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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

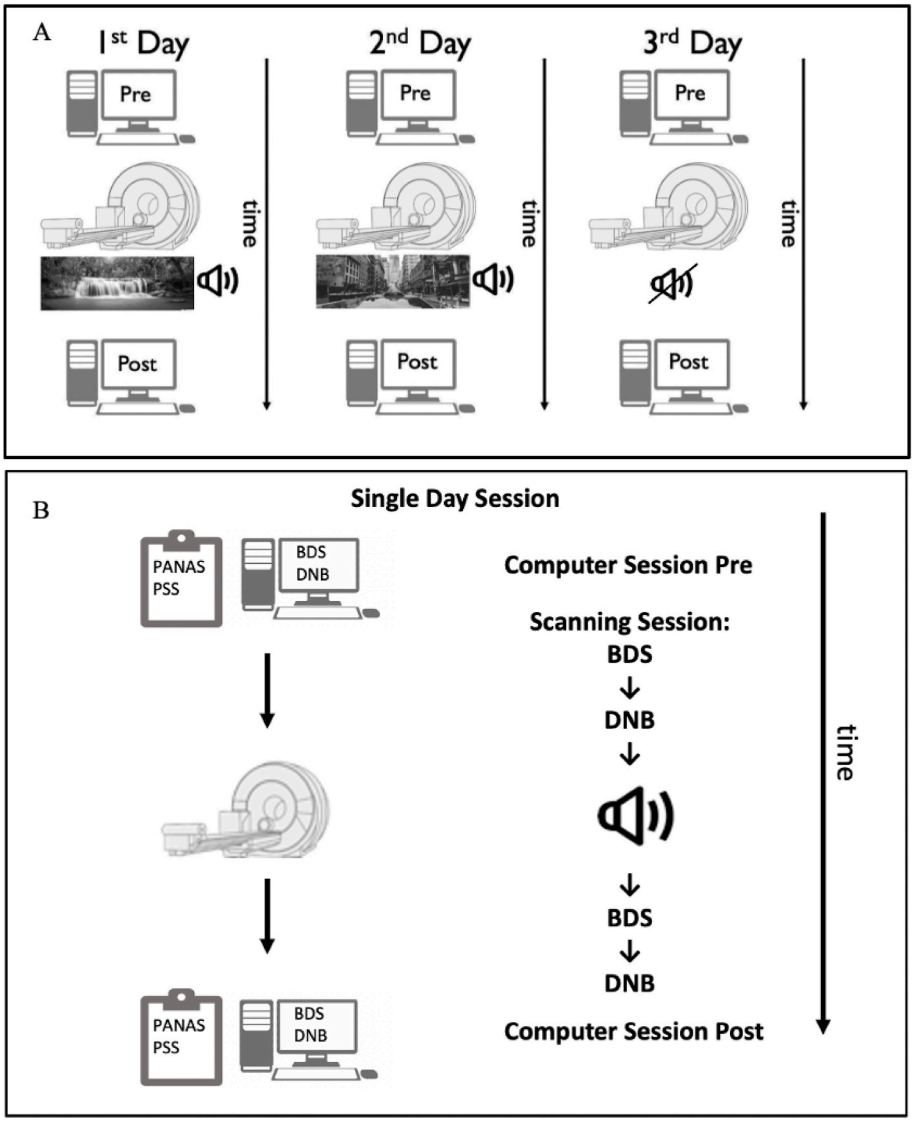

Fig. 1. Experimental Design. Panel A depicts the procedure of the entire experiment which consisted of three testing days. Each day the participant performed two computer sessions (marked with the computer symbol). In-between those computer sessions the scanning phase took place (marked with the scanner 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, η^2_G = 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, η^2_G = 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, η^2_G = 0.005) and no main effect of condition (F (2,50) = 0.21, p = .821, η^2_G = 0.001). The interaction effect was also non-significant (F (2,50) = 1.30, p = .280, η^2_G = 0.006).

Negative affect (NA) scores ($N = 26$) demonstrate a significant main effect of condition (F (2,50) = 4.185, p = .021, η^2_G = 0.035) and no main effect of time (F (1,25) = 1.464, p = .238, η^2_G = 0.004). The interaction effect was significant (F (2,50) = 4.347, p = .018, η^2_G = 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, η^2_G = 0.007) or time (F (1,29) = 0.21, p = .64, η^2_G = 0.0005). The interaction effect was likewise not significant (F (2,58) = 0.32, p = .73, η^2_G = 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, $p < .01$, η^2_G = 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, η^2_G = 0.012). The interaction effect was not significant (F (2,58) = 3.11, p = .052, η^2_G = 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, η^2_G = 0.002) and no main effect of condition (soundscape) (F (2,40) = 1.65, p = .20, η^2_G = 0.022). The interaction effect was not significant, but revealed a tendency (F (2,40) = 2.676, p = .081, η^2_G = 0.019). This tendency towards an interaction effect was again clearly driven by the pre to post

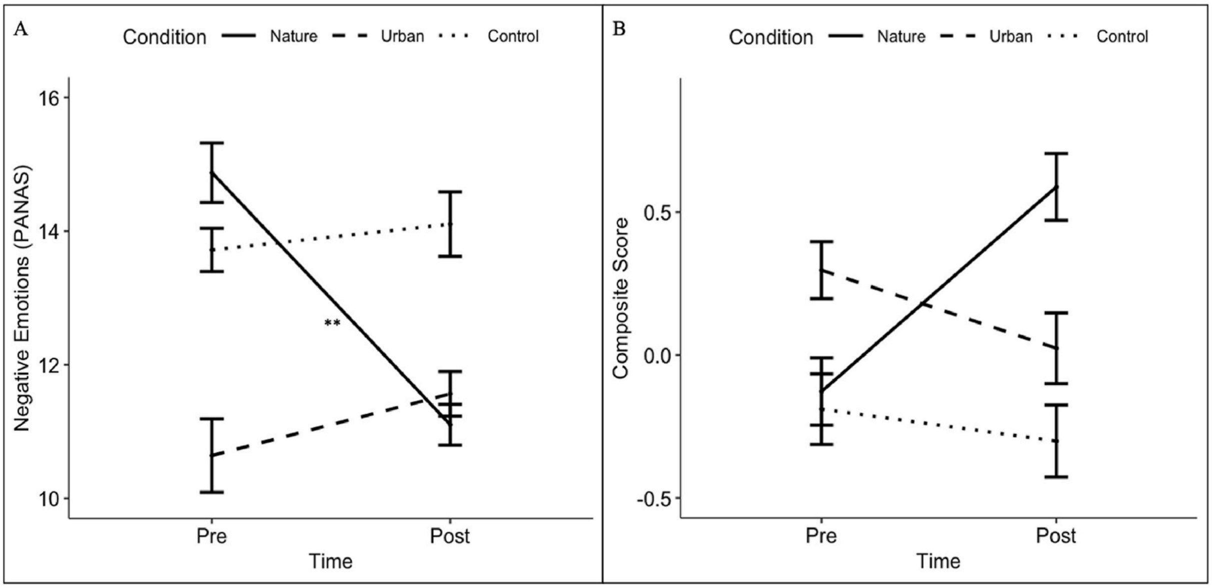

Fig. 2. Behavioural Data. Panel A displays negative emotions as measured with the PANAS questionnaire, plotted as a function of time (pre-intervention, post-intervention) and soundscape condition (natural, urban, control). Error bars represent +- 1.96 standard error of the mean. Double asterisks ** represent 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.

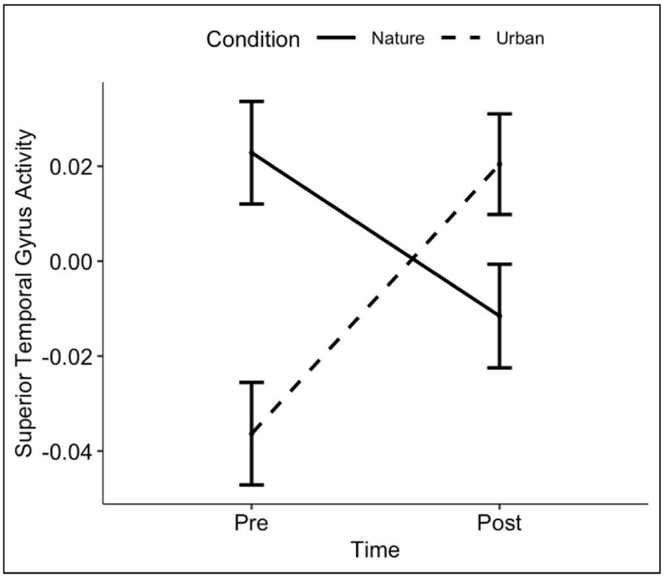

Fig. 3. Extracted brain data for visual inspection. BOLD signal from a cluster in the superior temporal gyrus (STG, MNI coordinate −50, −9, −4) plotted as a function of time (pre-intervention, post-intervention) and soundscape intervention (nature, urban). Error bars represent +- 1.96 standard error 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 ($F\,(2, 46) = 6.79$, $p = .003$, $\eta^2_G = 0.09$). 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 ($F\,(1,23) = 9.47$, $p = .005$, $\eta^2_G = 0.09$). 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, $r = 0.75$. $n = 20$, $p = 1.58\text{e-}4$. 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).

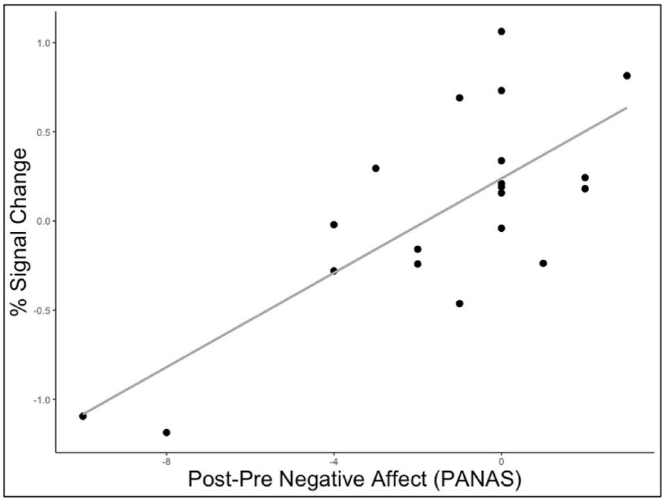

Fig. 4. Correlation between brain activity changes during the DNB task and changes in negative affect during the nature soundscape condition. Scatterplot graph with negative PANAS post-pre difference scores on the x-axis and percent signal change values from task related (dual n-back) neural activity (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

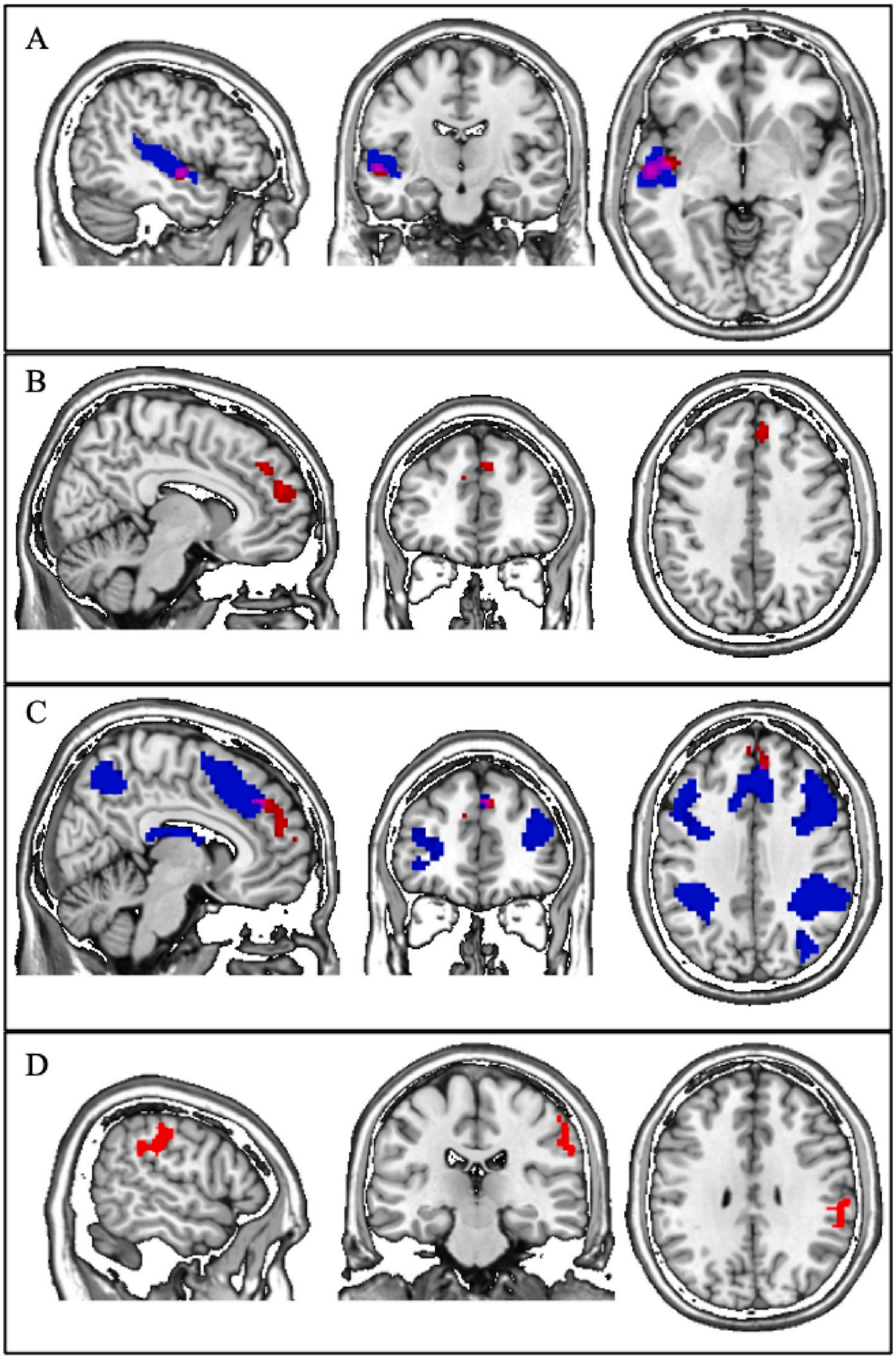

Fig. 5. ***Neural activity on template brains.*** *A: Anatomical template brain-image with superimposed brain activity in red and blue. The cluster (uncorrected) in red corresponds to the 2x2 interaction contrast found in the STG region. The cluster in blue corresponds to the mask contrasting auditory 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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