) with statistical significance, the data pattern displayed a cognitive benefit for subjects that were exposed to the natural soundscape. The analysis of a sub-part from the fMRI adjusted DNB task however, did reveal a significant benefit for those subjects exposed to the natural sound condition. Moreover, the analysis of cognitive performance in Paper III revealed a null-result indicating that natural versus urban sound exposure did not impact subject's cognitive performance. Critics emphasize the need for standardized methods to measure directed attention capacity in environmental restoration studies (Joye & Dewitte, 2018). While the absence of a cognitive effect in Papers I and III may be partially due to limitations in the fMRI task setting in Paper I and the lack of control over task execution in Paper III, it is important to establish standardized methods for measuring directed attention capacity. Similar to the results from Paper I, Abbott et al., (2016) report only marginally significant improvements in the BDS task when participants have been exposed to natural sounds. Van Hedger et al., (2019) report a cognitive benefit after natural sound exposure only when task scores from the BDS and DNB were aggregated into a composite score. The same composite score procedure for the same tasks did not reveal a cognitive benefit in the results of Paper I or III. Another study revealed a cognitive benefit after nature sound exposure for a working memory task including letter spans and mathematic calculations but not for the BDS task (Bratman et al., 2015). To date there is no adequate explanation for these mixed results with respect to cognitive benefits after nature exposure. The results of the current dissertation further highlight the lack of standardized methods to prove the existence of such a cognitive benefit in a replicable way. A strategy to address this concern could involve utilizing multiple tasks known to contribute to one latent working memory factor.

In addition, the dissertation focused on the impact of environmental sound exposure on affect and mental well-being. In Paper I, the subjects reported experiencing significantly fewer negative emotions after being exposed to natural sounds compared to the urban environment. In Paper III respectively, experiencing natural sound such as birdsong significantly alleviated anxious and paranoid states in healthy participants, suggesting that natural sound elements such as water, wind and birdsong can indeed reduce negative affect following a short exposure. Interestingly, in Paper II a reduction of positive affect was negatively correlated with the brain's signal complexity or BEN during the exposure to an urban soundscape. Although the interpretation of the relationship between affect and BEN remains speculative, it opens the possibility for future research to investigate how negative emotions are related to urban noise pollution and how this relationship is encoded in the brain.

The present dissertation unraveled insights into cognitive as well as affective benefits resulting from interactions with natural sounds. Moreover, these benefits could be linked to distinct brain regions (mPFC, STG, IPL) and functional networks (auditory-somatomotor) hinting at the type of mechanism that could underlie those phenomena. Interpreting these results in light of the previously introduced theories concerning nature's restorative effects (ART & SRT) it should be mentioned that the brain regions that were found to be associated with nature's benefits are fairly uniformly located in cognitive processing sites in the brain, hinting at a cognitive restoration mechanism as proposed by attention restoration theory (ART). ART postulates that natural stimuli possess certain characteristics that reduce the demands on directed attention, resulting in a replenishment of this capacity (Kaplan, 1995). Stress reduction theory (SRT) states that natural stimuli contain information that humans inherently associate with survival resulting in reduced arousal and stress. Given the reductions in negative affect (Paper I) and states of anxiety (Paper III), one might speculate about the complementarity of SRT and ART, as previously encouraged (Hartig & Evans, 1993). Hartig and Evans (1993) argue, that ART and SRT seem to address disparate facets of restoration. SRT focuses on instantaneous psychophysiological stress recovery whereas ART is concerned with the restoration of attention capacity following cognitive fatigue induction. Central to their integration argument is the interrelatedness of physiological and cognitive states of well-being. Considering this thought, it seems plausible that cognitive as well as affective processes underlie the benefits of interacting with nature. These processes might be selectively emphasized depending on the type of outcome measures utilized in a given paradigm. Conditioned restoration theory (CRT) hypothesizes that positive experiences with nature are learned and that exposure to natural stimuli triggers this positive connection, resulting in the beneficial effects associated with natural environments. According to CRT, the mechanism behind the restorative effects of natural environments does not require an emphasis on physiology or cognition, as the conditioning framework can integrate phenomena from both perspectives. However, cognitive benefits in CRT are proposed to be driven by stress reduction, which is considered the core mechanism behind restorative nature effects (Egner et al., 2020). Importantly, CRT also allows for alternative mechanisms beyond conditioning to induce restoration. For instance, the appraisal of a scenario, such as a soundscape, determines whether it has a desired outcome, which subsequently affects core emotions and may contribute to restoration (van den Bosch et al., 2018). The restorative value of sounds thus seems to depend on the valence that it is associated with in the individual, either via evaluative conditioning or appraisal. Van den Bosch et al., (2018) demonstrate pleasantness and eventfulness to be important descriptor variables in soundscape appraisal. In line with the previous arguments, Paper I demonstrates that natural sounds are perceived as significantly more pleasant than urban sounds. Moreover, in Paper III it was shown that the more eventful but less pleasant diverse traffic noise sound had a greater impact on depressive states than the less eventful monotone traffic sound. This provides an example of the link described above, where soundscape appraisal directly influences core affect.

In conclusion this current dissertation provides psychological and neuroscientific insights into the question how environmental sound influences brain activity, FC, BEN, cognitive performance, affect and mental well-being. These insights could provide valuable guidelines for the design of recovery areas within cities, possibly reducing the impact of traffic noise sources while increasing the audibility of birdsong and natural water sources (Murgui & Hedblom, 2017). It has been shown that better access to urban green spaces leads to greater public interest in and awareness about birdlife. (Clergeau et al., 2001). Considering this, along with the previously discussed benefits of birdsong exposure, advocates for urban design that provides greater access to green spaces. Moreover, the current results highlight the lack of theoretical agreement about the mechanisms underlying psychological restoration through nature experience, encouraging future studies to design experiments and formulate hypotheses that specifically test, for example, CRT's assumptions. With respect to the knowledge gained concerning variations in brain activity in response to sounds from natural and urban environments, it is concluded that future research should aim to understand if these differences arise from disparities in acoustical features or from differences in how the listener attaches meaning to the sounds based on their prior knowledge. Understanding this fundamental question will complement our understanding of environmental sound related psychological and neural restoration, helping to maximize nature's benefits through tailored interventions while providing effective techniques to escape the negative consequences of daily urban life. In order to proof its effectiveness, one should conduct field studies investigating the effect of short exposures to stimuli such as birdsong in urban areas, including shopping malls and doctor's waiting rooms. Transferring the established benefits of exposure to birdsong to real-life settings could provide an opportunity to counteract the negative aspects associated with such urban environments. Moreover, it should be tested whether such effects as demonstrated in Paper III are unique with respect to birdsong exposure or if other natural sound elements such as water, wind or sounds of other animals can produce similar effects. Additionally, it could be examined whether an immersive combination of natural sound elements increases the effectiveness regarding the alleviation of anxious, paranoid or depressive states in healthy subjects. Further, it would be valuable to investigate in future studies whether short- or long-term exposure to birdsongs can alleviate clinical symptoms of anxiety, paranoia, or depression in patients with these mental conditions. This could provide an accessible and cost-effective intervention in clinical settings.

In summary, the current dissertation underscores the importance of investigating the complex relationship between environmental sound, brain function, and psychological well-being, and provides a foundation for further exploration and practical applications in environmental neuroscience.

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*Appendix A.*

# INDIVIDUAL WORKS

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# On how natural and urban soundscapes alter brain activity during cognitive performance

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ABSTRACT

Listening to natural or urban soundscapes has previously been shown to differentially modulate performance in a subsequent cognitive task. The present study inquired the effect of listening to urban (traffic and machinery noise) vs. natural (birds, water and wind) soundscapes on cognitive performance, mood, stress reactivity and the consequences for brain activity during a cognitive task assessed before and after soundscape exposure. In a randomized experiment, 30 participants were exposed to three conditions on three separate testing days: urban, natural and no soundscape. Before and after the functional MRI session participants performed a dual n-back, a backward digit span task and filled out mood, stress reactivity and aesthetic preference questionnaires. The natural soundscapes did lead to better cognitive performance however, the effect did not reach significance. Exposure to the natural soundscapes resulted in a significant decrease of negative affect and participants rated them as significantly more aesthetic. On the brain level, listening to the urban soundscape was associated with an increase in superior temporal gyrus (STG) activity during the subsequent dual n-back task. However, this result was statistically not corrected and remains exploratory in nature. This result could potentially hint at information processing becoming less efficient in early primary sensory area as a result of exposure to the urban soundscape. Correlations between affect/cognition and task related brain activity revealed clusters in the attention-network.

## 1. Introduction

Steadily increasing levels of urbanization all around the globe impose new challenges on our mental well-being. One severe consequence of urbanization is noise pollution which has been associated with increased levels of stress reactivity and distraction (De Paiva Vianna et al., 2015). Additionally, noise pollution is known to be the cause for several physical and mental health issues like sleep disturbance, poor academic performance due to decreased learning ability, poor reading comprehension and concentration deficits (Hammer et al., 2014). On the contrary however, sounds that are widely associated with natural environments have been shown to aid recovery from stressors relatively to urban soundscapes (Alvarsson et al., 2010). Furthermore, bird songs have been demonstrated to increase perceived attention restoration in healthy subjects (Ratcliffe, 2021; Ratcliffe et al., 2013). Taking into account that natural environments have also been associated with improved cognition (Berman et al., 2008; Van Hedger et al., 2019) as well as health and well-being (Twohig-Bennett & Jones, 2018; White et al., 2019; Zhang et al., 2020) the interesting question arises, whether the positive driver for these effects is the presence of something beneficial in natural environments or rather the absence of detrimental urban features. The ultimate goal of this line of research is to fully understand the underlying neural pathways behind the above-mentioned environmental effects. Insight into these may enable tailored interventions seeking out to either maximize nature's benefits or to minimize the negative side effects of urbanization.

Prior research reporting cognitive improvement following a soundscape intervention comes from Van Hedger et al. (Van Hedger et al., 2019). In their experiment subjects completed two cognitive tasks, known to place demands on directed attention (intentional allocation of attention to specific information or cognitive processes) (R. Cohen, 2017): the backward digit span task (BDS) and the dual n-back task

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(DNB). During the BDS task subjects actively listened to a series of spoken digits and were then asked to repeat these digits in reversed order. During the DNB task subjects were presented with two streams of information one being a series of spoken letters and the other a series of squares that appeared in eight different locations around a fixation cross, subjects were asked to detect trials where either one or both of the two types of information were matching the content from those presented two trials previously. Subjects were asked to complete both tasks before and after a blocked sound intervention where one group listened to soundscapes from the nature category and the other group listened to soundscapes from an urban setting. After the sound intervention subjects completed the same cognitive tasks again. The results showed a significant interaction effect where the improvement from pre to post-test (composite score derived from averaging the z-scores of both tasks) was significantly higher for the nature group compared to the urban group. The result was driven by an increase in cognitive performance as a result of exposure to natural soundscapes (Van Hedger et al., 2019).

One widely shared account how cognition might be improved by nature has been suggested by Steven Kaplan (S. Kaplan, 1995) and is termed attention restoration theory (ART). The foundation of this theory lies in the distinction between voluntary (deliberately applied and cognitively controlled) and involuntary (spontaneously captured) attention (Posner & Rothbart, 2007) and identifies voluntary or directed attention as the cognitive capacity that is restored by interactions with nature (S. Kaplan, 1995). The inspiration for Kaplan to use the term "voluntary attention" stemmed from William James (James, 1892; Kaplan, 1973) and was subsequently shifted to use the term "directed attention" to avoid confusions existing for James' terminology. (Kaplan & Kaplan, 1989). In the field of environmental psychology terms like "directed" and "undirected attention" have frequently been used in the past (Stevenson et al., 2018). The key component of this theoretical approach evolves around the proposition that undirected attention is occupied by environments rich with inherently fascinating stimuli (like for example sunsets), allowing voluntary or directed attention capacities, that are e.g. depleted by urban environments, to recharge (Kaplan, 1995). In contrast, spending time in urban environments can deplete these directed attention capacities. In other words, according to ART, natural environments are well-suited to minimize or at least to reduce the demands on the voluntary or directed attention system (Van Hedger et al., 2019). While the BDS task is commonly used in order to operationalize directed or voluntary attention (Berman et al., 2008) the DNB task was selected for the current study based on its reported similar demands on the directed attention capacity (Lilienthal et al., 2013). Additionally, a composite score was computed from these two tasks to make the results comparable to the previous study, that our study design was based on (Van Hedger et al., 2019). Attention in general is viewed as being at the centre of the human psychological architecture and especially directed attention has been argued to play a crucial role in effective cognitive functioning (Posner & Rothbart, 2007) as well as in short-term memory (Jonides et al., 2008).

Another reason why listening to sounds from natural environments may improve cognition is provided by stress reduction theory (SRT) (Ulrich, 1983). SRT states that affective and aesthetic values that are derived from experiences with nature can lower stress levels which then in turn create room for improved cognitive performance(Van Hedger et al., 2019). Support for this comes from physiological measures of stress reactivity which have been demonstrated to be reduced after exposure to natural soundscapes (Alvarsson et al., 2010). Furthermore, in line with SRT, natural sounds have been demonstrated to also improve affective states (Benfield et al., 2014). Consequently, benefits in cognitive functioning arising from experiences with natural environments are in principle compatible with both ART and SRT. From a neuroimaging perspective one would expect to find conditional differences in brain activity originating from attention-related brain networks according to ART and affective or stress processing-related brain regions according to SRT. The predictions from both theories are quite similar however, ART puts slightly more emphasis on cognition while SRT puts it on affect. This would imply that both theories are not exclusive of each other and might explain co-existing phenomena resulting from experience with natural stimuli.

The present study set out to investigate the underlying neural mechanism of natural soundscapes improving cognitive performance (Van Hedger et al., 2019) by means of functional magnetic resonance imaging (fMRI). Based on the behavioural effect reported by Van Hedger et al. (Van Hedger et al., 2019) it was hypothesized that this effect has some kind of neural representation resulting in different patterns of brain activation during the behavioural tasks following stimulation with either natural or urban soundscapes. It was hypothesized that if attention-task-relevant brain regions like the ventrolateral prefrontal cortex (VLPFC), the dorsolateral prefrontal cortex (DLPFC), lateral prefrontal cortex (LPFC), anterior cingulate cortex (ACC) and the tempo parietal junction (TPJ) would show a different level of activation following natural or urban soundscape exposure, the cognitive phenomenon described by ART might be revealed on a neural level. It has been demonstrated that the DLPFC is able to maintain task-relevant information e.g. when digits have to be mentally stored between the encoding and recall phase of the BDS task (Dosenbach et al., 2008). This top-down control of task relevant information is also needed when subjects continuously update the incoming information during the DNB task. Both, the maintenance and updating of information, are processes driven by an attentional mechanism. If experience with nature restores attention, as postulated by ART, a modulation of attention within the DLPFC could be hypothesized. According to Dosenbach and colleagues top-down control is accomplished by a large number of brain regions distributed throughout the prefrontal, frontal and parietal cortex for example showing one of the reasons why the brain regions (PFC, TPJ, ACC) mentioned before have been hypothesized to be target of the current study design. Another reason for this hypothesis stems from the work on attention networks by Posner and Rothbart (Posner & Rothbart, 2007) where executive or directed attention has been linked to regions like the ACC, PFC & VLPFC). At this point it remains to say that directed or voluntary attention has previously been linked to the concept of top-down processing which is mainly executed by PFC neurons (Buschman & Miller, 2007; S. Kaplan & Berman, 2010). However, this link is based on similarities that both concepts (directed attention & top-down control) share. As Gaspelin and Luck (Gaspelin & Luck, 2018) discuss, directed attention must be seen as a constituent of top-down control. On the other hand, if activity in stress related brain regions like the amygdala would differ following natural or urban soundscape exposure the affective phenomenon described by SRT would be revealed on a neural level. A recent study on environmental exposure and stress has demonstrated the involvement of the Amygdala in stress processing. The activation of this region during a stress related task was modulated by differences in environmental exposure (nature vs urban exposure) (Sudimac et al., 2022). The administration of challenging cognitive tasks such as the BDS and DNB task can be a stressful experience for participants. Following this thought the Amygdala was additionally hypothesized to be of interest for the current study. Stress is also well known to exert its effects on the hippocampus (Kim et al., 2015) and would be possibly modulated by the current paradigm if SRT holds. The current study was designed in order to investigate neural substrates of the effects of environmental exposure on attentional processing, by which logically the emphasis was put on ART. The global aim with this approach is to better understand how the brain represents the beneficial effect of interacting with nature. The involvement of specific brain regions such as the prefrontal cortex or even primary sensory regions might provide more insight into the underlying mechanism that takes place when one interacts with the environment.

## 2. Methods

### 2.1. Participants and design

Thirty-five participants (12 female, 23 male and 0 non binary, mean age = 27,6 years) were invited. Participants had normal or corrected-to-normal vison and were not taking any psychotropic medications. Each participant was invited for three subsequent days on which they were exposed to one of the three experimental conditions (see Fig. 1A). The order of conditions in these three sessions was counterbalanced to avoid unwanted order effects. During each session, participants were asked to perform two cognitive tasks on a computer (identical to the versions used by van Hedger and colleagues) (Van Hedger et al., 2019) as well as two surveys (see Fig. 1B). Afterwards each subject underwent the scanning procedure during which they were asked to perform the same two tasks (adjusted for fMRI) before and after a soundscape intervention. fMRI data was acquired during the execution of the tasks as well as during the soundscape exposure. It is important to note that the fMRI data acquired during the exposure to the soundscape will be analysed and discussed within another article (Stobbe et al., in preperation, 2023). After the MRI session participants returned to the computer where they were again asked to complete the two cognitive computer tasks. All participants provided informed consent and the study was approved by the local psychological ethical committee at the Centre for Psychosocial Medicine at University Medical Centre Hamburg-Eppendorf in Hamburg, Germany (LPEK-0077). All participants were debriefed and received monetary compensation after participation. The study has been pre-registered here: https://aspredicted.org/B6F_3G1. The experiment made use of a 2 (time: pre-intervention, post-intervention) x 3 (soundscape: natural, urban, no-soundscape) factorial design, with time and soundscape as within-subject factors. While 35 participants have been invited to account for drop-outs and to reach the required sample size (n = 28) following our a-priori power analysis, 30 data sets could be used for

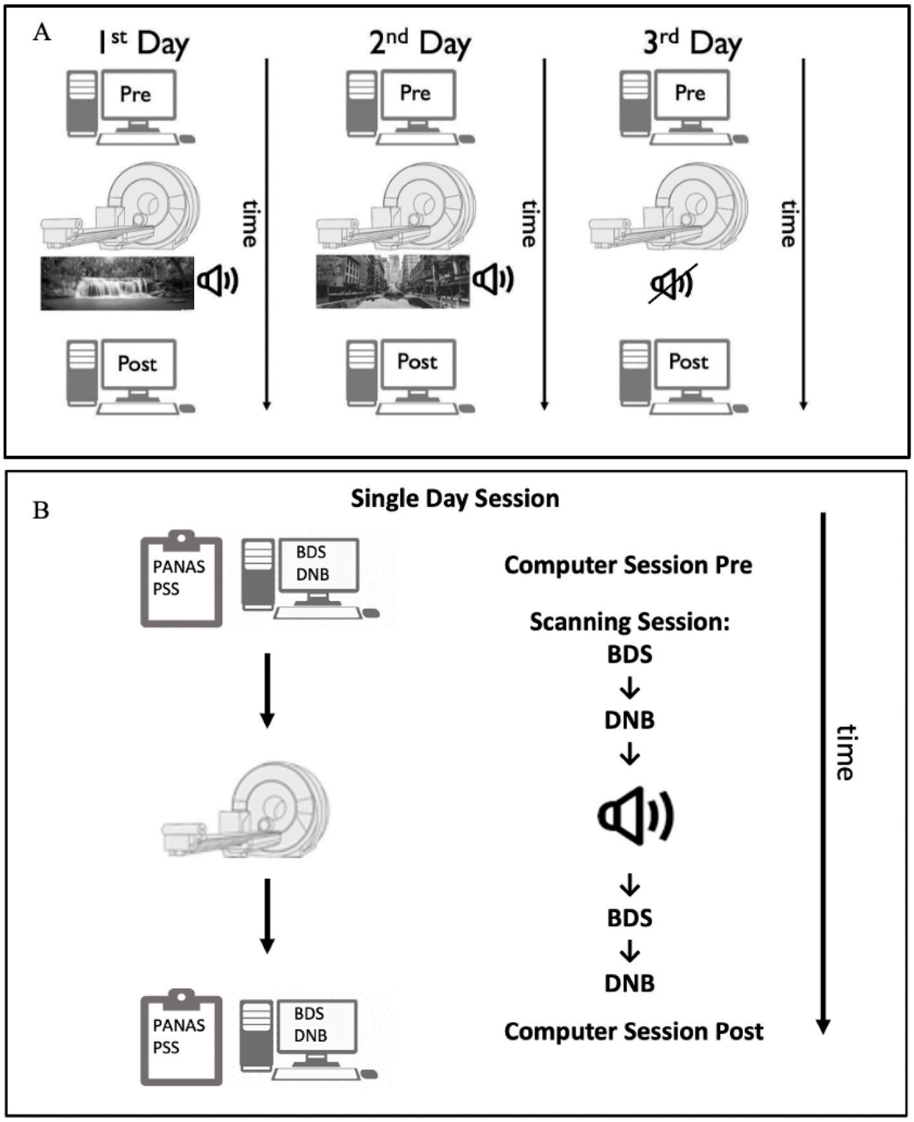

**Fig. 1. Experimental Design**. Panel A depicts the procedure of the entire experiment which consisted of three testing days. Each day the participant performed two computer sessions (marked with the computer symbol). In-between those computer sessions the scanning phase took place (marked with the scanner and sound symbol). Each day the participant was provided with a different sound condition (marked with the picture below the scanner symbol, there was a natural sound condition, an urban sound condition and a no-sound control condition). Panel B shows the timeline of a session on a single day, zooming into one of the three subpanels in A. The computer session consisted of two surveys (PANAS and PSS) and two cognition tasks (BDS and DNB). The subsequent scanning session included a pre and post measurement of the scanner tasks (BDS and DNB) separated by the soundscape intervention. The second (post) computer session comprised the last stage of the testing day.

most of the analyses in the current experiment (4 participants dropped out before finishing their third testing day and one participant was excluded due to an anatomical abnormality). Some data sets have been found to contain missing-data and a technical error caused the loss of several log-files from one of the fMRI tasks. This resulted in varying sample sizes for some of the analyses described in the results section.

### 2.2. Materials

Forty natural and forty urban soundscapes from a previous study were used (Van Hedger et al., 2019) provided via the Open Science Framework. The natural soundscapes consisted of bird-songs, water, insects and wind. The urban soundscapes were predominated by traffic sounds, café ambiance (unintelligible speech), and machinery sounds. It is important to note, that each soundscape could contain sounds from multiple sound sources in order to create a realistic simulation of what one might hear in these two settings. Each soundscape was 20s long with a 500-ms linear fade in and fade out. Due to this fading in and out an impression of a continuous environmental sound exposure was accomplished. The total duration of the soundscape exposure was 13.3 min. The amplitude of the sounds was normalized in order to accomplish consistent loudness during the intervention. Additionally, the selected soundscapes have previously (Van Hedger et al., 2019) been categorized by participants in order to verify that these soundscapes actually represent natural and urban categories. The result of this test verified that there is no overlap in ratings meaning that the lowest-rated natural soundscape (7- point rating where 1 was “very urban” and 7 was “very natural”) was rated higher than the highest-rated urban soundscape (Van Hedger et al., 2019).

### 2.3. Measures

#### 2.3.1. Affective

The Positive and Negative Affect Schedule (PANAS) (Watson et al., 1988) assesses participants’ feelings during the last hour by presenting 10 positive and 10 negative affective states. The Perceived Stress Scale (PSS) (S. Cohen et al., 1983) was employed to assess participants level of self-perceived stress reactivity using 14 items. This questionnaire was also administered before and after the scanning session on each subsequent day. Both affective questionnaires used a standard 5-level answer format. Aesthetic ratings were only collected at the end of the experimental session on each day, assessing the subjective beauty and pleasantness perception of the soundscapes (see procedure for more detail).

#### 2.3.2. Cognitive

In a previous study with a comparable design a composite measure was computed from the dual n-back (DNB) and the backward digit-span (BDS) performance (Van Hedger et al., 2019). In order to do so the measure from the BDS and DNB tasks were converted into $z$ scores (raw score minus grand mean divided by standard deviation) and averaged together across tasks separately for each *soundscape condition* (nature, urban, control) and *time* point (pre- and post-intervention). As the goal of the current study was to investigate the replicability of these findings, we decided to use the identical tasks outside of the scanner. In addition, these tasks were adjusted for fMRI design requirements and then re-run during the scanning procedure in order to reveal the neural correlates of any possible behavioural effect. Within the ART literature the BDS task has repeatedly been used (Benfield et al., 2014; Berman et al., 2008).

The BDS task conducted outside of the scanner consisted of 14 trials with digit spans ranging from 3 digits to 9 digits, and each length was tested twice. In a standard trial each digit was presented auditorily, 1000-ms after the stimulus onset the next digit was presented. Participants had to insert the presented digit span backwards into a textbox via the computer keyboard. The BDS task outside the scanner was administered in a non-adaptive fashion meaning that the presented digit spans were not increased or decreased based on participant performance. Participants were not time limited and took approximately 5–10min for this task. Behavioural performance was calculated as the total number of correct trials out of 14. The BDS task was administered in a separate experimental room and was presented on a computer using E-Prime 2.0 (Schneider et al., 2002).

In order to design a comparable BDS test to be performed in the MRI scanner the task was adjusted in several ways. The responses were recorded with an MR-compatible 3-button-box device. After presentation of the digit span, the subject was provided with a circular number dial showing the numbers from 0 to 9. With two of the buttons from the button-box the subject was able to move the active number in the number dial and to select a specific number (see Figure S1 in the supplementary material). The third button indicated the confirmation of the selection. Then the corresponding digit was displayed in the answer box. Digit spans used in this fMRI task ranged from 4 up to 8 digits. The order of experimental and control trials was pseudo-randomized in a way that trials of the same type (control trials and experimental trials with a given span-length) could not occur repeatedly. Similar to the BDS version administered on the computer the scanner version of this task was also non-adaptive. Once the answer box was filled with the number of digits from that specific trial the dial disappeared from the screen and a fixation cross was shown until the start of the next trial. The break between trials ensured that there was enough time for the hemodynamic response to return to baseline before the next trial started. There was a maximal break of 30 s until the next trial was presented. Subjects had the opportunity to practice giving responses via the circular number dial beforehand. We also included control trials in this version of the task. On a control trial, the presented digits were only zeros to prevent, that participants memorized anything during these trials. The total of 14 trials was separated into 10 experimental trials and 4 control trials per session and took 15 min for completion. The task was presented using Presentation® software (Version 18.0, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com).

The DNB task was chosen as the second cognitive measure as it is known to play a critical role in directed attention (Lilienthal et al., 2013). Here participants were required to perform two working memory tasks one visual, one auditory, at the same time. The behavioural version was first administered on a computer outside the scanner. Participants underwent a series of training slides and training runs before the real data collection started. Participants were informed about the rules of the task and then trained those in 80 training trials. The actual task consisted of a pair of 2-back blocks and a pair of 3-back blocks. Each experimental block consisted of 20 trials +N. In a 2 -back block this then resulted in 22 trials e.g. For the first N trials of a block no target could appear so each block contained 20 trials which were included in the performance analysis. Participants performed 40 2-back and 40 3-back trials during one run of the task. On each trial, a blue square and a spoken letter were simultaneously presented. There were eight possible letters, which have been recorded from a German native speaker (Salminen et al., 2016). The square could appear in eight possible locations around a centre fixation cross (see Fig. 1B). Participants were instructed to respond with the “A” key if the current location of the square matched the location of the square $n$ trials before (either 2- or 3-back). The same was true for the letter and participants responded with the “L” key. It was possible that both the letter and the square were matching in this case, participants had to respond with both keys. For non-matching trials no keys had to be pressed. Depending on how many training blocks were performed participants completed this task within 5–10 min. For each participant a single d’ score (Macmillan, 2005) was derived by calculating the proportion of ((v_TotalHits – v_TotalFA) + (a_TotalHits - a_TotalFA)/2)/number of total experimental blocks, where visual hits (v_TotalHits) refer to the correct response with regard to the visual domain of the task (square location) and where auditory hits (a_TotalHits) refer to the correct response with regard to the auditory domain (spoken letter). False alarms refer to the situation where participants falsely indicate a visual (v_TotalFA) or auditory target (a_TotalFA). Note, that the described paradigm for this task was identical to van Hedger et al., (Van Hedger et al., 2019). The score was aggregated across the 2- and 3-back blocks in line with a previous study (Van Hedger et al., 2019). The DNB task was administered in a separate experimental room and was presented on a computer using Presentation® software (Version 18.0, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com).

For the DNB task inside the scanner, we mainly adapted two aspects. First, the responses were recorded with two buttons operated with the participant's index (button 1) and middle finger (button 2) via an MRI compatible button box. Secondly the task only contained 2-back and 0-back blocks. During 0-back blocks, participants were instructed to press the buttons if a pre-specified target appeared. In these blocks, subjects did not have to monitor previous steps in order to make a correct response, which enables the comparison of a condition with memory load (2-back) and no memory-load (0-back) (see (Salminen et al., 2016)). Lastly, while the computer version consisted only of one type of trial, namely the dual modality trials the fMRI task blocks have been split up into auditory, visual or dual modality blocks. For each type of modality (auditory, visual & dual) 6 blocks (3 0-back blocks and 3 2-back blocks) occurred. Each block consisted of 20 trials. The auditory trials only contained the spoken letters while the visual trials only consisted of the blue square. The dual trials were a combination of both. The task was completed after 15 min. This task was also presented using Presentation® software (Version 18.0, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com).

### 2.4. Procedure

Participants signed the informed consent form and filled out the MRI exclusion criteria screening sheet before the experiment started. Afterwards participants completed the first computer session which included a survey on demographic information, the PANAS, the PSS and the pre-intervention administration of the BDS task as well as the DNB (see Fig. 1B). Once the computer session was finished, participants entered the MRI scanner. During the scan participants first completed the pre-intervention runs of the task inside the scanner where they first did the BDS task followed by one run of the DNB task. Subsequently the sound intervention took place where participants were exposed to the soundscapes from one of the three categories via MR-compatible headphones inside the MRI scanner. After completing the intervention participants completed another run of the BDS and DNB task as a post-intervention measure inside the scanner (see Fig. 1B). Following the completion of the scanning procedure participants were asked to complete the post intervention computer session and to additionally answer some simple questions about the beauty and pleasantness of the soundscape intervention. The computer as well as fMRI versions of the tasks were administered after each other without any major delays. The delay between the pre and post measurement was 15 min for the fMRI tasks and the length of the scanning procedure (1.5 h plus a break afterwards) for the computer tasks. The delay between sessions was dependent on the participants availability but was tried to be limited to 10 days. After having completed their third testing day, participants were debriefed and compensated monetarily.

### 2.5. Image acquisition

Scans were acquired using a Siemens Tim Trio 3T scanner (Erlangen, Germany) using a 32-channel head coil. High-resolution T1-weighted MR images of 192 slices with an in-plane resolution of 1 $mm^2$ were acquired (magnetization prepared gradient-echo sequence (MPRAGE) based on the ADNI protocol (www.adni-info.org), repetition time (TR) = 2500 ms; echo time (TE) = 4.77 ms; TI = 1100 ms, acquisition matrix = 256 × 256 × 176, flip angle = 7°). This was followed by an echo planar imaging sequence (TR = 2000 ms, TE = 30 ms, acquisition matrix = 216 × 216 × 129, flip angle = 80°, slice thickness = 3.0 mm, distance factor = 20%, FOV = 216 mm, 3 × 3 × 3 $mm^3$ voxel size, 36 axial slices, using GRAPPA) with 5 blocks, with an acquisition time of 15 min each.

### 2.6. Power analysis

An a-priori power calculation was conducted targeting an interaction effect (repeated measures ANOVA, within factors), in G*Power 3.1.9.7. For an effect size f of 0.25 with 3 measurements in 1 group and a power of 0.80 the required sample size of 28 subjects was calculated. The correlation among the 3 repeated measures was assumed to be at $r = 0.5$. According to the general rule of thumb for Cohen's f statistic, $f \geq 0.10 < 0.25$ is a small effect, $f \geq 0.25 < 0.40$ is a medium effect, and, $f \geq 0.40$ a large effect (J. Cohen, 1988, pp. 20–26). The pre-registration of the current study can be found via the link below and contains the number of subjects that have been pre-registered based on the power analysis above. Note that in the pre-registration we state the recruitment of a few subjects more (30) by which we aimed to compensate for drop-outs and other data collection problems. During data collection we already faced some drop-outs and therefore invited 5 more participants to account for that (https://aspredicted.org/blind.php?x=B6F_3G1).

### 2.7. Data analysis

Ratings on pleasantness as well as on beauty perception of the soundscape stimulation were analysed using a within-subject repeated measures One-way ANOVA model. The PANAS, PSS and cognitive performance data has been analysed using a 2 (time: pre-, post) x 3 (soundscape: nature, urban, no sound) within-subject repeated measures ANOVA model in R (R Core Team, 2022). Figures were produced using the package ggplot2 (Wickham, 2016).

The fMRI data of the BDS task was analysed in the following way: Onset-times were extracted from pre and post run for each of the three conditions (nature, urban & control). The duration of each trial in the BDS task was split up into an encoding- and recall-phase. The encoding phase was marked as the time from the onset of the trial until the last digit from the current span was presented. The recall phase was marked as the time from the offset of the last spoken digit until the participant responded. The data from both phases was analysed using a 2 (time: pre, - post-) x 3 (soundscape: nature, urban, no sound) full factorial design within SPM. For the DNB task onset times were extracted marking the beginning and end of a dual modality block (block containing visual and auditory trials). The data from the DNB task was analysed with the same 2 (time: pre, - post-) x 3 (soundscape: nature, urban, no sound) full factorial design in SPM. This whole brain analysis is statistically based on an ANOVA model comparing so called 1st level contrasts. These contrasts are derived from regressors which represent the factors for the ANOVA model (time and soundscape condition). For both tasks in the current experiment an experimental trial was always contrasted against a control trial. In the BDS task control trials contained only 0's as digits to recall and in the DNB task the control blocks were made of 0-back blocks (see section 2.3.2). The neural data during the times where the brain was processing these types of trials or blocks were contrasted against the neural data obtained during the experimental trials or blocks (e.g., 2-back blocks for the DNB task). This was done for each level of the two factors to create the 1st level contrasts. Because for the DNB task there were 3 types of blocks (dual, visual and auditory), a 2 assessment times-level factor (time pre, post) and a 3 soundscape conditions-level factor (soundscape condition nature, urban, control) there were in total 3x2x3 = 18 basic 1st level contrasts. The subsequent analysis of these 18 contrasts was split into 3 sub-analyses resulting in 2x3 = 6, 1st level contrasts used for the ANOVA model for each block type respectively. The computation of the ANOVA model then provides 2nd level group comparison contrasts for the main effects and for the interaction effect. Subsequently, the analysis design was reduced to a 2 (time: pre, - post-) x 2 (soundscape: nature vs urban) full factorial design, as an exploratory approach which focuses on the two sound conditions. This is similar to the model described above while excluding the control condition in order to unravel potential differences between the natural and urban condition. An interaction contrast of the 2x2 factorial design analysis revealed an uncorrected cluster (60 voxel) in the superior temporal gyrus (STG) region. The MarsBar toolbox was used to extract the percent signal change for the STG cluster to enable visual inspection of the data. In order to test whether the cluster is part of the auditory processing stream, the results of a contrast of task-relevant auditory information vs the remaining trials was used to create a visual overlay image. Upon visual inspection, the STG cluster overlapped with the created auditory mask as well as with Heschl's gyrus which is part of the primary auditory cortex.

Lastly, the association between behavioural and neural change was investigated. Post- minus pre-task-change scores were calculated yielding the cognitive difference score representing performance gain for each task separately. In order to quantify the reliability of such difference scores, correlations between the variable's pre- and post-measurements have been calculated and are reported in the supplementary material (see Table S2.). Overall, the pre- and post-measurements seem to be significantly correlated., but not particularly highly correlated. This is further discussed within the limitations section. We computed post-minus-pre brain related changes in both tasks (BDS & DNB) as well as post-minus-pre changes in affect and cognition with a focus on the natural soundscape condition, because we observed behavioural changes in this particular condition. The contrasts representing change in the neural data were calculated based on the first level contrasts, namely the dual modality trials from the DNB task (nature soundscape condition) as these were the first level contrasts used to identify the STG cluster in the whole brain analysis. For the change contrasts in the BDS neural data, first level contrasts from the recall and encoding trials were used and the pre contrast was subtracted from the post contrast, to represent change. Only the DNB dual modality change contrasts revealed a result which was reported.

In a next step a multiple whole brain regression model incorporating performance gain as a covariate was examined. The resulting cluster was thresholded at $p < .005$ and corrected for multiple testing using a 3d cluster simulation within AFNI (Analysis of Functional Neuroimages) (Gold et al., 1998). Subsequently, the same whole brain regression model was examined taking into account the gain of negative emotions (negative PANAS items post score minus pre score) as another covariate. The resulting cluster was thresholded at $p < .005$ and corrected for multiple testing using a 3d cluster simulation within AFNI (Analysis of Functional Neuroimages) (Gold et al., 1998).

## 3. Results

### 3.1. Aesthetic ratings

Concerning pleasantness ratings (N = 31), we observed a significant difference between the means of the three conditions ($F$ (2,60) = 19.71, $p$ = 2.62e-7, $\eta_G^2 = 0.215$). Pairwise comparisons reveal that natural soundscapes were rated as significantly more pleasant than urban soundscapes ($t$ (30) = 3.42, $p$ = .005). Additionally, natural soundscapes were perceived as significantly more pleasant than listening to no soundscape (control condition) ($t$ (30) = 5.44, $p$ = 2e-5). Listening to urban soundscapes was not rated as significantly more pleasant than listening to no soundscape ($t$ (30) = 1.65, $p$ = .327).

Ratings on how beautiful participants perceived the soundscape stimulation were analysed similarly (N = 27). The results align well with the ratings on pleasantness. In general, the three conditions differed significantly from each other ($F$ (2,52) = 31.44, $p$ = 1.12e-9, $\eta_G^2 = 0.35$). The pairwise comparisons reveal that natural soundscapes were aesthetically preferred over the urban soundscapes ($t$ (26) = 4.69, $p$ = 2.29e-4). Additionally, natural soundscapes were aesthetically preferred over listening to no soundscape (control condition) ($t$ (26) = 6.84, $p$ = 8.79e-7). Listening to urban soundscapes was not preferred over listening to no soundscape ($t$ (26) = 1.66, $p$ = .327).

### 3.2. PANAS

Positive affect (PA) scores (N = 26) reveal no main effect of time ($F$ (1,25) = 1.49, $p$ = .234, $\eta_G^2 = 0.005$) and no main effect of condition ($F$ (2,50) = 0.21, $p$ = .821, $\eta_G^2 = 0.001$). The interaction effect was also non-significant ($F$ (2,50) = 1.30, $p$ = .280, $\eta_G^2 = 0.006$).

Negative affect (NA) scores (N = 26) demonstrate a significant main effect of condition ($F$ (2,50) = 4.185, $p$ = .021, $\eta_G^2 = 0.035$) and no main effect of time ($F$ (1,25) = 1.464, $p$ = .238, $\eta_G^2 = 0.004$). The interaction effect was significant ($F$ (2,50) = 4.347, $p$ = .018, $\eta_G^2 = 0.028$). The pairwise comparisons revealed one significant comparison within conditions, which is the pre vs post comparison in the nature condition. On average participants reported a reduction in negative affect only after the natural soundscape intervention ($t$ (25) = −3.11, $p$ = .005) but not after the urban soundscapes ($t$ (25) = 0.7, $p$ = .49) or no soundscape (control) ($t$ (25) = 0.34, $p$ = .73) (see Fig. 2A) (see Fig. 3).

### 3.3. PSS

The PSS scores (N =30) revealed no main effect of condition ($F$ (2,58) = 1.34, $p$ = .27, $\eta_G^2 = 0.007$) or time ($F$ (1,29) = 0.21, $p$ = .64, $\eta_G^2 = 0.0005$). The interaction effect was likewise not significant ($F$ (2,58) = 0.32, $p$ = .73, $\eta_G^2 = 0.002$).

### 3.4. Cognitive measure

A separate analysis of both task scores did not reveal any significant result. Pearson correlations between the task scores for each condition and timepoint are reported in the supplementary material (see Table S4.). The scores from the computer versions of the tasks correlate significantly overall. However, the scanner versions of the tasks are not significantly correlated except for the control condition in the pre-intervention measurements (see Table S4.). Even though an overlap between these two tasks has previously been reported (Redick & Lindsey, 2013) the current study was able to replicate this only for the computer versions. The missing overlap between the BDS and the DNB task inside the scanner might be due to the adaptions that have been made to the tasks in order to make them feasible for usage inside the scanner. This is critically reviewed within the discussion section.

#### 3.4.1. Composite score computer session

The composite score data (N = 30) was derived from the single task scores of the DNB task and the BDS task. The analysis of the behavioural computer session scores revealed a significant main effect of time ($F$ (1,29) = 13.1, $p < .01$, $\eta_G^2 = 0.05$) with participants post-scores being higher compared to pre-scores, representing a learning effect. The main effect of condition (soundscapes) was not significant ($F$ (2,58) = 1.91, $p$ = .15, $\eta_G^2 = 0.012$). The interaction effect was not significant ($F$ (2,58) = 3.11, $p$ = .052, $\eta_G^2 = 0.009$), but showed the expected direction, namely a tendency for an improvement in the nature condition.

#### 3.4.2. Composite score MRI session

The composite score from the behavioural data of the MRI session (N = 21) was derived from the task scores of the DNB task and the BDS task assessed during the functional MR scan. Because there was no adequate overlap between the two tasks (see above), the following composite score data should be viewed as an attempt to replicate the previously reported result by van Hedger and colleagues (Van Hedger et al., 2019). There was no main effect of time ($F$ (1,20) = 0.41, $p$ = .52, $\eta_G^2 = 0.002$) and no main effect of condition (soundscape) ($F$ (2,40) = 1.65, $p$ = .20, $\eta_G^2 = 0.022$). The interaction effect was not significant, but revealed a tendency ($F$ (2,40) = 2.676, $p$ = .081, $\eta_G^2 = 0.019$). This tendency towards an interaction effect was again clearly driven by the pre to post

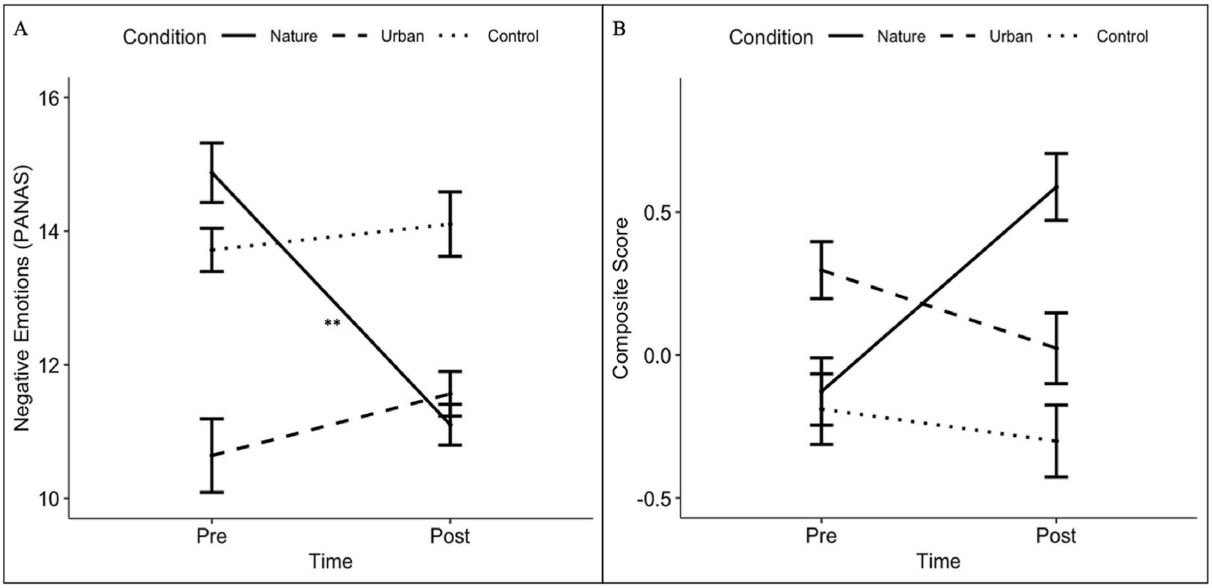

**Fig. 2. Behavioural Data.** Panel A displays negative emotions as measured with the PANAS questionnaire, plotted as a function of time (pre-intervention, post-intervention) and soundscape condition (natural, urban, control). Error bars represent +- 1.96 standard error of the mean. Double asterisks ** represent a p-value <.01. Panel B displays the composite cognitive measure from the fMRI tasks, plotted as a function of time (pre-intervention, post-intervention) and soundscape condition (natural, urban, control). Error bars represent +- 1.96 standard error of the mean. Composite scores have been calculated by standardizing and aggregating individual task scores from the dual n-back and backward digit span task.

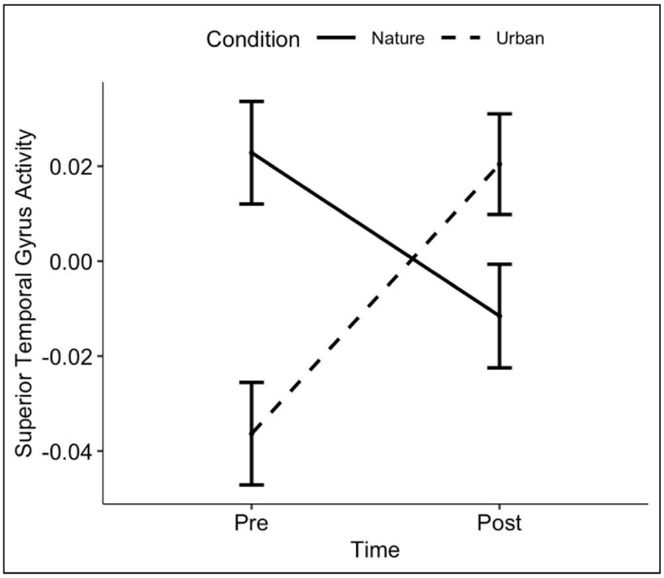

**Fig. 3.** Extracted brain data for visual inspection. BOLD signal from a cluster in the superior temporal gyrus (STG, MNI coordinate −50, −9, −4) plotted as a function of time (pre-intervention, post-intervention) and soundscape intervention (nature, urban). Error bars represent +- 1.96 standard error of the mean.

improvement in the nature condition (see Fig. 2B).

### 3.5. fMRI data

The whole brain 2x3 factorial design analysis from the BDS (recall and encoding phase) and the DNB task did not reveal any statistically significant results. In order to further inspect the data, we focused on the two sound conditions which constitutes an exploratory approach.

When zooming in and only focusing on the nature and urban sound condition (2 timepoints x 2 conditions) a whole brain ANOVA (as described in 2.7) of the DNB task, during dual modality blocks resulted in a time x condition interaction in an uncorrected cluster in the superior temporal gyrus (see Fig. 3) (STG, MNI coordinate: −50, −9, −4, uncorrected $p < .05$). The 2x2 factorial design did not reveal any result for the recall and encoding phase of the BDS task. In order to visually inspect whether the STG cluster belongs to the auditory processing stream, it was superimposed on the contrast representing the neural processing of auditory trials from the DNB task (see Fig. 5A). In order to illustrate the interaction, we extracted data from the STG cluster for each participant.

In order to further explore the DNB behavioural data in relation to the indicated changes in STG activity (nature vs urban) for the dual modality blocks, the DNB behavioural data has been reduced to the dual modality blocks and was re-analysed with the 2 (time: pre-, post) x 3 (soundscape: nature, urban, no sound) within-subject repeated measures ANOVA as described in section 2.7. The result of this analysis revealed no main effect of condition or time, while the interaction effect was significant ($F$ (2, 46) = 6.79, $p$ = .003, $\eta_G^2 = 0.09$). Pairwise comparisons between pre- and post-run for each condition separately revealed a significant performance increase from pre to post in the nature condition ($t$ (23) = 3.0, $p$ = .006) and a significant decrease in performance from pre to post in the control condition ($t$ (23) = −2.3, $p$ = .032). No significant difference was observed for the urban condition. To enhance congruity with the neural data result, which primarily emphasizes the distinction between the two sound conditions (nature and urban) in the STG, the aforementioned ANOVA concerning the DNB behavioural data derived from the dual modality blocks has been simplified to a 2 (time: pre-, post) x 2 (soundscape: nature, urban) model. The result of this analysis showed no main effect of condition or time, while the interaction effect was significant ($F$ (1,23) = 9.47, $p$ = .005, $\eta_G^2 = 0.09$). The pairwise comparisons between pre-and post-run for both conditions unveiled a significant increase in performance from pre to post in the nature sound condition ($t$ (23) = 3.00, $p$ = .006).

### 3.6. Exploring the link between behaviour and brain

Behavioural effects of nature on affect and cognition have been reported previously, (Berman et al., 2008; Bratman et al., 2015; Van

Hedger et al., 2019). Therefore, we wanted to test to what extent the observed changes in behaviour were related to changes in neural activity. For behavioural difference scores (post minus pre-test) have been correlated with brain activity changes within a whole brain analysis. It was observed that the difference score from the DNB task (nature condition) negatively correlated with brain activity changes in the medial frontal superior cortex (MNI coordinate: 12, 56, 20, $p < .005$ cluster extent corrected) acquired during the fMRI task-runs in the natural soundscape condition, indicating that a gain in performance was associated with a decrease in medial prefrontal cortex activity. Fig. 5B shows this cluster superimposed on an anatomical brain-template. Then we visually inspected whether this cluster overlaps with the general task activation during the DNB task. General task activation in this case was defined as the 2-back vs. baseline contrast. The overlap is depicted in Fig. 5C.

Another relevant behavioural aspect in the current experiment was the subjective report of negative affect. As described above, a significant reduction in negative affect was observed while participants completed the experimental session in the natural soundscapes condition. In order to relate this to the brain data, another whole brain correlation analysis has been run. We observed that the difference score from the negative PANAS items (Post minus Pre) positively correlated with brain activity changes in the inferior parietal lobule (IPL) region (MNI coordinate: 60, −25, 32, $p < .005$ cluster extent corrected) acquired during the fMRI task-runs (dual n-back task) within the natural soundscape condition, $r = 0.75$. $n = 20$, $p = 1.58e\text{-}4$. The positive relationship indicates that, a decrease in negative emotions was associated with less activity in the IPL region during the dual n-back task following the exposure to natural soundscapes. The removal of one extreme outlier revealed a similar correlation, $r = 0.65$, $n = 19$, $p = .002$. Fig. 5D shows this cluster superimposed on an anatomical brain template while Fig. 4 shows a scatterplot of both variables used for the whole brain correlation.

## 4. Discussion

The main purpose of this study was to investigate the neural underpinnings of a behavioural observation, namely that participants improved in cognitive performance after listening to natural soundscapes (Van Hedger et al., 2019). Independent from the current study's aim to replicate this behavioural effect, two additional points should be made with respect to the choice of tasks. From previous literature on environment-based restoration it is known that a number of tasks have been used in the past (Bratman et al., 2015; Ohly et al., 2016; Stevenson et al., 2018). In the field no standardized way of investigating environment-based restoration effects on cognition has been established (Joye & Dewitte, 2018). Within the current study we choose a task (DNB), since it has been previously applied in an MRI context (Salminen et al., 2016), although it has not frequently been used in restoration studies. Moreover, the replication of a previous study is in times of replication crisis more than ever a valuable research method, that justifies the use of the DNB and the BDS task in the current study. Furthermore, the embedded nature of the current study's design remains to be discussed. The cognitive data was split into the performance from the tasks administered on the computer and during the scanning sessions. The computer tasks were intended to enable a replication of the experiment by van Hedger and colleagues (Van Hedger et al., 2019) where the identical version of tasks was used. However, we wanted to also assess brain activity during task performance, and therefore implemented it as a pre/post intervention design inside the scanner. As a consequence, the time period between the intervention inside the scanner and the post test of computer administered tasks was much longer than in the original experiment by van Hedger and colleagues. The length of this period makes it difficult to interpret the behavioural results from the computer tasks. We do not know whether the cognitive modulation from listening to the soundscape carried over to this post intervention computer test. However, as discussed in the above section the effect on negative emotions did seem to carry over despite the time in between the intervention and the post measurement of affect. It could be that for a cognitive effect this time period was too long, but not for the affective modulation, supporting the notion of an independent multifaceted effect of environmental sound exposure. Another result of these specific design choices, was the need for an adjustment of the cognitive tasks for fMRI suitability. Pre- and post-measurement correlations between the tasks in the computer session show that both tasks share variance and seem to measure a similar construct. Nevertheless, neither the composite score nor the independent task scores derived from the computer tasks revealed any effect. In case of the parameters from the fMRI adjusted scan tasks, these between task correlations are actually too low to build an adequate composite score. However, we nevertheless report the results for the scanner task composite score since we planned and preregistered to replicate the behavioural result from van Hedger & colleagues (Van Hedger et al., 2019) inside the MRI scanner. In order to do so the same methodological approach was chosen. Considering the fact that the statistical analysis of the separate task scores did not reveal any differences between the conditions either, it remains to be investigated in future studies whether different design choices would enable replication of the behavioural result by van Hedger and colleagues (Van Hedger et al., 2019).

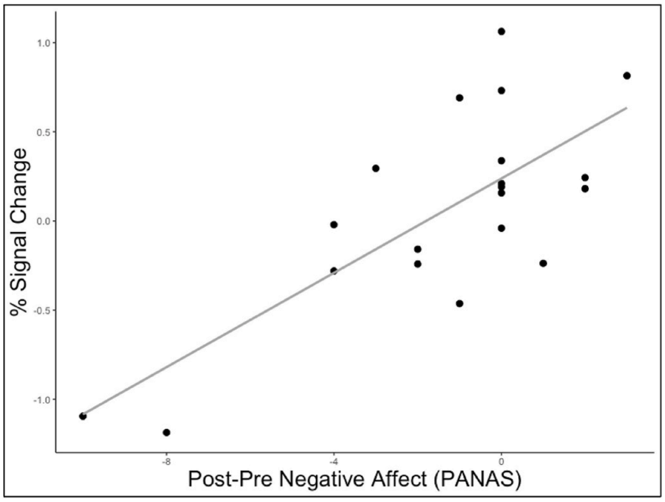

**Fig. 4. Correlation between brain activity changes during the DNB task and changes in negative affect during the nature soundscape condition.** Scatterplot graph with negative PANAS post-pre difference scores on the x-axis and percent signal change values from task related (dual n-back) neural activity (post-pre) during the nature condition on the y-axis. A decrease in negative emotions was associated with less activity in the inferior parietal lobule (IPL, MNI coordinate 60, -25, 32) after exposure to the natural soundscape intervention. After removal of one extreme outlier the correlation remained significant ($r = .65$, $n = 19$, $p = .002$).

The present experiment does not support the general pattern of the behavioural result by van Hedger & colleagues (Van Hedger et al., 2019), however the data was pointing into the hypothesized direction. Contrarily to the null-result concerning change in mood as reported by van Hedger and colleagues (Van Hedger et al., 2019) the current study demonstrated that participants reported significantly less negative emotions after listening to the natural soundscapes. Additionally, a condition specific change in brain activity resulting from stimulation with natural versus urban soundscapes was found in the STG. However, this result was statistically not corrected for multiple comparisons and subsequent interpretations remain exploratory and speculative only. The link between the behavioural effect and brain activity changes has also been examined, indicating a task-relevant brain region in the medial PFC, in which brain activity change was negatively correlated with the gain in performance. The link between the effect on negative

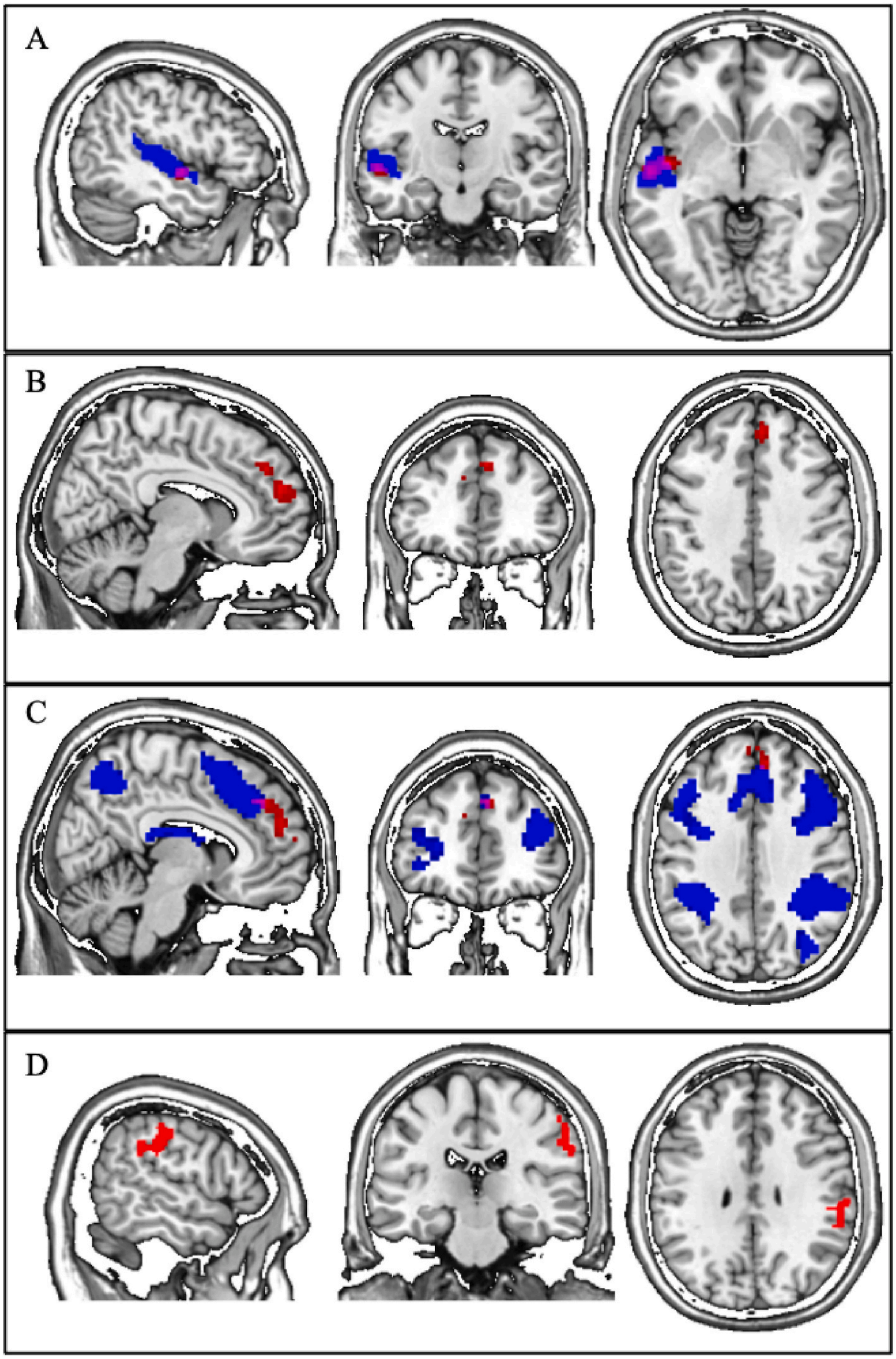

**Fig. 5.** ***Neural activity on template brains.*** *A: Anatomical template brain-image with superimposed brain activity in red and blue. The cluster (uncorrected) in red corresponds to the 2x2 interaction contrast found in the STG region. The cluster in blue corresponds to the mask contrasting auditory versus other trials. The overlay is shown in pink (additive overlay) B: Anatomical template brain-image with superimposed brain activity in red. SPM maximum intensity projection at [12, 56, 20]. The activity corresponds to voxels that show a negative correlation between n-back pre-post difference-scores and task related brain activity during the natural condition. C: The same image as above with additionally superimposed general n-back task activation derived from a 2-back versus baseline contrast.* D: *Anatomical template brain-image with superimposed brain activity in red. SPM maximum intensity projection at [60, -25, 32]. The activity corresponds to voxels that show a positive correlation between negative PANAS items pre-post difference-scores and DNB task brain activity during the nature soundscape condition.* (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

emotions and brain activity revealed a brain region in the parietal lobe indicating that a gain in negative emotions was positively correlated with an increase in brain activity in that region.

Participants' aesthetic ratings after the sound exposure demonstrate that natural sounds were significantly preferred over urban sounds in both pleasantness and beauty dimensions.

This is in line with the affective preferences about the soundscapes suggesting that emotional and aesthetic preference might be connected to the subjective restorative value of an environment. Environments which are connected to personally preferred emotions and aesthetics standards might be more successful in their restorative functioning. Participants reported a significant decrease of negative emotions on the testing day when they were stimulated with the natural soundscape. However, we observed no changes in positive affect. In Van Hedger and colleagues (Van Hedger et al., 2019) the author states that negative emotions might increase due to the complexity and exhaustive nature of the experimental paradigm. Considering the fact that in the present study these demands were even higher since the subjects performed the two cognitive tasks twice outside the scanner and twice within, the significant decrease in negative emotions following the exposure to the natural soundscapes seems to be a strong effect overshadowing any outcome in the opposite positive affective direction due to complexity and exhaustion.

While the cognitive data did not demonstrate a significant interaction effect, it is worth noting that there was an observed increase in the nature condition, while the urban and control condition rather displayed a decrease in performance which at least points into the direction of the data pattern described by van Hedger and colleagues. Although the effect was non-significant the direction of the effect supports the idea that listening to natural sounds may positively affect cognitive ability which in light of the fragility of this result remains only speculative.

However, when focusing solely on the behavioural data of the DNB task for which the fMRI analysis indicates a change in STG activity between the natural and urban sound condition. Namely only the dual modality blocks, an interesting result was observed. For those blocks a significant performance increase (from pre to post) was found for the natural sound condition but not for the urban one. This is particularly intriguing because as demonstrated by Berman and colleagues and in line with ART, attentional improvements caused by interactions with nature were only found “on the executive portions” of their task (Berman et al., 2008). These portions were characterized by trials with a distraction component similar to the case of the dual modality DNB trials where one modality is distracting the other one and vice versa (auditory vs visual). It might be the case that processing these trials requires executive attention which is related to directed attention and can be restored during interactions with natural environments. Executive functioning is a higher order capability required to guide an organized and ambitious life (Lezak, 1982). According to environmental psychologists directed attention seems to play an important role in executive functioning and can therefore be seen as a driver for effective cognitive functioning (Kaplan & Berman, 2010). An alternative explanation comes from a study demonstrating that motivation for a task was higher when participants have viewed aesthetic nature images in comparison to the pixelated counterparts (Joye et al., 2022). The increase in motivation could exert its effect on cognitive ability explaining the beneficial aspect of nature in cognitive studies. Regardless of the mechanisms behind the cognitive phenomenon described, the knowledge gained from the above described, as well as the current study, should be used in future educational contexts. The ultimate goal or consequence for such findings should be to incorporate this knowledge into a developmental and educational context. Executive functions have been shown to be more strongly associated with school readiness than intelligence quotient or entry-level reading or math skills (Diamond et al., 2007). This implies that already in early age it might be academically beneficial to train children how to increase their attention. The best way to make this practice inherently useful is to create a situation where children actively realize the attentional benefits of restorative environments for example by repeated outdoor exploration sessions before the classical classroom schooling. In subsequent classroom session nature sounds could be played gently in the background in order to evoke the restorative effect learned before.

Using an exploratory approach, a comprehensive whole brain analysis that specifically considered the influence of the nature and urban sound conditions unveiled an uncorrected cluster located in the superior temporal gyrus (STG) while participants performed the DNB task. Notably, the activity within the STG exhibited an increment from pre-exposure to post-exposure to urban soundscapes. Due to the statistical insignificance of this result all of the following interpretations remain of speculative nature. In light of the fact that the STG is part of the primary auditory network it is particularly interesting to find this increase in STG activity following urban soundscape stimulation. We hypothesized that differential changes in the natural and urban condition would involve regions typically known for their relevance in attention processes (VLPFC, DLPFC, ACC and TPJ). The current results might be taken to reflect that, attentional mechanisms, affected by the soundscape stimulation, intervene as early as at the primary processing stage. Evidence for the idea that early attentional demands are regulated in a primary sensory cortex such as the STG comes from a fMRI study investigating neural activity in the primary auditory cortex (PAC) during the processing of syllables. Activations in PAC were highest when subjects were instructed to detect a target syllable and lowest when subjects were instructed to ignore the stimuli, suggesting that attention can selectively modulate activity in the primary auditory cortex (Jäncke et al., 1999). In light of the results from the current study it could be suggested that such early attentional modulations, driven by the exposure to the two different soundscape types (nature and urban), could account for the activity difference in the STG. However, it remains to be unravelled why exposure to the urban soundscape resulted in an increase of activity in STG. One explanation revolves around a study with contradictory results to the ones by Jäncke and colleagues, they found that the PAC exhibited reduced activation when attention was explicitly recruited (Hugdahl et al., 2000). In light of this result, it could be argued that for subjects who have been exposed to the natural soundscape, attentional capacities have been restored (by mechanisms outlined by ART) in a way that more attentional capacities are available resulting in reduced PAC activity during recruitment of the replenished attention. Nevertheless, this is very speculative considering the contradiction of results in the aforementioned studies. In order to gain a better understanding of the reality early attentional mechanisms should be investigated more closely in combination with potentially modulating experiences with physical environments.

The behavioural performance data only hints at an improvement of BDS and DNB task performance caused by the nature sound exposure, and relative stability in the urban condition. This supports the idea, according to Hugdahl and colleagues, that less activity in the STG during the DNB task could reflect increased attentional capacities as a consequence of restoration through nature exposure, resulting in superior behavioural performance.

In order to explore links between the behavioural and neural effects, a whole brain correlation was run to associate changes in cognitive performance in the DNB task in the nature condition with brain signal changes in the nature condition, where a negative correlation was found in the medial prefrontal cortex (mPFC). The increase in executive functioning after subjects had listened to the natural soundscape condition was associated with a decrease in activity in the mPFC. This could potentially be interpreted as a more effective or economical way of processing the task relevant information. In order to strengthen this argument, the overlap from this cluster, linked to behavioural performance change and the general task activation (2-back vs baseline) was visually inspected. There was some overlap between both activation patterns however the overlap was only minor in spatial extent. This outcome suggests that there might be a subregion (region of overlap) of the prefrontal executive network that processes information more efficiently, thus with less activity, if the subject was exposed to a potentially restorative natural sound. In other words, subjects might be attentionally restored after being exposed to natural sounds resulting in less necessary executive control within this subregion in turn leading also to an increase in cognitive performance. Another whole brain correlation was run to associate the demonstrated reduction of negative emotions within the natural soundscape condition with brain signal changes after the exposure to natural soundscapes. A positive correlation was found in the IPL region, indicating that a decrease in reported negative emotions after exposure to nature soundscapes was associated with a brain activity reduction in the IPL. The IPL is known to be part of the cognitive control network (Fassbender et al., 2006; Westerhausen et al., 2010) suggesting that participants were able to process task related information with reduced cognitive control effort after they had been exposed to the natural soundscape condition. On top of that it might be the case, that this reduced effort in turn resulted in less reported negative emotions.

Taken together the current experiment demonstrates that task-related brain activity can differentially change with respect to an a priori experienced environmental sound stimulation. Brain activity in task-related primary sensory auditory increased following exposure to an urban soundscape. When correlating changes in cognitive performance with changes in brain activity levels it also became apparent that activity levels in a medial prefrontal cluster decreased with increasing levels of cognitive performance in those task runs, when participants were exposed to the natural soundscape. However, the effects reported in the current study are not particularly strong considering the fact that, the whole brain analysis did not reveal anything based on the t contrast including all three conditions, but only in an exploratory follow-up analysis and the fact that the cognitive effect was not significant. Therefore, more research like the current is needed to gain a deeper understanding of how nature affects the brain. Despite the fact that the explanations for the observed results remain mainly speculative, the current study provides valuable insights into the neural basis of a long-known phenomenon of cognitive benefits in response to interacting with natural environments. With respect to the previous theoretical accounts, it is worthwhile to mention that the brain regions that were found to be associated with behavioural or neural benefits after exposure to nature sounds were quite consistently located in cognitive processing related brain regions (PFC, STG, IPL) which is hinting towards cognitive restoration as described by ART. However, frontal regions such as the PFC e.g., subserve many functions making a direct link with cognitive restoration only speculative. The influence of nature soundscape exposure on negative affect presented here could be interpreted to demonstrate affective restoration as described in SRT, however it is unclear whether the decrease in negative affect after exposure to nature is due to and secondary to the restored cognitive ability which may reduce the fatigue experience when undergoing this complex cognitive paradigm. In a recent study by Sudimac and colleagues (Sudimac et al., 2022) it was demonstrated that Amygdala activity during a stress related task decreased after a 1-h walk in nature, arguing for a more SRT favoured conclusion about the effect of a real-life nature exposure. Considering this, it might reasonable to assume that ART and SRT are not necessarily conflicting theories but better said two accounts that explain two different pathways of a similar mechanism through which people benefit from interactions with nature. Potentially it comes down to the context of the tasks administered, reflecting the brain activity that can explain those differential outcomes. While the outcomes of the current study reflect an attentional restoration mechanism it might be that this is the case because participants were brought into a cognitive processing context due to the choice of tasks and that exposure to nature demonstrates its benefits in a context dependent manner. Alternatively, it might be the case that changes in both stress- and attention-related processes are the result of exposure to natural stimuli, selectively highlighted by the analysis of the corresponding dependent variables e.g., affect or attention. However, more research investigating the neural underpinnings of nature-based experiences is needed for a boarder understanding of how nature affects the brain.

## 5. Limitations

One limitation of the present study is the numerically higher number of male participants (23 males vs 12 females), which is a recruitment problem. Due to the time intensive investment of participating in the current study we recruited interested participants without balancing the sample in this regard. Future studies should stratify the subgroup by sex, such as to balance the sample. Furthermore, the addition of a neutral sound condition as control was to our methodological understanding necessary however it is not easy to justify what such a neutral sound condition should consist of. In the current study where we did not provide the participant with any auditory input during the neutral control condition, they were still exposed to the sound environment that the MRI scanner produced. During the nature or urban soundscape condition this scanner noise was also present however it might be that it was less perceivable due to the extra auditory input played via the headphones. The raw scanner noise is perceived differently for participants so we did not have much control over how participants perceived it besides the reported aesthetic ratings. Future studies could aim to develop a neutral control condition giving similar auditory inputs as the nature or urban soundscapes however it remains debatable what this neutral sound condition should be comprised of. Another limitation refers to the usage of the differences scores that have been created by subtracting post and pre intervention scores of several variables. Correlations between these scores constitute a measure of reliability and in the present study those correlations are not particularly high. However, it remains to be noticed that these pre and post measurements are separated by the experimental manipulation (soundscape intervention) which is expected to have an impact at least for the natural and urban conditions. For the control condition where no intervention impact is expected those correlations are adequately higher (around .70 on average). Lastly, the within-subject design of the current study resulted in an exhaustive task procedure for the participants potentially resulting in confounding effects of learning. Future studies which investigate a similar research question should consider employing a between-group (urban vs nature vs no sound) design while maintaining the pre- and post-sound exposure measures as a within-subject factor.

## 6. Ethics

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all participating subjects. The experimental protocol was approved by the ethical committee from the University Clinic Hamburg Eppendorf.

## 7. Data availability statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

## 8. Reviewer disclosure statement

This statement is to confirm that for the presented work all measures, conditions, data exclusions and sample size determination rules have been disclosed.

## Declarations

There are no conflicting interests to declare. The study was funded by the Max Planck Society and by the European Union (ERC-2022-CoG-BrainScape-101086188*)*. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Research Council Executive Agency (ERCEA). Neither the European Union nor the granting authority can be held responsible for them.

## CRediT authorship contribution statement

**Emil Stobbe:** Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, preparation, Visualization, Writing – review & editing, Project administration. **Robert C. Lorenz:** Formal analysis, Reviewing. **Simone Kühn:** Conceptualization, Supervision, Reviewing, Resources, Funding acquisition.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvp.2023.102141.

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# Impact of exposure to natural versus urban soundscapes on brain functional connectivity, BOLD entropy and behavior

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ABSTRACT

*Background:* Humans have been moving from rural to urban environments for decades. This process may have important consequences for our health and well-being. Most previous studies have focused on visual input, and the auditory domain has been understudied so far. Therefore, we set out to investigate the influence of exposure to natural vs urban soundscapes on brain activity and behavior.

*Methods:* Resting-state fMRI data was acquired while participants ($N = 35$) listened to natural and urban soundscapes. Two affective questionnaires (the Positive and Negative Affect Schedule (PANAS) and the Perceived Stress Scale) and two cognitive tasks (dual n-back (DNB) and the backward digit-span (BDS)) were assessed before and after each soundscape condition. To quantify brain function we used complexity and network measures, namely brain entropy (BEN) and whole brain functional connectivity (FC). To study the link between brain and behavior, changes in BEN and whole brain FC were correlated to changes in cognitive performance and self-reported affect.

*Results:* We found higher BEN when listening to urban sounds in posterior cingulate gyrus, cuneus and precuneus, occipital lobe/calcarine as compared to nature sounds, which was negatively correlated to (post-pre) differences in positive affect (PANAS) in the urban soundscape condition. In addition, we found higher FC between areas in the auditory, cinguloopercular, somatomotor hand and mouth networks when listening to nature as compared to urban sounds which was positively correlated to (post-pre) differences of the of the composite score of Digit span and N-back for nature soundscape.

*Conclusions:* This study provides a framework for the neural underpinnings of how natural versus urban soundscapes affect both whole brain FC and BEN and bear implications for the understanding of how the physical auditory environment affects brain function and subsequently observed behavior. Moreover, correlations with cognition and affect reveal the meaning that exposure to soundscapes may have on the human brain. To the best of our knowledge this is the first study to analyze BEN and whole brain FC at rest during exposure to nature and urban soundscapes and to explore their relationship to behavior.

## 1. Introduction

Urbanization describes the tendency of the human population to move from small rural communities into cities. Amongst the biggest differences between rural and urban living is the exposure to noise pollution. In a magazine article about noise maps of New York City, noise exposure is portrayed as one of the biggest threats to quality of life. Citizens are actively complaining about noise over 100 times per day (Metcalfe, 2013). According to Goines and Hagler, evidence for the link between noise exposure and health effects is more extensive than for any other environmental hazard (Goines and Hagler, 2007). Several of these negative health outcomes consist of mental health problems showing that exposure to noise pollution can cause sleep disturbances and malfunctioning of attentional resources due to stress and distraction (Hammer et al., 2014) There are also hints at subconscious effects of noise pollution, suggesting that noise can be perceived as a danger signal even during sleep (Suter, 1991). On a cortical level it has been demonstrated that “safe” sounds, which are played at volumes distinctly below

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the safety standard sound pressure level, do not impact hearing, and can still show negative cortical consequences in the auditory system of rats (Zhou and Merzenich, 2012). Additionally, Cheng and colleagues suggest that long-term exposure to noise pollution can have severe neuropsychological consequences by showing that working memory impairments are associated with long-term aircraft noise exposure in pilots (Cheng et al., 2019). Urban sounds are potentially hazardous because they contain multiple sources of noise, and according to Goines and Hagler, health effects related to noise exposure are associated with the sum of noise pollutants from various sources rather than any particular noise source (Goines and Hagler, 2007).

In order to escape urban noise pollution at least partially, humans tend to seek quality time in natural environments where they can flee from the stimulants of the city. Sound exposure from natural environments has been shown to be beneficial for several mental health outcomes. Evidence comes from studies showing that natural sounds can help to recover from psychological stressors (Alvarsson et al., 2010), or to increase executive functioning in direct comparison to urban sounds (Van Hedger et al., 2019). Birdsongs have been associated with perceived stress recovery and attention restoration (Ratcliffe et al., 2013). Moreover, birdsongs have been demonstrated to alleviate state anxiety and paranoia in healthy subjects (Stobbe et al., 2022) suggesting that they can counteract psychological risk factors of urban exposure (Krabbendam and Van Os, 2005). In their meta-analysis Krabbendam and Van Os (2005) report more than 10 studies that demonstrate a potential relation between incidences of schizophrenia and urban environmental factors (urbanicity).

In order to understand why humans might benefit from exposure to natural sounds, while they tend to suffer from exposure to urban sounds, it is essential to take into account the prevailing theories on the effects of nature. There are two theories most prominent in the discussion on restorative environments, attention restoration theory (ART) and stress reduction theory (SRT). ART claims that exposure to natural settings allows for a restorative experience by replenishing cognitive resources depleted during voluntary attentional tasks in urban environments. Nature's intrinsic qualities, such as its "soft fascination" and the presence of non-threatening stimuli, engage our involuntary attention resources and promote cognitive restoration (Berman et al., 2008). In a study by van Hedger et al. (2019) this has been demonstrated in a laboratory setting making use of the natural soundscapes used in the present study (Van Hedger et al., 2019).From a somewhat different perspective, SRT focuses primarily on the role of nature in reducing stress. It emphasizes the physiological and psychological benefits of natural environments, which humans encountered through the course of evolution. SRT argues that nature is perceived as a hard-wired context signaling the presence of resources essential for survival, facilitating relaxation and overall well-being (Ulrich, 1983). Although there appears to be data supporting both of these explanations, a valid counterargument exists.

When humans encounter different environments in their daily life, another important factor becomes relevant. Prior experiences with a certain environment will shape the perception of such experiences in the future. These experiences are individual and can be positive or negative for a given environment (natural or urban). In order to explain the overall beneficial effects of natural environments Conditioned restoration theory (CRT) proposes that humans may have learned the restorative benefits from natural settings by means of personal significance, triggering positive emotions and memories such as those formed during a tranquil and picturesque forest walk in the past (Egner et al., 2020). Another theoretical account, directly challenging ART, comes from Joye et al. (2022). In their study motivation has been found to be an underlying factor why exposure to natural stimuli could enhance cognitive performance (Joye et al., 2022). Motivation is reported to be higher when participants viewed beautiful nature images, highlighting the relationship between subjective perception and the restorative effects on cognitive performance. This is especially interesting considering CRT as described above. Motivation and personal significance may play an important role in how natural stimuli express their benefits. These roles are not considered by ART and SRT.

Considering the numerous health hazards that follow urban noise pollution, the health benefits associated with natural sound exposure and the lack of theoretical agreement on the underlying mechanisms, studying the neural processes that underlie such auditory stimulations is highly relevant.

To study the effects of natural versus urban sound stimuli in brain and behavior, we previously conducted a pre-post comparison of e.g., cognitive tasks and brain activity before and after the stimulus intervention, for details see (Stobbe et al., 2023). In Stobbe et al. (2023), we investigated pre-posttest differences in task performance and the brain activity in task-fMRI during the execution of the tests *before and after* the soundscape intervention. In the present article, we set out to investigate brain activity at rest and brain connectivity *during* soundscape exposure, by means of brain entropy (BEN) and whole brain functional connectivity (FC). Additionally, the association between affect, cognition and the two resting state brain parameters were of interest. BEN quantifies the complexity of brain signal dynamics and is a powerful tool to study brain function (Keshmiri, 2020). It has been stated that the brain needs to maintain a certain level of BEN in order to function properly (Bergström, 1969), where higher levels of BEN reflect more complexity and randomness of signals within the system (Costa et al., 2005). Differences in BEN during resting-state-FMRI demonstrated its value to partially explain individual differences of task activations (Lin et al., 2022). In addition, BEN is relevant for studying mental disorders. Differences in BEN have been reported in several mental health conditions such as schizophrenia (Xue et al., 2019), autism spectrum disorder (Easson and McIntosh, 2019; Maximo et al., 2021), and Alzheimer's disease (Xue and Guo, 2018) in comparison to healthy controls. In the case of Alzheimer's disease and the autism spectrum disorder higher levels of BEN have been demonstrated in patients compared to healthy controls. Importantly, another study on patients with a high risk of developing Alzheimer's disease (Ni et al., 2021) reports decreased levels of BEN in several brain regions. This demonstrates that effects of BEN can be shown in both directions in the same disease. Research on other mental health conditions such as attention deficit hyperactivity disorder (ADHD) (Sokunbi et al., 2013) and post-traumatic stress disorder (Fu et al., 2023) demonstrate reduced levels of BEN when compared to healthy controls. Taken together, these studies demonstrate, that levels of BEN can fluctuate in both directions when comparing healthy controls with patients across various mental health conditions. This on the one hand, highlights the potential of BEN as a biomarker of various brain-related diseases, but on the other hand also illustrates the lack of studies to enable a more comprehensive understanding of this neural signal and its function within the brain.

To our knowledge, as of now no study has investigated differences in BEN and whole brain FC at rest while subjects were listening to environmental sounds. It is particularly interesting to investigate BEN in resting-state data acquired during natural versus urban sound exposure because BEN is thought to provide complementary insight into brain function due to its relative independence of the more commonly acquired measures of brain activity changes in task designs (Nezafati et al., 2020). Nezafati et al. (2020), point out that different brain regions and networks show different levels of BEN, suggesting that this difference is due to functional specialties that these regions are engaged in, e.g., the auditory network processes auditory information while visual network process visual information, etc. The frontoparietal network has the highest entropy during rest, for example while the dorsal attention network shows the lowest entropy during rest. With respect to the whole brain, entropy decreases during the execution of a working memory task in a region-dependent manner (Nezafati et al., 2020). It might be possible that exposure to different environmental sounds (nature versus urban) can affect BEN. Considering the fact that several functional networks exhibit different levels and level changes of BEN it becomes very speculative to formulate directional hypotheses regarding BEN. Hence, a more exploratory approach has been employed.

Differences in how the brain processes information can also be studied using FC. The literature in which differences in FC are investigated comparing naturalistic scenarios and man-made scenarios in both the visual and auditory domain are scarce and the topic has only begun to be investigated lately (Gould Van Praag et al., 2017; Kingelbach et al., 2023; Kühn et al., 2021; Salvari et al., 2019; Vanderwal et al., 2019). In a study by Gould Van Praag et al. (2017), it was revealed that changes in heart rate were correlated with baseline FC within the default mode network (DMN) and baseline parasympathetic tone in response to naturalistic sound exposure, suggesting an association between nature exposure, stress relief and FC in the DMN. FC measured by means of magnetoencephalography (MEG) showed significant interconnection differences between sounds categorized as having a living vs a man-made source in various brain regions such as prefrontal cortex (PFC), the anterior-superior temporal gyrus (aSTG), posterior cingulate cortex (PCC) and supramarginal gyrus (SMG) shortly (80–120ms) after the stimulus. This suggests that the processing of those different sound categories relies on distinct cortical networks (Salvari et al., 2019). This highlights the importance of further investigating brain FC differences in response to auditory processing of natural versus urban soundscapes using resting state fMRI data analysis tools. Based on the association between nature exposure and increased FC mentioned above, we hypothesize that the brain processes these two sounds distinctively, which can be attested by finding different levels of BOLD complexity reflected in BEN and in different strengths of FC in brain networks during passive listening to natural versus urban soundscapes. Due to the scarcity of the previous literature, we refrained from hypothesizing a directionality of the brain change or targeting brain networks besides the auditory ones, deciding for a more exploratory data-driven approach where the whole brain and all brain networks are taken into account.

## 2. Methods

### 2.1. Participants and design

Thirty-five participants (12 female, mean age = 27,6 years) were recruited via the participant pool of the Max Planck Institute for Human Development and took part in this study. Participants had normal or corrected-to-normal vision and were not taking any psychotropic medication. Each participant was invited on three separate days, each day being exposed to one of the three experimental conditions (nature, urban, control). Before and after the sound exposure, participants were asked to perform two cognitive tasks on a computer outside of the scanner (identical to the versions used by (Van Hedger et al., 2019)). During the scanning procedure participants were required to perform an fMRI variant of the two cognitive tasks administered directly before and after the soundscape intervention. The order of the soundscape intervention across the three testing days was counterbalanced to eliminate any stimulus-order effects. fMRI data was acquired for the following stages of the experiment: cognitive task pre-test, soundscape intervention and cognitive task post-test. After the MRI session, participants returned to the computer where they were again assessed with the two cognitive computer tasks and additional questionnaires. All participants provided informed consent and the study was approved by the Local Psychological Ethical Committee at the Centre for Psychosocial Medicine at University Medical Centre Hamburg-Eppendorf in Hamburg, Germany (LPEK-0077). All participants were debriefed and received monetary compensation after participation. Therewith the experiment consisted of a 2 (time: pre-intervention, post-intervention) x 3 (soundscape: natural, urban, no-soundscape) factorial design, with time and soundscape as within-subject factors. The current manuscript covers the analysis and interpretation of data related to the resting state brain activity recorded during the soundscape presentation. All other variables are analyzed within a separate manuscript (Stobbe et al., 2023).

### 2.2. Material

Forty natural and forty urban soundscapes were used from a previous study (Van Hedger et al., 2019) that made the soundscapes openly available via the Open Science Framework. The natural soundscapes consisted of birdsongs, moving water, insects and wind. The urban soundscapes were predominantly traffic sounds, café ambiance (unintelligible speech), and machinery sounds. It is important to note that each soundscape could contain sounds from multiple sound sources in order to create a realistic simulation of what one might hear in these settings. The soundscapes were of 20s duration with a 500-ms linear fade in and fade out. Due to this fading in and out an impression of a continuous environmental sound exposure was accomplished. The total duration of the soundscape intervention was 13.3min. The amplitude of the sounds was normalized in order to get consistent loudness during the intervention. Additionally, the selected soundscapes had previously been categorized by participants in order to verify that these soundscapes were actually classified as belonging to a natural and urban category. The result of this test verified that there was no overlap in ratings meaning that the lowest-rated natural soundscape (7- point rating where 1 was “very urban” and 7 was “very natural”) was rated higher than the highest-rated urban soundscape (Van Hedger et al., 2019).

### 2.3. Measures

#### 2.3.1. Affective

The Positive and Negative Affect Schedule (PANAS) assesses participants’ feelings during the last hour by presenting 10 positive and 10 negative affective adjectives (Watson et al., 1988). The Perceived Stress Scale (PSS) (Cohen et al., 1983) was employed to assess participants level of self-perceived stress using 14 items. Both affective questionnaires used a standard 5-option answer format (0-never until 4-very often). These questionnaires were also administered before and after the scanning session on each subsequent day. Aesthetic ratings were collected at the end of the experimental session each day, assessing the subjective beauty and pleasantness perception of the presented soundscape.

#### 2.3.2. Cognitive

Two tasks were chosen to reflect directed attention. In the previous study, with a comparable design, a composite score was computed from the dual n-back (DNB) and the backward digit-span (DBS) performance (Van Hedger et al., 2019). In order to do so, the performance measures from the DBS and DNB tasks were converted into $z$ scores (raw score minus grand mean divided by standard deviation) and averaged across tasks separately for each *soundscape condition* (nature, urban, control) and *time* point (pre- and post-intervention). More detail on the tasks and how they have been adapted for fMRI can be found in the Supplementary Material; taken from (Stobbe et al., 2023).

### 2.4. Procedure

Participants signed the informed consent form and filled out the MRI contradiction screening sheet before the experiment started. Afterwards participants completed the first computer session which included a survey on demographic information, the PANAS, the PSS and the pre-intervention administration of the DBS task as well as the DNB. Once the computer session was finished, participants entered the MRI scanner. During the MRI scan for event-related fMRI, participants first completed one fMRI run of the DBS task followed by one run of the fMRI DNB task. Subsequently, the resting-state-fMRI acquisition during the sound intervention took place in which participants were exposed to the soundscapes from one of the three categories via MR-compatible headphones inside the MRI scanner. After the intervention participants completed another run of the DBS and DNB task as a post-intervention measure inside the scanner. Following the completion of the scanning procedure, participants were asked to complete the post intervention computer session and to additionally answer some simple questions about the beauty and pleasantness of the soundscape intervention. The computer as well as fMRI versions of the tasks were administered after each other without any major delays. The delay between the pre and post measurement was 15 min for the fMRI tasks and the length of the scanning procedure (1.5 h plus a break afterwards) for the computer tasks. The delay between sessions was dependent on the participants availability but was limited to 10 days. After having completed their third testing day, participants were debriefed and compensated monetarily.

### 2.5. *Image acquisition - MRI and resting-state fMRI*

Here we describe the structural and resting-state sequence. This study comprised also a task-fMRI acquisition described in a previous publication (Stobbe et al., 2023).

Structural images were acquired using a Siemens Tim Trio 3T scanner (Erlangen, Germany) using a 32-channel head coil. High-resolution T1-weighted MR images of 192 slices with an in-plane resolution of 1 $mm^2$ were acquired (magnetization prepared gradient-echo sequence (MPRAGE) based on the ADNI protocol (www.adni-info.org), repetition time (TR) = 2500 ms; echo time (TE) = 4.77 ms; TI = 1100 ms, acquisition matrix = 256 × 256 × 176, flip angle = 7°). Functional data was acquired after the T1 image using an echo planar imaging (EPI) sequence with a duration of 15min (TR = 2000 ms, TE = 30 ms, acquisition matrix = 216 × 216 × 129, flip angle = 80°, slice thickness = 3.0 mm, distance factor = 20%, FOV = 216 mm, 3 × 3 × 3 $mm^3$ voxel size, 36 axial slices, using GRAPPA).

### 2.6. *Resting-state fMRI preprocessing*

This study focused on the resting-state fMRI data. The first 5 images were discarded to ensure steady-state longitudinal magnetization. The acquired data was corrected in terms of different time of acquisition by means of slice timing correction and then realigned. Structural T1 images were co-registered to the functional images and segmented into gray matter, white matter and cerebrospinal fluid. Next, the data was spatially normalized to the Montreal Neurological Institute (MNI) template. To improve signal-to-noise ratio, the data was spatially smoothed with a 6-mm FWHM kernel. To reduce physiological high-frequency respiratory and cardiac noise and low-frequency drift, the data was filtered (0.01–0.09 Hz). Regression of motion and signals from white matter and cerebrospinal fluid were performed and finally the data was detrended. To exclude excessive movement, the voxel-specific mean frame-wise displacement (FD; (Power et al., 2012) was calculated. Subjects with FD higher than the commonly used threshold of 0.5 were excluded. All subjects had FD values lower than the default threshold of 0.5. FD per condition was: control = 0.163 ± 0.011, nature sounds = 0.142 ± 0.013 urban sounds = 0.182 ± 0.018. Movement given as mean FD was not significantly different between conditions (repeated measures ANOVA, $F$ (2,60) = 0.083, $p$ = 0.92). All steps were conducted using SPM12 (Statistical Parametric Mapping package; Welcome Department for Imaging Neuroscience, London, United Kingdom, https://www.fil.ion.ucl.ac.uk/spm/) with exception of filtering, which was performed in the REST toolbox (Song et al., 2011) under MATLAB 2016b (www.mathworks.com). The complete analysis workflow can be seen in Fig. 1.

### 2.7. *Whole brain FC*

We extracted time series of the resting-state fMRI data from regions of interest (ROIs) to build brain networks that consist of nodes and edges. The nodes were ROIs taken from brain atlases: a functional parcellation from Gordon and colleagues (Gordon et al., 2016) and the anatomical automated anatomical labeling (AAL (Tzourio-Mazoyer et al., 2002),). The Gordon parcellation contains 333 nodes in 12 networks and has the advantage of being highly homogeneous which means the nodes share similar resting-state FC patterns. The AAL parcellation contains 116 anatomically defined nodes. Once the nodes were established, we calculated the edges. The edges represent the FC between ROIs (nodes). To calculate those, we first extracted the time series of BOLD in each ROI and then calculated Pearson's correlation coefficients between each pair of ROIs. Networks formed using Gordon's parcellation yielded symmetric matrices with size 333 by 333 and those using AAL 116 by 116. The complete analysis workflow can be seen in Fig. 1

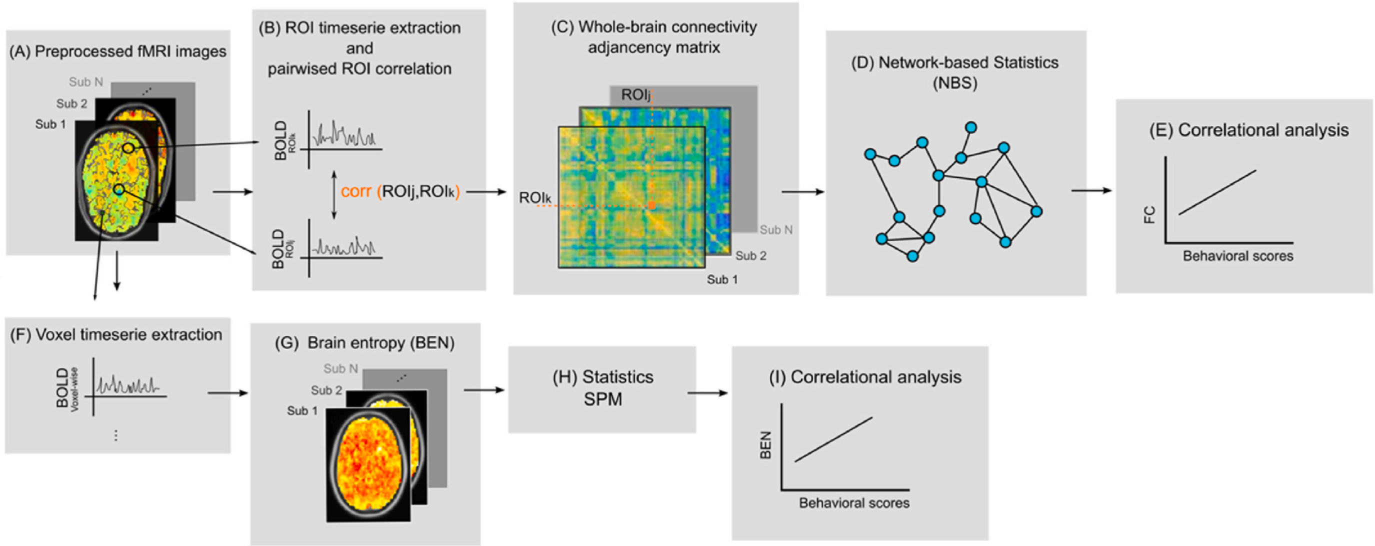

**Fig. 1.** Analysis workflow. (A) Resting state fMRI images were preprocessed. (B) Average BOLD timeseries of each ROI (Gordon atlas, AAL atlas) was extracted. (C) Whole brain pair-wise correlation of timeseries using Pearson's correlation coefficient forming one adjacency matrix per participant/condition. (D) Network-based statistics was performed to reveal the differences in subnetworks between conditions. (E) correlational analysis FC with behavioral scores (F) BOLD timeseries of each voxel in whole brain were extracted. (G) voxel-wise sample entropy (BEN) was calculated resulting in one entropy map per participant/condition. (H) Individual BEN maps were taken to the second level in SPM12. (I) Correlational analysis of BEN and behavioral scores.

### 2.8. BEN estimation

BEN was estimated using sample entropy (Richman and Moorman, 2000), which was developed for short-term time series. Sample entropy is a nonlinear signal processing technique developed to estimate complexity in biomedical signals. A signal with high complexity has a high occurrence of multiple different patterns, also known as having high variability. The opposite is true for signals with low entropy, where the complexity of the signal is lower and fewer patterns occur indicating lower variability. Entropy is also related to the concept of predictability and randomness. This relationship is better understandable when examining extreme cases. If we take the extreme case where just one pattern occurs, this means that the system does not change and there is no variability and therefore the entropy will be 0. The absence of variability, or differently put, the regularity of the system, makes it fully predictable. The other extreme case is where several different patterns occur with the same probability, this represents the opposite of regularity (randomness). The entropy value therefore reaches its maximum, the numerical value 1.

Here we applied BEN to measure the complexity of the brain dynamics present in the BOLD signal in the resting-state fMRI in three experimental conditions: listening to nature sounds, listening to urban sounds, and in the absence of sound.

In order to calculate BEN we used MATLAB 2016b and the function used to calculate it was downloaded from MATLAB File Exchange (https://de.mathworks.com/matlabcentral/fileexchange/69381-sample-entropy (Martínez-Cagigal, 2018);).

To do this, two parameters need to be selected in advance, namely the embedding dimension *m* and the tolerance coefficient *r*. Parameter *r* is related to the percentage of the standard deviation of the time series and *m* to pattern length. Since the choice of these parameters is arbitrary, we followed the suggestions from Pincus and Goldberger (Pincus and Goldberger, 1994) where the data length of the BOLD time series is recommended to be between $10^m$ and $30^m$, thus our *m* was set to 2. For *r*, previous studies have used values between 0.2 and 0.6 (Molina-Picó et al., 2011; Nezafati et al., 2020; Wu and Bogdan, 2021). Based on these previous studies we set *r* to 0.4. BEN was calculated per voxel from pre-processed BOLD time series resulting in a whole brain BEN map per subject.

The complete analysis workflow can be seen in Fig. 1

### 2.9. Statistical analysis

#### 2.9.1. BEN

Individual BEN maps were taken to the second level in SPM12 (https://www.fil.ion.ucl.ac.uk/spm/). Differences between conditions, no sound, nature soundscape and urban soundscape, were calculated using a repeated-measures ANOVA and paired *t*-test, as we were mostly interested in differences between nature and urban conditions, with $p \leq 0.001$ and additional threshold set to $p \leq 0.05$ using family-wise error (FWE) at cluster-level. FD was entered as a covariate. SPM12 ran under MATLAB 2016b.

#### 2.9.2. Whole brain FC network

We performed the statistical analysis comparing whole brain networks between conditions using network-based statistics (NBS) (Zalesky et al., 2010). NBS is a non-parametric statistical tool developed to compare whole brain networks. From all links present in the whole brain networks, NBS identifies sets of links that differ significantly between conditions while controlling for family-wise error (FWE). For that, NBS applies a cluster-based threshold in statistical parametric maps. Firstly, a *t*-test is applied to every single link. Secondly, a statistical threshold is computed. The remaining links of these first steps are called suprathreshold links. Finally, a breadth-first algorithm is applied to the suprathreshold links to obtain connected sets where the size is determined by the total number of links in a set. For each set, an FWE corrected *p*-value is estimated by permutation testing based on its size. In our study, we applied NBS configured to perform repeated-measures ANOVA in all conditions, no sound, nature soundscape and urban soundscape to the functional networks explained above and FD was used as covariate. The parameters were set as follows: N = 5000, threshold F = 15, component size = extent, significance = 0.05 and we report results with *p*-values$\leq$0.001 corrected for multiple comparisons. The analysis was performed using the NBS Toolbox v1.2 and MATLAB 2016b. Results were visualized using the BrainNet Viewer (Xia et al., 2013).

#### 2.9.3. Correlational analysis with behavioral variables

Then we investigated whether differences between conditions in BEN and in whole brain FC were correlated to behavioral indicators (positive and negative PANAS, DBS, DNB and composite DBS-DNB). The behavioral data for the PSS scale did not reveal any differences between the conditions (Stobbe et al., 2023) so we did not include this variable in the brain correlation procedure. For each subject, BEN values were extracted from the cluster where significant differences between conditions were found and then averaged. The same procedure was applied to the subnetworks revealed by NBS, for each subject, the FC of all links in the subnetwork were extracted and then averaged. Finally, the average BEN as well as the average FC was correlated to the behavioral indicators using either Pearson's or Spearman's correlation coefficients according to the distribution of the variables. For this analysis we report *p*-values $\leq$0.05 uncorrected. Correlational analyses were computed in MATLAB 2016b.

## 3. Results

Our analysis workflow is displayed in Fig. 1.

### 3.1. BEN

We found differences in BEN when comparing all conditions (nature, urban, no sound) in a cluster comprising posterior cingulate gyrus, cuneus and precuneus, occipital lobe/calcarine (MNI: 0,-62,16, cluster size = 382 voxel, $p < 0.0001$ FWE at cluster-level, $T = 5.09$), while higher BEN was shown when listening to urban sounds as compared to nature sounds (Fig. 2 A and B). This indicates that listening to urban sounds increases the complexity of the BOLD signal dynamics.

### 3.2. Whole brain FC

We analyzed differences in connectivity between all areas in the whole-brain functional connectome between all conditions (nature, urban, no sound) using functional and anatomical atlases. For the functional atlas, we observed differences in FC, namely, lower FC between areas in the auditory, cinguloopercular, and somatomotor hand and mouth networks when listening to urban sounds compared to nature sounds (Fig. 3 A and B). No robust differences were found using the anatomical atlas (AAL).

### 3.3. Correlation with behavioral indicators

#### 3.3.1. BEN

The entropy of the cluster in which we found significant differences between conditions (Fig. 2) was extracted per participant for each condition and correlated with the difference (post-pre) of positive and negative affect in PANAS, cognitive performance in the DNB and DBS tasks, as well as a composite score of DNB and DBS. We found a negative correlation between the mean BEN when listening to urban sounds and the change in positive affect (PANAS) from before to after the sound exposure ($r(\text{df2} = 24 \text{ but } N = 21) = 0.4, p = 0.04$ uncorrected) (Fig. 2C). Thus, the interpretation is the higher the BEN, the stronger the decrease in positive affect in the urban sound condition.

No correlations were found with the remaining variables (p-values

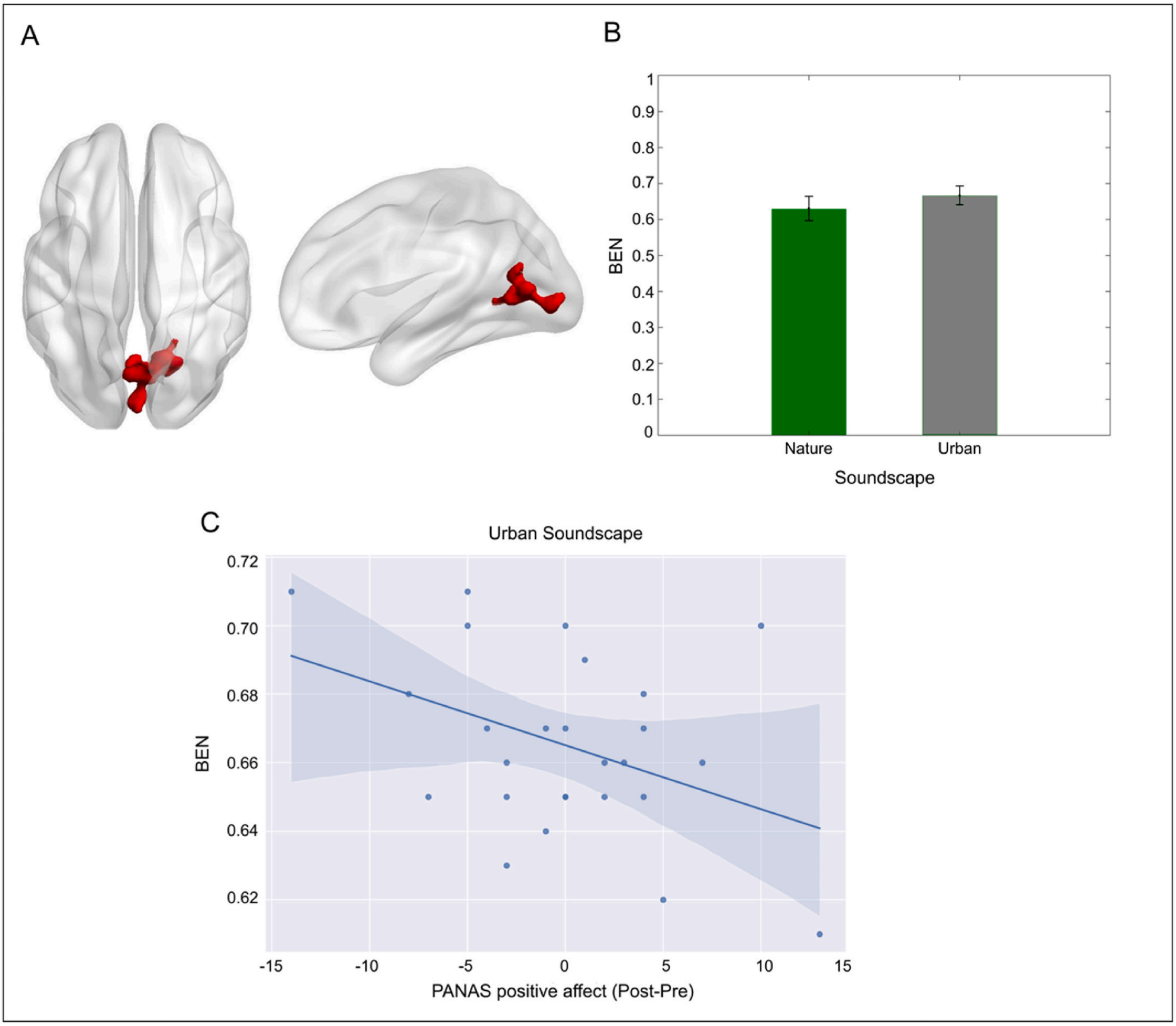

**Fig. 2.** Entropy urban vs nature sounds. A- We observed higher brain entropy (BEN) in a cluster comprising posterior cingulate gyrus, cuneus and precuneus, occipital lobe/calcarine (MNI: 0,-62,16, cluster size = 382 voxel, $p < 0.0001$ at cluster-level FWE, $T = 5.09$) when listening to urban sounds as compared to nature sounds. B- average entropy extracted from the cluster in A. C- Correlational analysis. We found a negative correlation (p value = 0.04 uncorrected) between the mean entropy when listening to urban sounds and the change in positive affect (PANAS) from before to after the sound exposure.

>0.3).

### 3.3.2. *Whole brain FC*

The mean *z*-score FC of the set of connections resulting from the NBS analysis (Fig. 3C) was extracted per participant for each condition and correlated with the difference (post-pre) of positive and negative affect in PANAS, cognitive performance in the DNB and DBS tasks, as well as a composite score of DNB and DBS. Here we observed a positive correlation between the mean FC when listening to nature sounds and difference (post-pre) of the composite score of Digit span and Nback ($r(19) = -0.46$, $p = 0.04$ uncorrected). A positive correlation reflects that the higher the FC the higher the increase of the composite score after listening to nature sounds. No significant correlations were found for the urban sound condition. However, the reported correlations have to be treated with caution, since they would not survive conservative multiple test correction (Bonferroni correction).

No correlations were found with the remaining variables (p-values >0.15).

## 4. Discussion

The main purpose of the current study was to investigate the differences in parameters of the brain at rest by means of BOLD entropy and whole brain FC while participants were listening to either natural or urban soundscapes. In general, the approach was data-driven and exploratory in nature. With regard to BEN, a significantly more complex BOLD signal was demonstrated in the PCC, the precuneus and the calcarine while subjects were listening to the urban soundscapes. With respect to whole brain FC, the current study revealed lower FC between areas in the auditory, cinguloopercular, and somatomotor hand and mouth networks while subjects were listening to the urban compared to the nature soundscapes. Exploring the link between behavior and brain activity, a negative correlation between positive affect items (PANAS) and the BEN measure was observed in the urban soundscape condition,

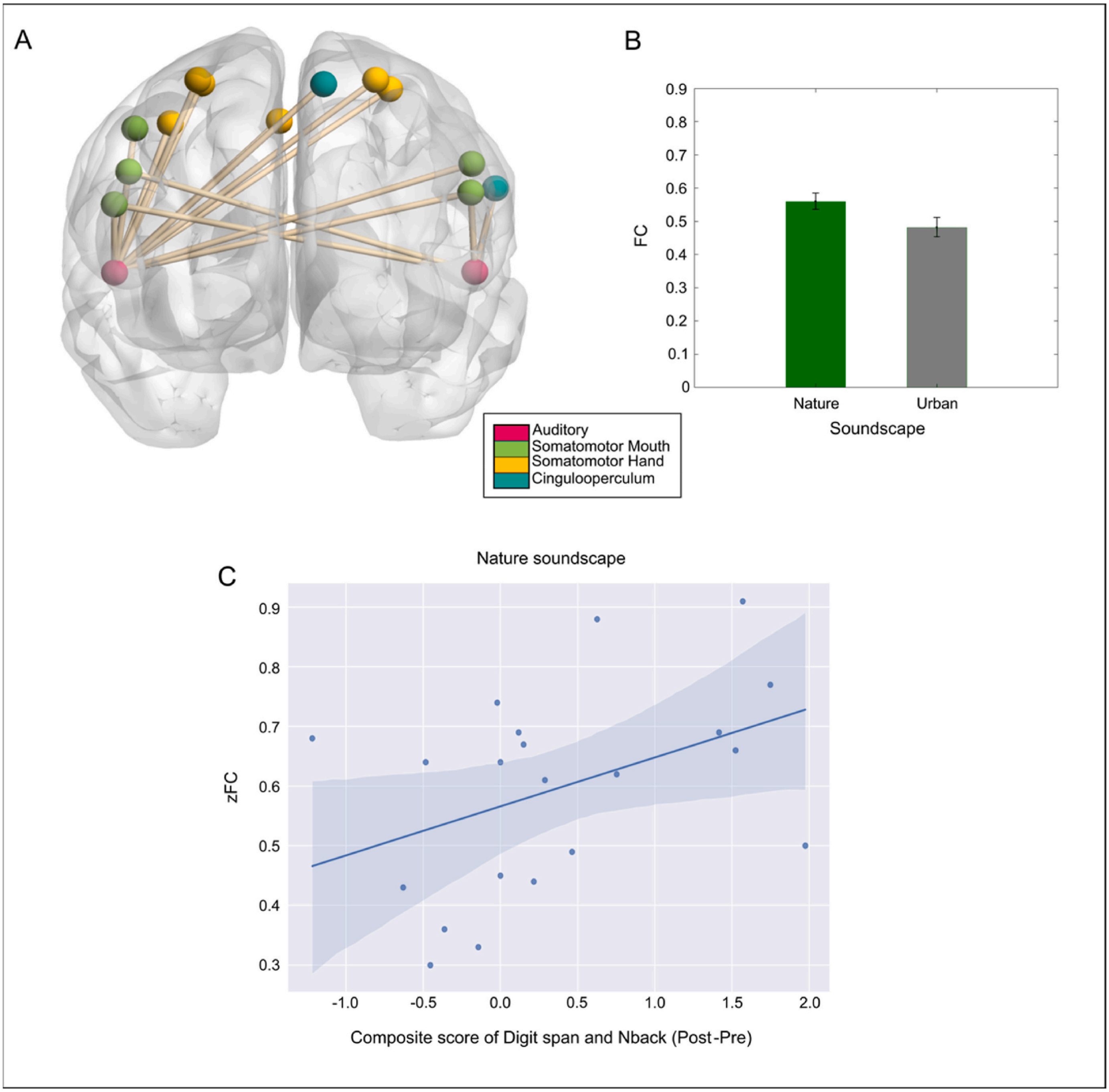

**Fig. 3.** A - Differences in whole brain FC between conditions. We found a significant higher FC between areas in the auditory, cingulooppercular, somatomotor hand and mouth networks when participants listened to nature sounds as compared to urban sounds. B - Average FC extracted from regions in A. C - Correlational analysis: FC and the composite score of Digit span (DBS) and Nback (DNB) (post-pre). We observed a positive correlation ($p = 0.04$ uncorrected) between the mean FC when listening to nature sounds and difference (post-pre) of the composite score; that is, the higher the connectivity the higher was the increase of the composite score after listening to nature sounds[ES3].

indicating that after participants had listened to the urban soundscapes an increase in BEN was associated with a stronger decrease in reported positive affect. Linking participants' cognitive performance (composite score DNB & DBS) with brain FC, a positive correlation was found in the nature condition, indicating that a gain in performance was associated with higher FC in the areas from the auditory, cinguloopercular, somatomotor hand and mouth networks after participants had been exposed to nature sounds.

Living in cities is usually accompanied by a constant level of noise pollution. Similarly, pilots of aircrafts are exposed to constant noise pollution at their job, causing their working memory abilities to decrease over time (Cheng et al., 2019). Another study revealed that increased BEN can be seen as an essential driver of neural and cognitive decline (Drachman, 2006). This becomes particularly interesting considering the fact that the results of the current study reveal that BEN increases after subjects listen to a short urban soundscape audio file, possibly reflecting a reaction to the exposure to noise pollution. One might suggest that urban sounds convey a lot of uncertainty which might be translated into a more chaotic processing of information, which may in turn may lead to greater BEN. Potentially this is happening via noise induced stress which has been demonstrated can lead to a reduction of neurogenesis in rodents (Henckens et al., 2015; Hu et al., 2014). Thus, living in highly urbanized areas consequently exposes its habitants to higher levels of noise pollution-related stress constituting a factor facilitating cognitive decline. The current study reveals increased levels of BEN after subjects were exposed to such sources of noise pollution (urban soundscape) as compared to nature soundscape.

The second neural outcome measure that we focused on in the current study was brain FC. It was demonstrated that after listening to urban sounds brain FC was lower than when listening to nature sounds. This finding sheds light on another relationship, namely the association between urbanicity and risk for schizophrenia (Krabbendam and Van Os, 2005; Vassos et al., 2012). Schizophrenia has long been associated with decreased FC strength and has been described as a dysconnectivity syndrome (Friston, 1998; Lynall et al., 2010). It remains to be further explored if the underlying mechanisms that explain why urban living heightens the risk for schizophrenia are the same as the ones that link schizophrenia to decreased FC. Schizophrenia patients suffer from reduced connectivity between prefrontal brain regions and other regions of the brain (parietal cortex, temporal regions, default mode network regions). This reduction has been associated with cognitive impairments (such as impaired working memory) (Zhou et al., 2015). In a study of chronic aircraft noise exposure on children's working memory and attention performance, only effects on attention were reported (Matheson et al., 2003). Working memory is assumed to be dependent on attention, given that attention potentially serves as a "gatekeeper" for working memory (Awh et al., 2006). Whether the impairment in working memory and the heightened risk of schizophrenia in cities are both caused by chronic exposure to urban noise seems possible but needs to be validated in future studies.

Listening to urban sounds is generally less preferred by participants compared to natural soundscapes (Van Hedger et al., 2019). The current study demonstrates an association between decreased positive affect and increased values of BEN, when subjects are actively listening to urban sounds, highlighting the notion that urban sound exposure may result in negative consequences for the listener which might explain the self-reported dislike for those stimuli. The correlation between reduced positive affect and increased BEN again points to the fact that in this situation increased BEN can be viewed as a potentially negative consequence of exposure to noise pollution. As a limitation in this regard, it remains to be said that the described correlation does not survive multiple comparison correction and therefore needs to be treated with caution. Links between BEN and behavioral variables are quite rarely reported in the field of resting-state-fMRI, therefore future research should try to verify whether exposure to urban sounds results in higher values of BEN which consequently reduces positive affect.

The ability to exert cognitive control as an executive function has been linked to the fronto-parietal attention network, and has previously been shown to benefit from exposure to natural stimuli (Berman et al., 2008; Van Hedger et al., 2019). In line with this, the current study demonstrates a correlation between change in cognitive performance in the two working memory tasks and the brain's FC when listening to the natural soundscapes, illustrating that a gain in working memory performance is associated with higher connectivity within - among others - the auditory functional brain network while listening to nature. Similarly, as above the described correlation does not survive multiple comparison correction and needs to be treated with caution. Bearing in mind that higher FC has been shown to constitute a powerful predictor for cognitive performance (van den Heuvel and Hulshoff Pol, 2010), the above described correlation suggests that listening to natural soundscapes can potentially boost the brain's processing efficiency, resulting in a performance gain for the cognitive task performed after the listening experience. The behavioral data investigating this performance gain was reported elsewhere (Stobbe et al., 2023). While this data did not demonstrate a significant (condition x time) interaction effect, it is worth noting that there was an observed increase in the natural condition while the urban and control condition rather displayed a decrease in performance. This data pattern is in accordance with the hypotheses stated in the study by Stobbe et al. (2023), which were formulated based on a prior study demonstrating the exact same pattern of results after subjects were exposed to the identical natural and urban soundscapes (Van Hedger et al., 2019). Previously it has been shown that in-situ nature experiences enhance brain FC as measured by means of electroencephalography (EEG) (Chen et al., 2016). The present study adds to this finding showing that also a mere auditory exposure to natural soundscapes can produce this effect. Similarly, it was previously demonstrated that the brain shows interconnection differences when processing natural versus man-made sounds in prefrontal areas, aSTG, PCC, and SMG as measured with MEG. These results suggest that regions beyond the auditory cortex can be affected by auditory processing (Salvari et al., 2019). While the current study can confirm these findings, it also adds to the notion that subsequent cognitive processing seems to be modulated by these differences in interconnectivity between exposure to natural versus urban soundscapes.

More studies are required to unravel which particular active ingredients of the auditory stimuli drive these changes in BEN and brain connectivity when humans experience different environments such as in nature or urban areas. It remains to be investigated whether these active ingredients can be found in the sound pattern itself or if the effect is based on a belief-based construction by the listener. In order to unravel, for example, the underlying mechanism through which natural sounds might increase the brain's functional connectivity, additional investigation is essential. One promising approach in this regard makes use of a source-attribution manipulation where participants are exposed twice to the exact same sound-clip consisting of ambiguous pink noise. Before the exposure the participants belief about the environmental source of this sound is manipulated such that the participant thinks one sound originates from a natural scene while the other (same sound) originates from an urban environment (Haga et al., 2016). Transferring this sophisticated design into the field of brain imaging one could potentially illuminate a mechanism that explains how belief-based differences in self-reported restorativeness are represented in the brain (Stobbe et al., in preparation).

Further explanations can be borrowed from visual brain science theory, that claims that, since the brain has developed within natural environments, it is evident that it has adapted to process natural stimuli more efficiently (Valtchanov, 2013), while urban visual stimuli tend to be less efficiently processed and therewith discomforting and stressful for the brain (Chen et al., 2016). Correlations between the brain's connectivity and the psychological measure of coherence of an environment have been demonstrated, supporting the notion mentioned above. People find natural environments more coherent and therefore more restorative. Potentially this coherence also applies to the neural information that the brain is processing while being in a natural environment. To connect this visuospatial approach to auditory perception, future research should explore whether this enhanced processing of natural visual stimuli, potentially stemming from the increased coherence within such stimuli, similarly aligns with analogous phenomena in the domain of natural sounds.

Regarding BEN, the underlying neural mechanism that explains why exposure to urban stimuli tends to increase the levels of BEN is much more speculative. It is known that in order to perform normal day to day tasks the brain needs to maintain relatively low levels of BEN. This maintenance requires escaping from the equilibrium of high states of entropy while still being flexible enough to process and respond to novel input (Carhart-Harris et al., 2014). As we have shown here, listening to urban sound (traffic, machinery etc.) heightens the brain's level of entropy in comparison to a natural sound, this could explain the general benefit of interactions with nature.

Ultimately, it boils down to the central question of whether it is the sound's feature structure (perhaps the entropy of the stimulus) or the participant's perception and interpretation of the sound that elicit the observed changes in brain activity. In order to answer this question, further research is needed that e.g., systematically studies soundscapes with multiple levels of sound entropy and relates it to the BOLD entropy in those networks presented in the current study. Apart from that, the current study lacks the methodological framework to answer the important question of whether experience with nature is beneficial or if experience with urbanicity is detrimental instead. This lack stems from the fact that within the current study resting state brain data was only acquired during the soundscape exposure and not before and after the intervention. A future study could complement this by acquiring resting state data before and after natural versus urban soundscape exposure.

Taken together, the results of the present study provide a framework for the neural underpinnings of how natural versus urban soundscapes affect FC and entropy in the brain. Additionally, the two resting state measures show correlations with cognition and affect respectively, revealing the impact that exposure to soundscapes from these environments can have on the human brain.

## 5. Conclusion

The present study shows that the brain processes information differently when listening to nature and urban soundscapes and that BEN as well as FC are associated with differences in behavioral scores, revealing the impact that exposure to soundscapes can have on human brain-behavior interactions: a gain in performance was associated with higher FC in nature soundscapes. The reduced positive affect seen with increased BEN can be viewed as a potentially negative consequence of noise pollution. Our results provide a framework for the neural underpinnings of how natural versus urban soundscapes affect FC and BEN and bear implications for the understanding of how the physical auditory environment affects brain function and observed behavior. To the best of our knowledge this is the first study to analyze BEN and whole brain FC at rest in nature and urban soundscapes and to unravel its relationship to behavior.

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## Ethics

All participants provided informed consent and the study was approved by the Local Psychological Ethical Committee at the Centre for Psychosocial Medicine at University Medical Centre Hamburg-Eppendorf in Hamburg, Germany (LPEK-0077).

## CRediT authorship contribution statement

**Emil Stobbe:** Conceptualization, Formal analysis, Methodology, Project administration, Software, Writing - original draft, Writing - review & editing. **Caroline Garcia Forlim:** Formal analysis, Methodology, Software, Visualization, Writing - original draft, Writing - review & editing. **Simone Kühn:** Conceptualization, Formal analysis, Funding acquisition, Resources, Supervision, Writing - review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2023.117788.

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# Birdsongs alleviate anxiety and paranoia in healthy participants

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**The present study investigated the effect of urban (traffic noise) vs. natural (birdsongs) soundscapes on mood, state paranoia, and cognitive performance, hypothesizing that birdsongs lead to significant improvements in these outcomes. An additional goal was to explore the differential impact of lower vs. higher diversity of the soundscapes by manipulating the number of different typical traffic sounds or songs of different bird species within the respective soundscapes. In a randomized online experiment, N = 295 participants were exposed to one out of four conditions for 6 min: traffic noise low, traffic noise high, birdsong low, and birdsong high diversity soundscapes. Before and after the exposure, participants performed a digit-span and dual n-back task, and filled out depression, anxiety, and paranoia questionnaires. The traffic noise soundscapes were associated with a significant increase in depression (small effect size in low, medium effect size in high diversity condition). Concerning the birdsong conditions, depression exclusively decreased after exposure to the high diversity soundscape (small effect size). Anxiety and paranoia significantly decreased in both birdsong conditions (medium effect sizes). For cognition, no effects were observed. In sum, the present study suggests that listening to birdsongs regardless of diversity improves anxiety, while traffic noise, also regardless of diversity, is related to higher depressiveness. Moreover, for the first time, beneficial, medium-sized effects of birdsong soundscapes were demonstrated, reducing paranoia. Overall, the results bear interesting implications for further research, such as actively manipulating soundscapes in different environments or settings (e.g., psychiatric wards) and testing their effect on subclinical or even clinical manifestations of anxiety and paranoia.**

The impact of environmental influences on psychological well-being and cognition in humans have for a long time been neglected in traditional psychology. At present, human living environments are changing drastically. According to the UN 2007 was a turning point for humankind as for the first time the majority of the global population lived in urban areas[1]. Until 2050, it is estimated that 68% of the world population will be living in cities[2]. In Europe the urbanization rate is already as high as 75%. Urbanization coincides with increasing rates of mental illness. An earlier review from 2005 came to the conclusion that about 30% of the incidence in schizophrenia may be attributed to urban factors in interaction with genetic liability and social adversity[3]. A meta-analysis[4] shows a link between the increase of schizophrenia incidence and the increase in urbanicity, highlighting the fact that the risk for schizophrenia in the most urban environment was estimated to be 2.37 times higher than in the most rural environment. In a study investigating environmental factors known to trigger paranoia[5], it was shown that urban cyclers commonly report to experience at least one state paranoia reaction, reported on a paranoia scale, in response to what the authors call an interpersonal threat situation. This was caused by the presence of potentially dangerous traffic participants, such as motor vehicle drivers. According to Ellet et al.[5] the key environmental factors known to trigger paranoia include threat and ambiguity, which may be more often found in urban compared to natural environments. A recent review on depression and urbanicity reported mixed results, however with the majority of studies suggesting an elevated risk of depression in more (vs. less) urbanized areas[6]. Concerning mood and anxiety disorders, a review on studies conducted in Europe concludes that most studies showed elevated risks for mood/anxiety symptoms when comparing some (albeit not all) of the urban to rural areas[7]. In sum, there is hence accumulating evidence that living in urban areas is related to worse mental health outcomes.

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Contrary to the negative effect of urban environments on mental health, a recent study shows that increasing access to total and usable green space within the neighborhood can decrease anxiety/mood disorder treatment counts. This demonstrates the service that urban green spaces may provide for general mental health and well-being[8]. Another study, which looked at the perceived sensory dimensions (PSD) relevant for attentional and stress recovery in green spaces, found that natural environments which are serene, provide refuge, and are rich in species diversity, as well as are perceived as highly 'natural', are rated as most restful[9]. These effects are often explained by two predominant theories. Stress reduction theory (SRT) posits that landscapes, containing vegetation, water and other aspects that provide benefits for survival, help to moderate and reduce states of arousal and negative thoughts and thus reduce the psychological and physiological symptoms of stress[10]. Similarly, Attention Restoration Theory (ART) states that stimuli from natural sources restore cognitive function by reducing attention demands of the endogenous attention system[11].

Experimental research in the field has so far predominantly studied visuo-spatial aspects of the environment concerning mental health effects, such as by using photographs, videos, slideshows, or other visual stimuli. Other sensory modalities have been much less studied[12]. Man-made (urban) soundscapes (the so-called anthrophone) can constitute constant stressors that may impair cognitive function and well-being. Urban noise contains salient stimuli that likely trigger an alert physiological and psychological state. Corroborating this notion, a systematic review on traffic noise exposure found consistent evidence for an association between traffic noise and depression, as well as cognitive decline[13]. On the other hand, natural soundscapes, which are typically characterized by birdsongs, wind, or water[12], could be an important source of attention-restorative and stress-ameliorating effects, as they might be implicitly associated with a safe and vital natural environment. As documented by a narrative review, birdsongs, water-, and wind-sounds have been shown to be perceived as pleasant, and to have beneficial effects on mood, arousal levels, and cognitive performance[12]. Importantly, in several studies that have reported positive effects of birds on human well-being, higher species diversity was a relevant factor[14], perhaps because it may indicate the vitality or intactness of natural spaces. In a study across 26 countries conducted by Methorst et al.[15], the authors established a relationship between species diversity of birds within a region and self-reported life satisfaction of residents of those regions. Remarkably, it was found that a 10% increase in bird species diversity raises life-satisfaction approx. 1.53 times more than a proportional rise in income[15].

In a randomized controlled experimental study using auditory stimuli, hypotheses derived from ART and SRT were tested. Van Hedger et al.[16] compared a nature vs. city soundscape condition, whereby the former enhanced participants' performance in a dual n-back and digit span task, but did not improve mood. The present study broadly builds on the study by van Hedger et al.[16] but adds the factor of diversity to the soundscapes. In addition to mood and cognition (dual n-back and digit span task), the present study additionally focusses on state paranoia, as this is a very prominent symptom in psychosis which can be measured in a change-sensitive manner[17]. Furthermore, state paranoia has been shown to increase in response to traffic noise (e.g., building-site noise)[18]. However, investigating in how far natural vs. urban auditory stimuli might influence this symptom category has, to our knowledge, not systematically been studied yet. The present study thus addressed the following hypotheses: (1) birdsong (vs. traffic noise) soundscapes have a beneficial effect on mood and paranoia; (2) birdsong (vs. traffic noise) soundscapes have a beneficial effect on cognitive performance. Furthermore, it was investigated whether greater (vs. lower) diversity of bird species or noise sources within the soundscapes would be a relevant factor, modulating the effects. The outcomes (mood, paranoia, cognitive performance) were each measured before and after soundscape exposure. For each soundscape type a low vs. high diversity version was created. This resulted in a between 2 (*type*: birdsongs vs. traffic noise) × 2 (*diversity*: low vs. high) × within 2 (*timepoint:* pre vs. post) randomized experimental design.

## Results

### Perception of soundscapes.

The results of the MANOVA, revealed significant effects of *type* ($F(3, 276) = 78.6, p < 0.001, \eta_p^2 = 0.461$), *diversity* ($F(3, 276) = 3.16, p = 0.025, \eta_p^2 = 0.033$), as well as *type* × *diversity* ($F(3, 276) = 2.66, p = 0.028$), suggesting that all of these factors as well as their interaction had a significant impact on the perception of soundscapes (i.e., ratings on monotony/diversity, beauty, and pleasantness).

Univariate follow-up ANOVAs revealed for the factor *type*, that it only significantly affected beauty ($F(1, 278) = 168.8, p < 0.001, \eta_p^2 = 0.378$) and pleasantness perceptions ($F(1, 278) = 182.3, p < 0.001, \eta_p^2 = 0.396$), but not monotony/diversity *type* ($F(1, 278) = 0.06, p = 0.812, \eta_p^2 = 0.000$). Concerning the factor *diversity*, it only significantly affected the monotony/diversity ratings *type* ($F(1, 278) = 6.21, p = 0.013, \eta_p^2 = 0.022$), but not the other rating dimensions of beauty ($F(1, 278) = 0.84, p = 0.361, \eta_p^2 = 0.003$) or pleasantness ($F(1, 278) = 0.58, p = 0.448, \eta_p^2 = 0.002$). Finally, concerning the interaction *type* × *diversity*, there were no significant effects on monotony/diversity ($F(1, 278) = 0.75, p = 0.387, \eta_p^2 = 0.003$) nor beauty ($F(1, 278) = 2.84, p = 0.093, \eta_p^2 = 0.010$), but on pleasantness ($F(1, 278) = 5.36, p = 0.021, \eta_p^2 = 0.019$).

For statistical details on the post-hoc tests, see Table 1, (for descriptive data on the qualitative sound ratings see Supplementary Table 1). Low vs. high diversity conditions differed significantly from one another on the according monotony/diversity rating dimension, albeit with a small effect size. This effect was attributable to a significant small rating difference between the low and high traffic noise conditions; however, the low vs. high bird conditions were not perceived as significantly different concerning monotony/diversity. This speaks for only a partially successful manipulation of diversity. Both beauty and pleasantness were always perceived as significantly higher for the birdsong conditions in any given comparison with the traffic noise conditions (all $p < 0.001$), with large effect sizes.

#### *Mood and paranoia.*

Univariate analyses of variance revealed no baseline differences across the groups in the outcome variables at baseline for depression ($F(3, 291) = 0.31, p = 0.820$), or anxiety ($F(3, 291) = 0.31, p = 0.821$).

| DV | Conditions | *t*(df) | *p*-value | Cohen's *d* |
|---|---|---|---|---|
| **Monotony/diversity** | | | | |
| *Type* traffic noise vs. birdsongs | | 0.50 (278) | 0.619 | 0.06 |
| *Diversity* low vs. high | | −2.59 (280) | 0.010* | −0.21 |
| Traffic noise low vs. traffic noise high | | −2.38 (146) | 0.019* | −0.39 |
| Traffic noise low vs. birdsong low | | −0.81 (142) | 0.418 | −0.13 |
| Traffic noise low vs. birdsong high | | −1.89 (153) | 0.060 | −0.31 |
| Traffic noise high vs. birdsong low | | 1.69 (125) | 0.094 | 0.30 |
| Traffic noise high vs. birdsong high | | 0.45 (136) | 0.657 | 0.07 |
| Birdsong high vs. birdsong low | | 1.18 (131) | 0.240 | 0.21 |
| **Beauty** | | | | |
| *Type* traffic noise vs. birdsongs | | 13.1 (276) | 0.000*** | 1.54 |
| *Diversity* low vs. high | | −0.21 (280) | 0.831 | −0.03 |
| Traffic noise low vs. traffic noise high | | 1.77 (147) | 0.079 | 0.28 |
| Traffic noise low vs. birdsong low | | −7.65 (142) | 0.000*** | −1.24 |
| Traffic noise low vs. birdsong high | | −8.75 (146) | 0.000*** | −1.38 |
| Traffic noise high vs. birdsong low | | −10.8 (125) | 0.000*** | −1.79 |
| Traffic noise high vs. birdsong high | | −11.6 (136) | 0.000*** | −1.98 |
| Birdsong high vs. birdsong low | | 0.61 (131) | 0.546 | 0.11 |
| **Pleasantness** | | | | |
| *Type* traffic noise vs. birdsongs | | 13.4 (280) | 0.000*** | 1.59 |
| *Diversity* low vs. high | | −0.34 (280) | 0.732 | −0.04 |
| Traffic noise low vs. traffic noise high | | 2.14 (147) | 0.036* | 0.35 |
| Traffic noise low vs. birdsong low | | −7.60 (142) | 0.000*** | −1.28 |
| Traffic noise low vs. birdsong high | | −9.50 (152) | 0.000*** | −1.51 |
| Traffic noise high vs. birdsong low | | −9.78 (125) | 0.000*** | −1.74 |
| Traffic noise high vs. birdsong high | | −11.7 (136) | 0.000*** | −2.00 |
| Birdsong high vs. birdsong low | | 1.15 (131) | 0.252 | 0.20 |

**Table 1.** Comparison of soundscapes concerning beauty, pleasantness, and diversity/monotony ratings in the total sample. *$p < .05$; ***$p < .001$.

However, across the groups there were significant differences in state paranoia ($F(3, 291) = 3.34$, $p = 0.020$). For details (exact group differences and descriptive baseline data), see Supplementary Table 2.

For depression, there was a significant *time* effect ($F(1, 291) = 4.51$, $p = 0.035$, $\eta^2_{partial} = 0.015$), suggesting overall changes in depressive states from pre-to-post. The soundscape *type* × *time* interaction was significant ($F(1, 291) = 32.1$, $p < 0.001$, $\eta^2_{partial} = 0.099$), the triple interaction *type* × *diversity* × *time* was non-significant ($F(1, 291) = 1.52$, $p = 0.217$, $\eta^2_{partial} = 0.005$), suggesting that *diversity* was not a modulating factor of the differential pre-post-change by *type*. Additional analyses were run to check the robustness of the effects i.e., controlling for state paranoia age, and positive symptoms which differed significantly (paranoia) or at trend ($p < 0.10$; age, positive symptoms) at baseline as covariates, and excluding cases who did not type in at least one digit of the auditory codeword at the end of the soundscape correctly (= listening compliance check). The results of these analyses were comparable to the above reported ones. Post-hoc examination of the effects by computing within group dependent t-tests revealed that depressive symptoms significantly increased within both the low diversity urban soundscape ($T(1, 82) = 2.64$, $p = 0.010$, $d = 0.29$) and high diversity urban condition ($T(1, 68) = 4.88$, $p < 0.001$, $d = 0.59$), whereas there were differential effects in the birdsong conditions with no change in the low diversity condition ($T(1, 62) = -1.49$, $p = 0.142$, $d = -0.19$) but a significant decrease in the high diversity condition ($T(1, 60) = -2.57$, $p = 0.012$, $d = -0.29$) (see Fig. 1).

For anxiety, there was a significant *time* effect ($F(1, 291) = 39.9$, $p < 0.001$, $\eta^2_{partial} = 0.121$), suggesting overall changes in state anxiety from pre-to-post. The soundscape *type* × *time* interaction was significant ($F(1, 291) = 30.1$, $p < 0.001$, $\eta^2_{partial} = 0.094$), the triple interaction *type* × *diversity* × *time* was non-significant ($F(1, 291) = 0.15$, $p = 0.704$, $\eta^2_{partial} = 0.000$), suggesting that *diversity* was not a modulating factor of the differential pre-post-change by *type*. Additional analyses were run to check the robustness of the effects (for details see previous section), which revealed that the findings were not altered by entering the covariates and/or excluding cases with incorrect codeword (failed listening compliance check). Post-hoc within-group t-tests for anxiety revealed that there were no effects within both traffic noise conditions (low diversity: $T(1, 82) = -1.37$, $p = 0.174$, $d = -0.15$; high diversity: $T(1, 68) = 0.49$, $p = 0.629$, $d = 0.06$), whereas there were significant declines in both birdsong conditions (low diversity: $T(1, 62) = -6.13$, $p < 0.001$, $d = -0.77$; high diversity: $T(1, 60) = -6.32$, $p < 0.001$, $d = -0.70$) (see Fig. 1).

As paranoia levels differed significantly at baseline between the groups, instead of a 2 × 2 × 2 repeated measures ANOVA approach, univariate ANCOVA, with paranoia at baseline as covariate and post-test paranoia as outcome, predicted by *type* and *diversity* as factors, was computed. *Type* was a significant factor explaining post-test paranoia ($F(1, 290) = 45.5$, $p < 0.001$, $\eta^2_{partial} = 0.070$), *diversity* was non-significant ($F(1, 290) = 0.50$, $p = 0.480$,

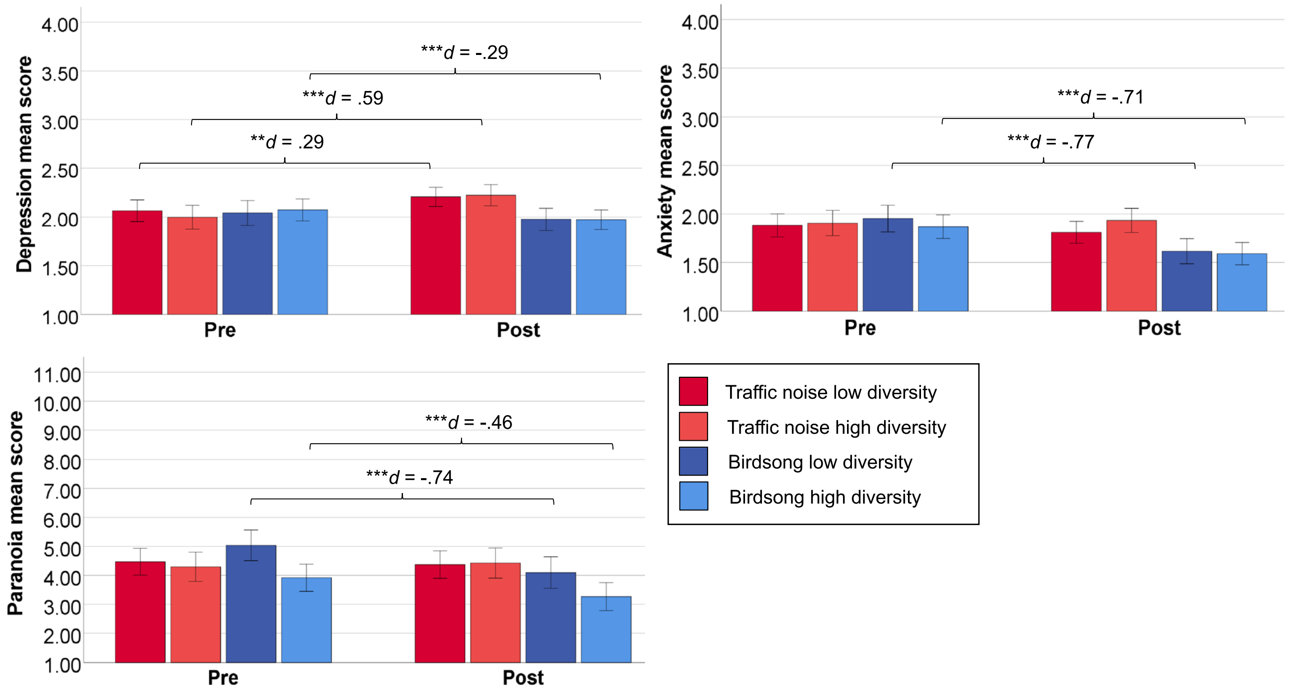

**Figure 1.** Within-group changes in mood and paranoia for all variables of interest. Y-axes have been formatted to reflect the possible data range. The interpretation of scores corresponds to the Likert-scale of the respective measure. Between-group differences (at baseline) and exact descriptives (means and standard deviations) for pre- and post-tests can be found in Supplementary Table 2. Paired t-test statistics for changes within groups in mood (anxiety, depression) and paranoia can be found in Supplementary Table 3.

$\eta^2_{partial} = 0.002$), as was the interaction *type* × *diversity* ($F(1, 290) = 0.18$, $p = 0.670$, $\eta^2_{partial} = 0.001$). Finally, for paranoia there were no changes in the traffic noise conditions (low diversity: $T(1, 82) = -0.55$, $p = 0.583$, $d = -0.06$; high diversity: $T(1, 68) = 0.67$, $p = 0.507$, $\mathrm{d} = 0.08$), but significant decreases in both birdsong conditions (low diversity: $T(1, 62) = -5.90$, $p < 0.001$, $d = -0.74$; high diversity: $T(1, 60) = -4.11$, $p < 0.001$, $d = -0.46$) (Fig. 1).

*Cognition.* Univariate analyses of variance revealed no baseline differences across the groups in the cognition outcome variable at baseline for the forward digit span two-error maximum length (TE_ML) measure ($F(3, 291) = 0.45$, $p = 0.720$), or the according backward digit span measure ($F(3, 291) = 0.15$, $p = 0.962$). Univariate analyses of variance also revealed no baseline differences across the groups in the cognition outcome variable at baseline for the dual n-back measure *d* prime ($F(3, 291) = 1.01$, $p = 0.388$).

Concerning the two-error maximum length digit span forward, there was no significant *time* effect ($F(1, 281) = 1.1$, $p = 0.298$, $\eta^2_{partial} = 0.004$). The *time* × soundscape *type* interaction effect was also not significant ($F(1, 281) = 0.2$ $p = 0.662$, $\eta^2_{partial} = 0.001$), as well as the *time* × *type* × *diversity* triple interaction ($F(1, 281) = 1.1$, $p = 0.296$, $\eta^2_{partial} = 0.004$). The same null-finding emerged for the according backward digit span measure: *time* ($F(1, 281) = 0.30$, $p = 0.582$, $\eta^2_{partial} = 0.001$), *time* × soundscape *type* ($F(1, 281) = 1.04$, $p = 0.308$, $\eta^2_{partial} = 0.004$) and *time* × *type* × *diversity* ($F(1, 281) = 1.2$, $p = 0.278$, $\eta^2_{partial} = 0.004$). For the n-back task total performance parameter, there were also consistent null-findings. There was no significant effect of *time* ($F(1, 287) = 0.37$, $p = 0.543$, $\eta^2_{partial} = 0.001$) or *time* × soundscape *type* ($F(1, 287) = 0.23$, $p = 0.635$, $\eta^2_{partial} = 0.001$) nor *time* × *type* × *diversity* ($F(1, 287) = 1.12$, $p = 0.279$, $\eta^2_{partial} = 0.004$). Additional analyses were run to check the robustness of the effects i.e., controlling for state paranoia age, and positive symptoms which differed significantly (paranoia) or at trend ($p < 0.10$; age, positive symptoms) at baseline as covariates, and excluding cases who did not type in at least one digit of the auditory codeword at the end of the soundscape correctly (= listening compliance check). The results of these analyses were comparable to the above reported ones. At last, an aggregation of both task scores into a composite *z*-score, which is an established practice in the field[16], did not yield a significant result either.

## Discussion

The present study built up a previous study by van Hedger et al.[16], who demonstrated that a natural vs. urban soundscape was related to better cognitive outcomes, but failed to demonstrate significant effects on mood. In the present study, birdsongs were contrasted with traffic noise, whereby a novel diversity factor (low vs. high number of birdsongs or traffic noise sources in the soundscapes that participants were exposed to) was introduced, and effects on paranoia were additionally tested (for the rationale see "Introduction" section).

Opposed to van Hedger et al.[16] in the present study only effects on mood (depression, anxiety) and paranoia, but not on cognition (dual n-back, digit span task), were found. Traffic noise soundscapes generally aggravated depressive states (small effect in low diversity, moderate effect in high diversity condition), whereby these soundscapes were also perceived as significantly different in terms of diversity in subjective ratings, which were conducted as a manipulation check at the end of the study. Exclusively the highly diverse birdsong soundscape decreased depressive states (small effect size). Generally, the birdsong conditions were not rated as significantly different in terms of diversity. Concerning anxiety, traffic noise soundscapes had no effect, whereas both birdsong soundscapes significantly alleviated anxiety (medium effect sizes). Finally, the traffic noise soundscapes had no effect on paranoia, whereas again both birdsong soundscapes significantly lowered it (medium effect sizes).

The beneficial effects of birdsongs in particular concerning mood and attention restoration have been previously observed[20]. Mood recovery (e.g., after a stressor) or beneficial mood effects have repeatedly been reported for exposure with natural sounds[21,22]. The present study thus confirms prior findings. Moreover, to the best of our knowledge, beneficial effects of natural soundscapes on state paranoia are shown for the very first time. This finding might be explained in several ways. Birdsongs might be implicitly associated with a vital natural environment, divert attention away from (internal and external) stressors, or could signal the absence of acute threat. Urban soundscapes on the other hand might trigger socio-evaluative concerns, involuntarily direct attention resulting in perceived loss of control and hence alter vigilance to potential threats which are processes proposed to elicit paranoia. However, somewhat contradicting the latter notion, the traffic noise soundscapes as used in the present study did not increase paranoia. Possibly, by adding human voices to the audio file, this effect could have been evoked. Human voices may more readily activate interpersonal sensitivity, to which a central role has been ascribed in the emergence and maintenance of paranoia[23]. Generally, classical learning paradigms (conditioning) might provide a framework to explain restorative nature effects. Hereby, first an unconditioned positive response occurs in reaction to nature, which gets later retrieved by similar natural cues, and can later generalize to an abstract level whereby even more abstract cues (e.g., words) may trigger the original response[24].

Neither urban (traffic noise) nor natural (birdsong) soundscapes had any effect on cognitive performance, which, at first glance, seems to contradict a previous study, which implemented the same cognitive tests (i.e., digit span and dual n-back)[16]. An explanation for the null effect could be the degree to which the administration of the tasks was controlled. The current study was performed online, practice was restricted to two blocks (i.e., in a laboratory setting, participants can often train for as long as they wish/need), and hence there was little control over the degree to which subjects understood the task correctly (albeit visual inspection of the raw data did not reveal severe deviations from an expected performance). In addition, the online as opposed to a laboratory situation does not allow for controlling context variables or systematically manipulating baseline levels of stress or fatigue[21]. Besides the highlighted methodological issues with respect to the cognitive outcomes of the current study, it could be debated whether such an effect of exposure to nature on cognitive performance as measured by executive functioning tasks really exists on a population level. Support for the existence of this effect originally comes from a study in which mere viewing of pictures from nature improved cognitive performance[11]. This was subsequently replicated with auditory exposure to nature in the form of soundscapes using the same cognitive tasks that were also administered in the current study[16]. Summing up this debate there hence seems to be preliminary support for the existence of such an effect on a population level, however future meta-analyses about this effect should be carried out in order to clarify the existence of the effect.

Concerning the fact that there was no difference between the high and low diversity soundscapes of birdsongs with respect to the effects on mood and paranoia it should be mentioned that in a study by Methorst et al.[15] where bird species diversity in a given region was shown to be related to reported life-satisfaction in that region, the authors suggest two explanations which are also relevant in the light of the afore-mentioned result. It is concluded that the multisensory experience of birds can be a crucial factor for diversity of birdsongs to have an effect on life-satisfaction. Yet another explanation is that beneficial landscape properties in fact drive the effects, promoting both bird diversity and people's life-satisfaction independently of one another. In the current study it might be the case that merely listening to a more diverse birdsong soundscape did not communicate the same multisensory experience than it does when people are experiencing bird diversity in a real-life situation. Furthermore, the appreciation of diversity might rely on certain knowledge or expertise, resulting in a benefit only for experienced listeners. Potentially, our sample did include mostly lay people concerning bird listening, which could partially explain the result with respect to the diversity variable (i.e., the soundscapes were not rated as significantly different from one another in terms of monotony/diversity). Future studies investigating this topic should aim to include some kind of expertise measurement in order to control for this factor.

## Limitations

One limitation of the present study is the numerically higher percentage of males relative to females (albeit non-significant), which is a typical problem encountered in online studies. Future studies should stratify the subgroups by sex, such as to balance the sample in this regard. Furthermore, the manipulation of low vs. high diversity of the soundscapes was only partially successful. Namely, although the soundscape composition followed a logical rationale in this regard, and the subjective diversity rating the urban soundscapes significantly differed in the traffic noise soundscapes, this was not the case for the birdsong conditions. To assure stronger contrasts, and hence to be able to test the diversity hypothesis more aptly concerning enhanced beneficial effects, the contrast between the soundscapes needs to be further enhanced in future studies. In addition, mixed conditions such as urban soundscapes containing birdsongs would be a highly interesting research target, as this could more readily reflect daily life exposure situations.

It remains to say that the current study made use of a non-clinical sample opening the debate if the observed effects can also be generalized to people diagnosed with high levels of e.g., paranoia. Taking into account the continuum hypothesis, which states, that psychotic symptoms which are seen in patients can also be observed in non-clinical populations, it might be the case that both populations share a mechanism by which symptoms can be relieved or improved. This remains speculative, nevertheless the current study can be seen as a pilot, exploring the existence and potential magnitude of effects, feasibility, and safety for a future transfer to a more vulnerable clinical sample. Future research could adopt the current design and investigate the effects of birdsong exposure on paranoia within a clinical sample. Such research can potentially result in low threshold environmental interventions to reduce distress in e.g., psychiatric wards or other clinical settings. In the sense of conditioning (see above), associations with natural environments might divert attention away from psychological stressors or signal the absence of acute threat. Future experiments could aim to explore if paranoia does in fact not decrease after exposure to threatening natural environments, such as the wilderness, or situations which signal the acute presence of threat, such as natural disasters.

Moreover, it is important to highlight the fact, that the results of the current study cannot provide any clarification concerning the sustainability or replicability (e.g., by repeated exposure) of the effect birdsongs can have on mood and paranoia. Future research should aim to test such effects in a longitudinal and/or repeated exposure study design. Yet another limitation in the current study is the lack of a neutral control sound condition which would enable the interpretation of results with respect to a neutral condition instead of the mere comparison between a traffic condition and a birdsong condition. The use of such a neutral control group within a similar design as implemented by the current study would be a great addition for future research. Finally, although the instructions required participants to set their audio system loudness to 80%, still subjectively perceived loudness of the soundscapes could constitute a confounding factor.

**Conclusion.** The present study provides evidence for the beneficial effects of birdsongs on mood (depression, anxiety) and paranoid symptoms, with the latter being shown for the first time. On the other hand, the negative effects of traffic noise were only confirmed concerning depressive symptoms. The manipulated low vs. high diversity of the soundscapes did not have a significant effect, which might in part be explained by no perceived subjective differences concerning monotony vs. diversity. Further replication in vulnerable, elevated risk- or clinical groups could be of interest to assess the magnitude of effects given pre-existing symptoms and cognitive performance deficits. In case of replication, using birdsongs as 'soothing' background soundscape could open interesting new possibilities in psychiatric hospitals or other therapeutic settings.

## Methods

**Power calculation and study registration.** A power calculation was conducted for an interaction effect (repeated measures ANOVA), in G*Power 3.1.9.7 with $f = 0.10$, $\alpha = 0.05$, power $= 0.90$, 4 groups, correlation between repeated measures $r = 0.60$, resulting in a minimum required total sample size of $N = 288$ ($n = 72$ per group). According to the general rule of thumb for Cohen's f statistic, $f \geq 0.10 < 0.25$ is a small effect, $f \geq 0.25 < 0.40$ is a medium effect, and, $f \geq 0.40$ a large effect (see Cohen, 1988)[25]. We opted for a small effect size as a similar study as ours, conducted by van Hedger et al.[16], also using a repeated-measures ANOVA data analysis approach, reported interaction effects *type* ([2] natural vs. urban soundscapes) by *time* ([2] pre-to-post exposure) on mood, whereby Cohen's d for negative affect was between 0.36 and 0.40. These results were non-significant, as the study was underpowered for detecting small effects. The interaction effects observed concerning cognition in that paper, applying the same tests as in the present paper, were large (d between 0.71 to 0.76). Since we were interested in detecting effects on mood and to study yet unknown effects on state paranoia, we opted for and intermediate effect size between small and medium.

The study was pre-registered at aspredicted.org (study name: "Sounds_Online", trial identifier: #67702, https://aspredicted.org/d5j7j.pdf) on 06/04/2021.

**Recruitment and in- and exclusion criteria.** The study was programmed using Inquisit 5[26] (https://www.millisecond.com) and accordingly run on the Millisecond server. Participants were recruited from the crowdsourcing platform Prolific and received 10€ reimbursement for their full participation. Adult individuals were pre-screened on Prolific (i.e., visibility of the study only for candidates with a suited profile) concerning fluent German language skills (as this was the study language), having no diagnosed lifetime mental illness, and having no hearing difficulties. Pre-screened individuals could then access the study, where in- and exclusion criteria were checked further. This included no regular substance or drug intake, no suicidal thoughts, or tendencies, and availability of headphones for the purpose of the study.

**Study procedure.** After providing informed consent, sociodemographic information was assessed, including education, income, and further variables, which were assessed for potential additional or exploratory analyses, but for the sake of conciseness are not reported in this paper. Psychosis liability was assessed. For an according overview on sample characteristics, see Table 2. Hereafter, pre-test assessments were conducted, including an assessment of mood (depression, anxiety), paranoia, the digit-span, and n-back tasks. Participants were randomized to one of four sound conditions: (1) low diversity traffic noise soundscape $n = 83$, (2) high diversity traffic noise soundscape $n = 69$, (3) low diversity birdsong soundscape $n = 63$, or (4) high diversity birdsong soundscape $n = 80$, (for details on the stimuli, see "Stimuli" section). The soundscapes each lasted for exactly 6 min. Participants were instructed to set their audio system volume to 80% (which was piloted with members of our research unit beforehand and deemed to be an optimal average volume) and to listen to the sounds until the end, when participants were required to continue by clicking with their mouse. Participants were told that a code, consisting of two spoken digits (in German), would be audible towards the end of the sound presentation, which they were required to type in correctly afterwards. This was implemented to assure listening-compliance and attention. After the sound presentation, the pre-test measures were repeated. Finally, several items to assess perceived sound quality, including beauty, pleasantness, and monotony (vs. diversity) were presented.

| Variable | Traffic noise low n = 83 | Traffic noise high n = 69 | Birdsong low n = 63 | Birdsong high n = 80 | Inferential statistics |
|---|---|---|---|---|---|
| Age mean (SD) | 27.0 (7.48) | 25.5 (7.10) | 26.5 (6.30) | 28.7 (7.72) | *F*(3, 293) = 2.53, *p* = 0.057 |
| Sex: % male (n) | 55% (45) | 64% (44) | 71% (45) | 54% (43) | $X^2$(3, 293) = 6.04, *p* = 0.110 |
| **School degree$^{1}$% (n)** | | | | | |
| None | 1.20% (1) | 2.90% (2) | 6.30% (4) | 3.80% (3) | $X^2$(9, 293) = 6.04, *p* = 0.285 |
| Low | 11.0% (9) | 11.6% (8) | 15.9% (10) | 7.60% (6) | |
| Middle | 13.4% (11) | 21.7% (15) | 17.5% (11) | 10.1% (8) | |
| High | 73.4% (61) | 63.8% (44) | 60.3% (38) | 78.5% (62) | |
| **Net income % (n)** | | | | | |
| < 1.250€ | 48.8% (40) | 43.5% (30) | 41.3% (26) | 40.5% (32) | $X^2$(21, 293) = 21.3, *p* = 0.443 |
| 1.250–1.749€ | 11.0% (9) | 7.20% (5) | 15.9% (10) | 16.5% (13) | |
| 1.750–2.249€ | 7.30% (6) | 8.70% (6) | 15.9% (10) | 8.90% (7) | |
| 2.250–2.999€ | 12.2% (10) | 8.70% (6) | 12.7% (8) | 10.1% (8) | |
| 3.000–3.999€ | 2.40% (2) | 10.1% (7) | 4.80% (3) | 3.80% (4) | |
| 4.000–4.999€ | 3.70% (3) | 0.00% (0) | 1.60% (1) | 1.30% (1) | |
| > 5.000 € | 2.40% (2) | 2.90% (2) | 3.20% (2) | 2.40% (3) | |
| Not wish to answer | 12.2% (10) | 18.8% (13) | 4.80% (3) | 15.2% (12) | |
| CAPE positive symptoms freq. score$^{2}$ mean (SD) | 1.62 (0.44) | 1.58 (0.43) | 1.73 (0.48) | 1.53 (0.41) | *F*(3, 294) = 2.52, *p* = 0.058 |

**Table 2.** Descriptive sample data and between-group differences for socio-demographic variables. [1]The German school system has three type of school degrees; lowest = 'Hauptschulabschluss', which can be acquired after the 9th, middle = 'Realschulabschluss', which can be acquired after the 10th, and high = 'Abitur', which can be acquired after the 12th or 13th school year. [2]Scores can range from 1 to 4, which indicate the average lifetime frequency of psychotic (positive or negative symptoms) symptoms (1 = never, 2 = sometimes, 3 = often, 4 = nearly always). For reference: Mossaheb et al.[19] report means (SD) for frequency on the positive symptom dimension individuals with ultra-high-risk for psychosis (n = 84) vs. without risk (i.e., healthy controls; n = 81): 1.9 (0.5), [CI 1.71–2.02] vs. 1.6 (0.4), [CI 1.47–1.70].

**Sample.** Initially, *N* = 401 individuals started the survey. Of those, *n* = 76 quit during the sociodemographic assessment, *n* = 24 lacked pre-test data, and *n* = 6 lacked post-test data. These *n* = 106 cases were excluded from the analyses, resulting in a final sample of *N* = 295. Of these, some participants had incomplete post-test data (*n* = 10 missing digit span, 5 missing n-back, and *n* = 8 missing the qualitative assessments [sound rating]).

For detailed information and inferential statistics comparing the groups at baseline see Table 2. The participants were in their middle to late twenties on average and there were in tendency more males than females. Net income was mostly reported to be in the lowest category (i.e., < 1.250€, 40–50% of participants of all groups), but also between 5 and 20% of participants did not wish to reveal their monthly net income. Positive symptom frequency levels did not differ significantly between the groups, albeit there were relatively marked descriptive differences (*p* = 0.058). The values were mostly similar and within a confidence interval range that has previously been reported for healthy individuals[19]. Due to the trend-level nature of the differences in positive symptom frequency, we decided to repeat the main analyses, controlling for this variable as covariate in the repeated measures ANOVAs.

**Measures.** For all mood and the paranoia scales, item scores were computed (i.e., summing up responses on all items and dividing this by the number of items). This way, the interpretation of scores is facilitated, as it corresponds to the Likert-scale of the respective measure.

*Psychosis liability.* Psychosis-liability or sub-clinical psychosis levels was assessed using the Community Assessment of Psychic Experiences (CAPE)[19], in its German version, to assesses lifetime positive, negative and depressive symptoms (http://www.cape42.homestead.com/index.html). The CAPE, including the German version, has been validated extensively[17]. Items refer to the lifetime prevalence of specific symptoms, rated on an ordinal response scale for frequency (categories: 1 = 'never', 2 = 'sometimes', 3 = 'often', 4 = 'nearly always'). The total scale consists of 42 items, whereby the positive symptom scale includes 20 (e.g., 'Do you ever feel as if things in magazines or on TV were written especially for you?'), the negative symptom scale 14 (e.g., 'Do you ever feel that your mind is empty?'), and the depressive symptom scale 8 items (e.g., 'Do you ever feel like a failure?'). To test for comparative baseline levels across all groups in psychosis liability, mean frequency scores for the positive symptom subscale was used, for which Mossaheb and colleagues have provided descriptive data for individuals with ultra-high risk for psychosis (n = 84) vs without risk (i.e., healthy controls; n = 81)[19]. The positive dimension (frequency) of the CAPE had excellent internal consistency in the present sample, with Cronbach's α = 90.

*Mood and paranoid symptoms.* Mood was assessed with the State Trait Anxiety Depression Inventory (STADI)[27]. The scale contains 40 items, whereby the same 20 items are once presented in trait and once in state format. Only the latter was used in the present study. The scale differentiates between depression (low euthymia [inverted items], dysthymia) and anxiety (hyperarousal and worry), whereby each of the subscales is assessed by 5 items. The response format is a 4-point Likert (1 = 'not at all', 4 = 'strongly applies'). Internal consistency (Cronbach's $\alpha$) at pre-test was good both for the state anxiety (0.85) and depression (0.86) scales.

Paranoia was assessed with a brief, change sensitive state version of the paranoia checklist, which has been validated and comparable to the long, state adapted 18-item version[17]. The scale comprises 3 statements (e.g., 'I need to be on my guard against others', 'Strangers and friends look at me critically', 'People try to upset me'), rated on an 11-point Likert-scale (each from 1 to 11) for the degree of agreement to the statement, associated distress and conviction, at present. The latter two categories were only presented if the rating of agreement to the statement was > 1 (which accordingly often results in a large amount of missing data). In the present study, only agreement was evaluated. Internal consistency at pre-test was acceptable with Cronbach's $\alpha = 0.78$.

*Cognition.* To assess digit span cognitive performance, both the forward and backward version were used, as available in Inquisit 5[26] [retrieved from https://www.millisecond.com] which is based on the original task reported by Woods et al.[28]. Two parameters are recommended for evaluation: the two-error maximum length (TE_ML) and the maximum length recalled (ML). The two-error maximum length is defined as the last digit span a participant gets correct before making two consecutive errors while the maximum length is the digit span that a participant recalled correctly during all trials irrespective of the number of errors in-between. Starting with a successive visual presentation of 3 digits, the participants need to correctly recall a by 1 digit increasing sequence of digits and reproduce it by clicking on the correct digits in correct order. After two wrongly recalled sequences of the same length, the digit span is decreased by 1 digit until the digit span length again reaches the starting point of 3. The total amount of trials is 14 making the shortest span possible 3 digits long and the longest span 16 digits long. The participants were explicitly reminded not to use any memory assisting methods such as paper and pencil. The dual n-back task, also available in the Inquisit 5[26] (retrieved from https://www.millisecond.com) was assessed. The task is based on the original work by Jaeggi et al.[29]. It consists of 4 experimental blocks demanding 2-back and 3-back level performance. While performing the task, subjects pay attention to their computer screen while also listening to a computer audio. On each trial a blue square appears in one out of eight grid-like locations around a central fixation cross, while at the same time a (German) letter is presented via the headphones. In the 2-back block condition, the subjects are instructed to press the "A" button on their keyboard when the current square position matches the square position from two trials before. Subjects are also instructed to press the "L" button on their keyboard if the spoken letter matched the letter two trials before. The same instruction, but having to match stimuli 3 trials back, is provided for the 3-back condition. In the present study, participants trained each condition once, and then went on with the experimental blocks. The performance parameter was the so-called *d* prime value calculated as the proportion of ((visual_TotalHits − visual_TotalFA) + (auditory_TotalHits − auditory_TotalFA)/2)/number of total experimental blocks. The highest possible *d* prime (greatest sensitivity) was 6.93 and the lowest was 0. Visual hits are defined as correct responses with respect to the location of the square and auditory hits are defined as the correct responses with respect to the spoken letter. Visual false alarms (FA) are defined as responses in the absence of a target in the visual domain, thus with respect to the location of the square and auditory false alarms are responses in the absence of a target in the auditory domain, thus with respect to the spoken letter.

*Soundscape perception.* The participant's perception of the soundscapes was assessed using a one item questionnaire per dimension (diversity/monotony, pleasantness, and beauty). Participants were asked to report on a 0 to 100 visual scale how diverse/monotone, beautiful, and pleasant they had perceived the soundscape they had listened to during the experiment. The items have been formulated by the authors themselves while the use of an aesthetic rating of the soundscapes per se was a replication from the van Hedger et al.[16] study where we exchanged the "like–dislike" affective response with a more detailed aesthetic rating splitting the response up into a pleasantness and a beauty dimension. The dimension of diversity/monotony has been to perform a manipulation check on diversity for the soundscapes used in the present study.

**Stimuli.** The soundscapes for all four categories have been generated in the same way. Single sound snippets were gathered and then adapted and merged within the audio software *Steinberg Cubase10*. An exemplary visualization of the resulting soundscape can be seen in the Supplementary Material (see Supplementary Fig. 1). For the nature category a database of birdsong recordings (https://www.xeno-canto.org/explore/region) from a central European origin was used. For the low diversity birdsong condition, eight recordings from the same two species were used (common chiffchaff & wood warbler). For the high diversity birdsong condition, the same approach was chosen, but recordings from eight different bird species were used to create the soundscape (garden warbler, honey buzzard, woodlark, Eurasian sparrow hawk, coal tit, greenshank, common crane, and black woodpecker). In both birdsong conditions, additionally subtle water and wind sounds were played in the background, to create a constant auditory experience. For the traffic noise conditions, sound snippets from eight car recoding's (https://freesound.org/search/?q=city) were used for the low diversity traffic noise condition while audio-snippets from eight diverse sources of noise pollution associated with the city were used for the high diversity traffic noise condition (ambulance siren, construction, trucks, train, motorcycle, airplane, bus and fire-fighter siren). In both traffic noise soundscapes, a constant subtle traffic flow was audible in the background.

To ensure that all soundscapes were perceived with a similar loudness level, all soundscapes were engineered to have a similar loudness value. The loudness values from all four conditions range between 19.4 and 27.8 loudness units relative to full scale (LUFS). All soundscapes had a duration of 6 min. Prior to the experiment the soundscapes have been presented to a small set of pilot participants rating the similarity of the audio level ensuring a comfortable audio level across all conditions. As a result, at the beginning of the experiment, participants were instructed to set their headphone loudness level to 80%. Soundscapes can be accessed openly via this link https://osf.io/4y3vh/.

**Statistical analyses.** Analyses were run in SPSS 27 (IBM Corp., 2020). To test the differences of all measures at baseline, several univariate analyses of variance (ANOVA) were run. In order to test the effects of high vs. low diverse traffic noise vs. birdsong soundscapes on mood, paranoia, and cognition, repeated measures analyses of variance (ANOVA) were run testing for a 2 (*timepoint*: pre vs. post) × 2 (*soundscape type*: birdsong vs. traffic noise) × 2 (*diversity*: low vs. high) interaction effect. The analyses were once run with all participants, and then only with those who entered at least one of the digits (control of compliance of listening to audio, see "Study procedure" section) correctly, to check for the robustness of findings. In order to further check for the robustness of effects on mood and cognition repeated measures ANOVAs were run controlling for baseline sample differences on sample characteristics or outcomes (i.e., state paranoia, age and positive symptoms) as covariates. To check the robustness of effects on paranoia a univariate analysis of covariance (ANCOVA) with paranoia at baseline as covariate and post-test paranoia as outcome, predicted by *type* and *diversity* as factors, was computed. Significant interactions (i.e., of interest were the *type* × *time* and *type* × *diversity* × *time*) interactions identified for any of the outcomes were followed up by subsequent detailed post-hoc-tests. To explore mean differences between the qualitative ratings of soundscapes (i.e., beauty, pleasantness, and monotony vs. diversity), a one-way multivariate analysis of variance (MANOVA) was conducted. In case of significant omnibus tests indicating global differences across the qualitative sound rating dimensions, follow-up between group t-tests were conducted. Due to the exploratory nature of the study, no *p*-level correction was applied.

The partial eta squared effect size was used to interpret the ANOVA based analyses, with the corresponding rule of thumb defining $\eta^2 = 0.01$ as a small effect size, $\eta^2 = 0.06$ as a medium effect size and $\eta^2 = 0.14$ as a large effect size[30]. Cohen's d effect size was used to interpret post-hoc test effect sizes, with the corresponding rule of thumb defining a value of ≥ 0.2 as a small effect size, a value of ≥ 0.5 as a medium effect size and a value of ≥ 0.8 as a large effect size. The criteria for interpreting the effect size for Hedge's g stem from the corresponding rule of thumb with the same definition[30].

**Ethics statement.** All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all participating subjects. The experimental protocol was approved by the ethical committee from the University Clinic Hamburg Eppendorf.

## Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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## Author contributions

E.S. and L.A. wrote the main manuscript text and prepared all Figures. J.S. prepared parts of the online experiment. All authors reviewed the manuscript.

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## Competing interests

The authors declare no competing interests.

## Additional information

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1038/s41598-022-20841-0.

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*Appendix B.*

# DECLARTION OF RESEARCHER CONTRIBUTIONS

Annex Declaration pursuant to Sec. 7 (3), fourth sentence, of the Doctoral Study Regulations regarding my own share of the submitted scientific or scholarly work that has been published or is intended for publication within the scope of my publication-based work

**I.** Last name, first name: Stobbe, Emil
Institute: Department of Educational Psychology
Doctoral study subject: Psychology
Title: M.Sc. in Cognitive Neuroscience; B.A. in Psychology

**II. Numbered listing of works submitted (title, authors, where and when published and or/submitted):**

1. Stobbe, E., Lorenz, R. C., & Kühn, S. (2023). On how natural and urban soundscapes alter brain activity during cognitive performance. *Journal of Environmental Psychology.*
2. Stobbe, E., Forlim, C. G., & Kühn, S. (2024). Impact of exposure to natural versus urban soundscapes on brain functional connectivity, BOLD entropy and behavior. *Environmental Research.*
3. Stobbe, E., Sundermann, J., Ascone, L., & Kühn S. (2022). Birdsongs alleviate anxiety and paranoia in healthy participants. *Scientific Reports.*

**III. Explanation of own share of these works:**

The amount of the work completed by myself is evaluated of the following scale: all – the vast majority – most – part.

Regarding II. 1: Data collection (all), data analysis and programming (the vast majority), data visualization (all), discussion of results (vast majority), writing manuscript (vast majority)

Regarding II. 2: Data collection (all), data analysis and programming (part), data visualization (part), discussion of results (vast majority), writing manuscript (most)

Regarding II. 3: Conceptualization and design (most), stimuli generation (most), data analysis (part), discussion of results (vast majority), writing manuscript (most)

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Berlin 28.02.2024

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