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Listening through a landline: Using degraded sounds to examine the relationship between cognitive restoration and preference

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ABSTRACT

Interactions with nature can improve attentional functioning and decrease mental fatigue. However, the perceptual quality of the experience might influence how effectively nature can improve these cognitive measures, as perceptual quality has been linked to how much nature sounds are liked, which may in turn influence aspects of psychological restoration. The current study manipulated the perceptual quality of both nature and urban soundscapes to examine how degraded sounds might influence the typically observed cognitive benefits of nature-based interventions. Participants (n = 227) completed a working memory task (n-back) and a self-reported mental fatigue measure before and after listening to one of four sound categories, using a 2 (sound type: unaltered, degraded) x 2 (environment: nature, urban) between-participant design. Participants additionally rated the restorativeness of the sound intervention via the Perceived Restorativeness Scale (PRS). Despite participants liking degraded sounds less and judging them as lower in sound quality, we found comparable restorative effects of unaltered and degraded nature sounds across all measures. However, the nature-related benefits for the PRS were entirely driven by how much participants liked the sounds. In contrast, the cognitive restoration measures showed nature-related benefits even after controlling for sound liking ratings and pre-intervention scores. The findings of this study suggest that nature-based restoration can be observed even when stimuli are degraded and liked less. However, measures that focus on the restorative experience itself (e.g., PRS) appear to be more related to stimulus preference than measures assessing participants' cognitive performance.

Individuals often seek out natural environments for the restorative qualities they possess. It is presently unclear, however, whether nature-based restorative effects are robust to variations in the perceptual quality of the experience (e.g., listening to birdsong while immersed in the outdoors versus listening to prerecorded birdsong through poor-quality speakers). Determining the extent to which lower-quality nature sounds may elicit restorative experiences is important for understanding the mechanisms through which nature improves cognitive restoration and psychological well-being, especially considering that perceptual degradation is an effective means of manipulating the aesthetic preference of nature sounds (Van Hedger, Nusbaum, Heald, et al., 2019). Thus, the present study examines whether degrading the perceptual experiences of natural environments alters the restorative benefits of interacting with nature.

Previous studies have established that interacting with nature has several cognitive benefits, including improved directed attention, working memory, and even cognitive development (Berman et al., 2008; Berto, 2005; Bratman et al., 2015; Dadvand et al., 2015; Stenfors et al., 2019; Tennessen & Cimprich, 1995). For instance, Tennessen and Cimprich (1995) found that interactions with nature improved directed attention relative to interactions with a built environment. Similarly, Stenfors et al. (2019) analyzed data from several independent studies and found beneficial effects of interacting with natural compared to urban environments on cognitive performance as measured with a backwards digit span task. Prior research has also shown improvements in working memory and attention after taking a nature walk (Berman et al., 2008, 2012; Bratman et al., 2015; Schertz et al., 2022), however, nature-related benefits are not limited to physical immersion within an

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environment. The benefits of nature on cognitive functioning and affective state have been found in several studies where participants have experienced videos of nature, photographs of natures, nature sounds, and virtual nature settings (Berto, 2005; Bourrier et al., 2018; Brancato et al., 2022; Ulrich et al., 1991; Valtchanov et al., 2010; Van Hedger, Nusbaum, Clohisy, et al., 2019; Gonzalez-Espinar et al., 2023). Van Hedger, Nusbaum, Clohisy et al. (2019) indicated that briefly listening to nature sounds in the lab resulted in improvements in cognitive functioning, including directed attention. Along these same lines, a recent meta-analysis of simulated natural environments found that the positive effects of these environments on mood and stress reduction were related to the degree of immersion in the simulated environment, with medium immersion producing the most robust effects (Li et al., 2023). Interestingly, high immersion in virtual environments did not yield additional benefits, and the authors suggest this could be due to cybersickness or a dislike of virtual reality environments among some participants. Taken together these studies provide evidence of the cognitive and affective benefits of interacting with nature and that these effects can be obtained even when interacting with simulations of nature either through pictures, videos, or sounds.

Nature-related benefits for cognitive functioning have primarily been explained by Attention Restoration Theory (ART; Kaplan, 1995). According to ART, natural environments have restorative potential to the degree that they can invoke feelings of being away, fascination, extent (which refers to a rich, coherent, and somewhat familiar environment that can keep an individual engaged and immersed), and compatibility with an individual's goals, purposes, and preferences (Kaplan, 1995). According to ART, one might not even need to like or enjoy the nature interaction to experience cognitive benefits (Berman et al., 2008; Stenfors et al., 2019). However, previous research has shown that some cognitive processes are enhanced by positive affect (e.g., Yang et al., 2013), suggesting that there could be a theoretic link between affect and cognition in the context of nature-based restoration. In comparison to natural environments, urban settings often do not afford the same opportunities for restoration of mental resources. Although urban environments typically contain various stimulating factors that demand an increase in directed attention that can impede restoration (Berman et al., 2008), there is also work suggesting that specific features of some urban environments (e.g., historical value, place attachment) can increase their restorative potential (Bornioli & Subiza-Pérez, 2023; Subiza-Pérez et al., 2021). In fact, ART does not require that the environment be natural to produce cognitive benefits, only that the environment have softly fascinating stimulation to capture involuntary attention (e.g., the dancing of flames in a fireplace or the breaking of waves on a beach), and not place demands on directed attention (Berman, Kardan, et al., 2019; Berman, Stier, & Akcelik, 2019; Kaplan & Berman, 2010).

In simulated nature interventions (e.g., showing participants pictures or playing participants sounds of nature through a computer), one understudied factor that might contribute to the restorative potential of nature-related stimuli is perceptual quality (i.e., the perceived quality of an image or sound). There are several potential factors that could influence the perceived perceptual quality of simulated nature experiences, including whether recordings were made on lower-quality recording devices or whether recordings are listened to through lower-quality speakers. Even beyond these hardware considerations, there are several contextual factors related to the listening environment (e.g., room acoustics) that could change the spectral properties of the sound (Heald et al., 2017) and thereby influence perceived sound quality. Regardless of how a sound's quality is degraded, there are several reasons to expect that the perceptual quality of the experience might relate to restorative effects. First, high quality stimuli might afford greater immersion in the depicted environment, allowing individuals to experience a heightened sense of *soft fascination*, *extent*, and *being away*, and therefore result in an enhanced restorative experience (cf. Kaplan, 1995). If an experience with nature involves the degradation of these perceptual experiences (e.g., listening to low-quality sounds), it is possible that one may not experience restorative levels of *soft fascination*, *extent*, or *being away*, even if the environment is still clearly identifiable as natural.

A second, related reason why perceptual quality of depicted nature and urban environments might relate to restorative effects is because degraded experiences with nature reduce aesthetic preference, which in turn could modulate some measures of restoration. Although a study conducted by Van Hedger, Nusbaum, Heald et al. (2019) seems to contradict this possibility, suggesting that individuals continue to show strong preferences for degraded nature (versus urban) sounds if participants could conceptually identify the sounds as originating from nature, this study found that overall aesthetic ratings were lowered when sounds were perceptually degraded. Moreover, the study focused exclusively on aesthetic preference and did not explicitly test how degraded sounds might influence the restorative benefits of nature sounds. Thus, it is unclear whether listening to degraded nature sounds still result in psychological restoration, and whether any observed effects would relate to how much the sounds were liked.

The present study thus sought to examine the extent to which nature-related restorative benefits were associated with perceptual quality. Prior research has mainly focused on physical immersion in nature (e.g., taking a walk through the woods) or high-quality media files to examine the influence of nature on cognitive performance. However, systematically investigating perceptual quality is important for determining the degree to which an environment needs to be immersive to elicit restorative benefits, and for being able to theoretically dissociate the conceptual understanding of the environment from how much it is liked. To address this question, the present study measured working memory and self-reported mental fatigue before and after an intervention that involved listening to and rating unaltered (i.e., high-quality) or degraded nature and urban sounds in terms of liking, sound quality, and naturalness. At the end of the experiment, participants also rated the perceived restorativeness of the sounds they heard.

We had several predictions about the effects of environment type (nature, urban) and sound quality (unaltered, degraded) on participant responses. First, as a manipulation check, we hypothesized that degraded sounds would be rated as lower in sound quality and would be overall liked less compared to unaltered sounds. Second, we hypothesized that listening to nature sounds, in contrast to urban sounds, would improve working memory, and decrease self-reported mental fatigue; however, we expected that perceptual quality would interact with environment, such that listening to degraded nature sounds would attenuate these benefits compared to unaltered nature sounds. In contrast, for participants listening to urban sounds, we predicted no effect of sound quality on cognition or perceived restorativeness, largely because the immersiveness of the experience was not expected to relate to psychological restoration for these sounds.

1. Method

1.1. Participants

A total of 320 participants were recruited from Amazon Mechanical Turk (MTurk), an online platform for recruiting research participants. CloudResearch (Litman et al., 2017) was used to further refine recruitment through MTurk. Participants were eligible to enroll in the study if they successfully passed internal attention checks conducted by CloudResearch and if they received a 90 % approval rating from prior MTurk tasks. Participants were based in the United States and were provided with $7.50 USD as compensation for their participation in the study. Of the 320 recruited participants, 227 (Age: M = 40.44 years old, SD = 11.33 years old, range of 21–71 years old; Gender: 130 men, 97 women) were included in the main analyses (see *Data exclusion* for details). Although the percentage of excluded participants is sizable (29.1 %), it should be noted that the present level of exclusion is within the range of prior perceptual studies with compliance checks that have used MTurk samples (e.g., Bainbridge, 2017) and aligns with work suggesting that upwards of 28.9 % of responses on MTurk might represent low effort or dishonest responses (Eickhoff & de Vries, 2013). There were 59 participants in the unaltered nature condition, 54 participants in the degraded nature condition, 54 in the unaltered urban condition, and 60 in the degraded urban condition. All participants provided informed consent, and the present study was approved by the Huron University Research Ethics Board (Protocol #18S-202211). Sample size was determined in part by the availability of funds, as well as a consideration of prior web-based research using nature and urban sounds to assess restoration (Stobbe et al., 2022), which also had four between-participant conditions and included between $n = 63$ and 83 per condition. Table 1 provides a descriptive comparison of the participants in each condition on demographic and pre-intervention measures.

1.2. Materials and procedure

Fig. 1 provides an overview of the procedure. The study was programmed in jsPsych 6 (de Leeuw, 2015), and participants were able to access the study from their own computers. Upon loading the study, participants were first presented with the Letter of Information and consent form. The Letter of Information did not make specific mention to nature or urban sound categories, nor did it make specific mention that some participants might listen to degraded sounds, to minimize demand characteristics. Individuals had to click on a checkbox ("I consent to participate in the study") before participating in the study.

1.2.1. Pre-intervention measures

Auditory Calibration and Headphone Assessment. Following the consent procedure, participants completed a short auditory calibration and headphone assessment. The initial calibration sound was a 30-s pink noise, root-mean-squared normalized to the same level as the rest of the sounds in the experiment. Participants were instructed to adjust their computer's volume such that the calibration noise was at a comfortable listening level.

Participants then completed the headphone assessment, which was based on Woods et al. (2017) and consisted of six trials. On each trial, participants heard three 200-Hz sine tones and judged which of the three tones was loudest. One of the tones was presented at the same comfortable listening level as the calibration noise, one was −6 dB relative to the two other tones (quietest), and one tone was presented at the comfortable listening level, but the left and right audio channels were presented in anti-phase, resulting in phase cancellation (leading to the perception of a quieter tone) only when the left and right audio channels are clearly separated. As noted in Woods et al. (2017), this task is designed to be easy over headphones (in which left and right channels are separated), but difficult over speakers, as the first and third tones should sound comparable in loudness. Across the six trials, the correct answer was in each position (first, second, third) exactly twice, to ensure that participants could not pass the headphone screening by responding with the same button press across all six trials. A score of 5 or 6 was taken to indicate headphone use, and although headphone use was not required, a majority of the included participants (178 of 227) passed the assessment.

Auditory N-Back Task. Following the auditory calibration and headphone assessment, participants completed the auditory *n*-back. In the *n*-back, participants were instructed to press one designated key if the current spoken letter matched the letter presented *N* position(s) previously, and a second designated key if the current spoken letter did not match the letter presented *N* position(s) previously. The spoken letters were sampled from a text-to-speech synthesizer (Amazon Polly: Kimberley - US) using the *TTSAutomate* program. Each participant completed five blocks of the *n*-back – one block of a 1-back (practice), followed by two blocks of a 2-back and two blocks of a 3-back in this order. Each block contained 30+*N* spoken letters (inter-letter interval of 2500 ms) and consisted of 10 target letters and 20 non-targets in randomized order. The final screen of the *n*-back was a self-report mental fatigue measure, in which participants rated their cognitive fatigue in the present moment on a Likert scale from 1 (*Not at all*) to 5 (*Extremely*). Immediately following the self-reported mental fatigue measure, participants were presented with an auditory attention check, in which participants had to click on one of four labeled buttons on the screen as designated by an unannounced auditory prompt.

Visual Analog Scale (VAS) Mood Rating. Following the *n*-back, cognitive fatigue measure, and auditory attention check, participants completed a VAS mood rating (Brancato et al., 2022). The VAS assessed how participants were currently feeling on five terms: happy, sad, lonely, calm, and anxious. Each item was rated on a 100-point slider scale. The VAS items in the present study had generally good test-retest reliability ($r = .44$ to .81), especially considering the prediction that both environment and sound quality might influence post-intervention rating scores. Moreover, these values were comparable to an earlier administration of the VAS (Brancato et al., 2022). Although the present study was not primarily focused on affective restoration, the VAS was included in part to assess whether changes in positive affect or negative affect were related to how much participants liked the sounds they heard, as well as whether any cognitive restorative benefits of nature were still observed when controlling for changes in positive and negative affect.

1.2.2. Intervention

Participants then listened to 40 sounds adhering to one of four sound types depending on their randomly assigned condition: (1) unaltered nature sounds, (2) degraded nature sounds, (3) unaltered urban sounds, or (4) degraded urban sounds. The unaltered recordings were identical to the recordings used by Van Hedger, Nusbaum, Clohisy et al. (2019).

Table 1
Descriptive comparison of participants across conditions for demographic and pre-intervention measures.

	Unaltered Nature (n = 59)	Degraded Nature (n = 54)	Unaltered Urban (n = 54)	Degraded Urban (n = 60)
Demographics				
Age (Years)	41.05 [38.07, 44.04]	38.96 [35.98, 41.95]	40.92 [37.85, 44.00]	40.73 [37.67, 43.80]
Gender	17/42	29/25	24/30	27/33
Education	.51	.54	.44	.55
Pre-Intervention Cognition				
2-Back (d')	2.11 [1.85, 2.38]	2.29 [2.00, 2.59]	2.11 [1.86, 2.35]	2.20 [1.98, 2.43]
3-Back (d')	1.19 [0.99, 1.39]	1.29 [1.07, 1.52]	1.36 [1.16, 1.56]	1.13 [0.96, 1.31]
Fatigue	2.88 [2.60, 3.16]	3.09 [2.77, 3.42]	2.96 [2.65, 3.27]	2.90 [2.60, 3.20]
Pre-Intervention Mood				
Happy	54.30 [47.56, 61.05]	54.09 [47.77, 60.42]	49.61 [42.83, 56.39]	48.07 [41.26, 54.87]
Sad	19.49 [13.61, 25.37]	17.83 [11.86, 23.80]	22.28 [14.56, 29.99]	21.58 [15.26, 27.91]
Lonely	25.54 [17.87, 33.21]	25.53 [18.12, 32.96]	27.70 [18.92, 36.48]	27.01 [19.49, 34.54]
Calm	64.19 [57.05, 71.32]	54.19 [47.39, 62.43]	56.41 [49.35, 63.46]	59.17 [52.49, 65.85]
Anxious	35.17 [27.33, 43.01]	46.72 [37.63, 55.81]	42.91 [33.55, 52.26]	38.15 [30.33, 45.96]

Note: Values in brackets represent 95 % confidence intervals. Gender is represented in terms of women/men. Education represents the proportion of participants with at least a bachelor's degree.

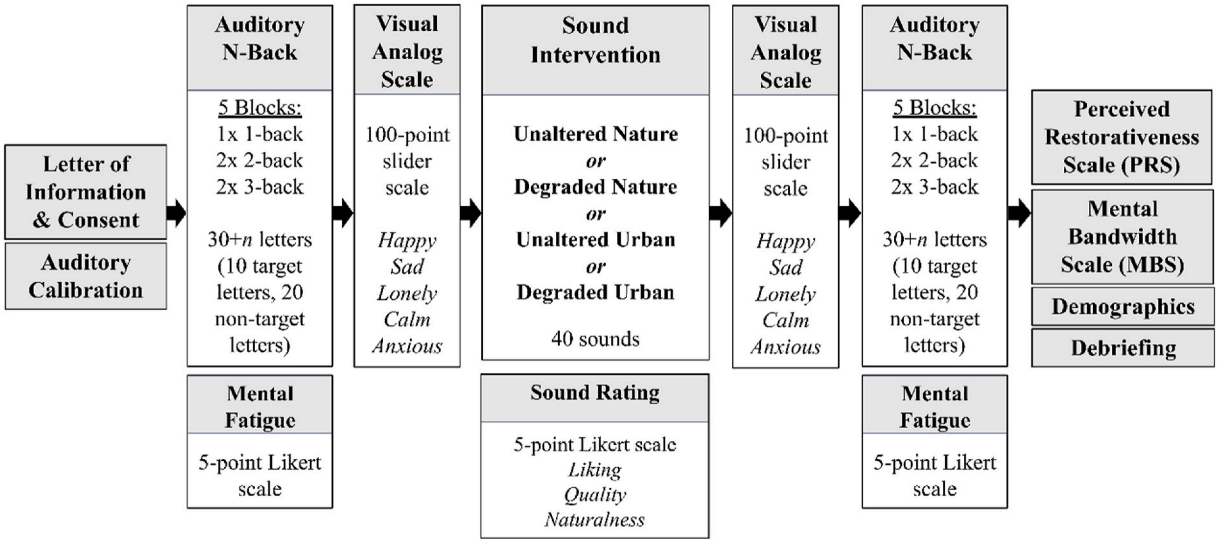

Fig. 1. Overview of the study tasks and procedure.

The degraded recordings were bandpass filtered between 400 and 2500 Hz, using a tenth-order Butterworth filter in Adobe Audition 3.0 (Adobe Inc.). This was not expected to substantially impact the categorization of sounds (cf. Van Hedger, Nusbaum, Heald, et al., 2019). However, this specific manipulation was expected to result in perceptually "thinner" sounds (see Fig. 2 for a visualization), akin to listening to the sounds over a landline telephone (cf. Hu et al., 2013). As such, the degraded sounds were hypothesized to be liked less and to be perceived as lower quality. Each general category of sounds (nature vs. urban) contained a diverse range of sounds within these general categories. Nature sounds included birdsong ($n = 11$), insects ($n = 4$), running water (rain, river, waves; $n = 15$), wind ($n = 5$), and the crackling of burning wood ($n = 5$). Urban sounds included traffic ($n = 5$), machinery noise ($n = 16$), background conversation (e.g., from a coffee shop or restaurant; $n = 10$), construction sounds ($n = 4$), streetscape recordings ($n = 3$), and sirens or alarms ($n = 2$).[1] Previous work using these recordings has found robust aesthetic preferences for nature sounds, which can be attenuated as a function of perceptual degradation (Van Hedger, Nusbaum, Heald, et al., 2019). Additionally, the unaltered versions of these recordings have been associated with nature-based cognitive benefits (Van Hedger, Nusbaum, Clohisy et al., 2019), making them well suited to answering the present research question. All recordings were 14 s in duration and were presented to participants in a randomized order.

After listening to each recording, participants answered three prompts on five-point Likert scales. Participants answered the first prompt ("How much did you like the recording you just heard?") on a scale ranging from 1 (*Strongly dislike*) to 5 (*Strongly like*). Participants answered the second prompt ("Please rate the sound quality of the recording you just heard."), on a scale ranging from 1 (*Low quality*) to 5 (*High quality*). Participants answered the third prompt ("To what extent did the recording convey an urban (versus natural) setting?"), on a scale ranging from 1 (*Very urban*) to 5 (*Very natural*). Question order was fixed. Although no time limit was imposed on answering the intervention questions, included participants took an average of 16.76 (SD = 4.12) minutes. The time it took to complete the intervention did not significantly differ as a function of condition, $F(3, 223) = 1.86$, $p = .137$, $\eta 2 = 0.02$, suggesting that any differences between conditions could not be explained by differences in the amount of time between the pre- and post-intervention measures. On average, participants in the unaltered nature sound condition took 15.77 (SD = 3.86) minutes, participants in the degraded nature sound condition took 16.73 (SD = 4.65) minutes, participants in the unaltered urban sound condition took 17.11 (SD = 3.41) minutes, and participants in the degraded urban sound condition took 17.45 (SD = 4.34) minutes.

1.2.3. *Post-intervention measures*

Following the intervention, participants completed the VAS and the *n*-back for a second time, in this order. Like the pre-intervention administration of the *n*-back, the final two screens consisted of a self-reported mental fatigue question and a new auditory attention check (i.e., with a different auditory prompt to select a different labeled button on the screen). Participants then completed questionnaires that were only administered post-intervention, as they asked about the sound intervention experience. These questionnaires are described in the next two subsections.

Perceived Restorativeness Scale. The Perceived Restorativeness Scale (PRS; Norling, Sibthorp, & Ruddell, 2008) contains nine items assessing the perceived restorativeness of the nature and urban sounds in the present study. The PRS contains three subcomponents, consisting of three items each: (1) *being away*, (2) *extent*, and (3) *fascination*. Participants rated each item on a Likert scale, ranging from 1 (*Very slightly or not at all*) to 5 (*Extremely*). In the current study, the three subscales were strongly correlated ($r = .78$ to $.85$), and each subcomponent had high internal reliability (*being away*: $\alpha = .93$, *extent*: $\alpha = .90$, *fascination*: $\alpha = .86$). These values were comparable to an earlier administration of the PRS (Brancato et al., 2022). There was an additional written attention check embedded into the scale, instructing participants to select *Moderately* for data quality purposes.

Mental Bandwidth Scale. The Mental Bandwidth Scale (MBS; Basu et al., 2019) contains seven items which assess the extent to which an activity expends mental bandwidth. In this study, the activity involved listening to either nature or urban sounds. The MBS involves three subcomponents: (1) *self-awareness* (two items), (2) *daydreaming* (three items), and (3) *planning* (three items). All items were rated on a Likert scale, ranging from 1 (*Very slightly or not at all*) to 5 (*Extremely*). Basu et al. (2019) found good internal reliability of each subcomponent of the MBS (*self-awareness*: $\alpha = .72$, *daydreaming*: $\alpha = .81$, *planning*: $\alpha = .83$). In the present study, the subcomponents of the scale exhibited weak to moderate correlations ($r = .28$ to $.52$), and the internal reliability of each subcomponent was acceptable apart from self-awareness (*self-awareness*: $\alpha = .18$, *daydreaming*: $\alpha = .77$, *planning*: $\alpha = .78$). Similar to the PRS,

[1] The classification of soundscapes here is based on the most audible sound source; however, a given recording could contain multiple sound sources (e.g., birdsong and running water).

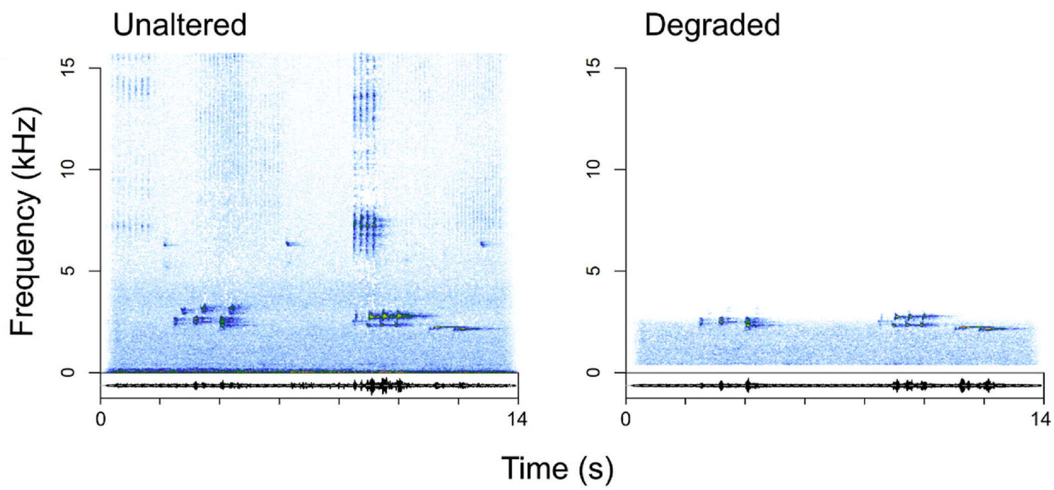

Fig. 2. Sample spectrograms from a single unaltered (left) and degraded (right) nature sound file.

there was an additional written attention check embedded into the scale, instructing participants to select *Extremely* for data quality purposes.

Demographic Questionnaire. Following the PRS and MBS, participants reported their age, gender, and highest level of education. The demographic questionnaire also asked participants to self-report their use of hearing aids (none, right ear, left ear, both ears) as well as describe any health concerns which may have influenced their performance in the study. Additionally, participants were provided with a free response space to attempt to guess the purpose of the study.

1.2.4. Debriefing and compensation

Following the demographic questionnaire, participants were given a unique completion code, which they used to verify participation and to receive compensation. Participants were also provided with a debriefing letter, which described the study and explained the reasoning behind the use of mild deception (i.e., not explicitly mentioning nature versus urban sound categories or degraded versus unaltered sound categories in the Letter of Information).

1.3. Data exclusion

Of the 320 recruited participants, data from five participants were not successfully saved to our server. The remaining 315 participants were excluded if: (1) they failed the auditory ($n = 33$) or written ($n = 12$) attention checks, (3) they indicated the use of a hearing aid or a neurological condition that affects auditory processing ($n = 36$), (4) they took too long (>3 *SD*) to complete the intervention, suggesting that it might not have been completed in one sitting ($n = 5$), (5) they failed to respond (not based on accuracy, but rather failing to produce any key press) to a minimum of 75 % of the spoken letters in the *n*-back, indicating task misunderstanding or task noncompliance ($n = 56$), or (6) their questionnaire responses suggested task misunderstanding or noncompliance ($n = 2$). One example of noncompliance from the questionnaire items was a participant who copied and pasted the study title for *both* free response questions (including the question assessing whether there were any health concerns that might have affected their responses in the study). The number of excluded participants for each consideration exceeds the total number of excluded participants because some participants met multiple exclusion criteria.

1.4. Data analysis

All data analyses were performed in R (v.4.3.0) and RStudio. For the intervention sounds, we analyzed (1) liking, (2) quality, and (3) naturalness using 2 (Environment: Nature, Urban) x 2 (Quality: Unaltered, Degraded) ANOVAs. These sound rating analyses primarily served as manipulation checks – specifically, to confirm that participants liked the nature sounds more than the urban sounds (cf. Van Hedger, Nusbaum, Heald, et al. 2019), to confirm that participants rated degraded sounds as lower in quality than unaltered sounds, and to confirm that participants rated nature sounds as more natural than urban sounds. Correlations between participants' mean liking ratings and changes in positive and negative affect were also assessed via Pearson correlations. Positive affect was calculated by averaging the difference scores (Post-Intervention – Pre-Intervention) of the happy and calm VAS terms, and negative affect was calculated by averaging the difference scores of the sad and anxious VAS terms.

To assess how the sound intervention influenced restoration, the analyses depended on whether the measure was administered twice (*n*-back, Self-Reported Mental Fatigue) or once (PRS, MBS). The measures administered twice used a 2 (Environment: Nature, Urban) x 2 (Quality: Unaltered, Degraded) ANCOVA, with the difference score serving as the dependent variable and pre-intervention scores added as a covariate. Although we opted to use difference scores as the dependent measure, it should be noted that both using a difference score and using a post-intervention score have both been shown to be effective against biased treatment estimates (O'Connell et al., 2017). Environment and Quality were between-participant factors. The restorativeness scales (PRS and MBS) used a 2 (Environment: Nature, Urban) x 2 (Quality: Unaltered, Degraded) between-participant MANOVA. For all analyses assessing restoration (i.e., *n*-back, Self-Reported Mental Fatigue, PRS, MBS), we created two versions of each model – one without aesthetic and affective covariates (i.e., sound liking ratings and changes in positive and negative affect), and one including these covariates to assess how these aesthetic and affective measures related to the restoration measures. Exploratory correlations between the measures of restoration and sound preference were assessed via Pearson correlations. Based on the results of the exploratory correlations, we additionally assessed whether the measures of restoration differed in how strongly they correlated to sound preference using the "cocor" package in R (Diedenhofen & Musch, 2015). Differences in correlation strengths are represented in terms of confidence intervals as outlined by Zou (2007), with a confidence interval not containing zero indicating that the compared correlations differed in strength.

2. Results

2.1. Sound intervention ratings

Fig. 3 provides an overview of the sound intervention rating results.

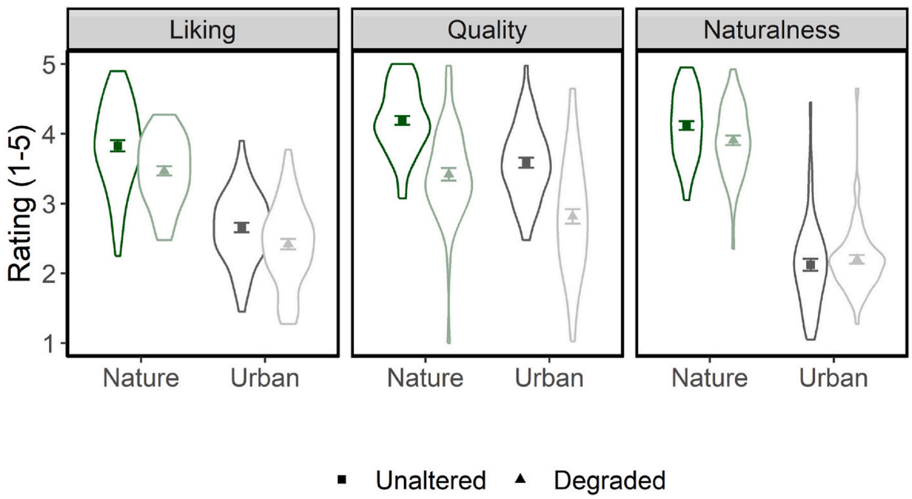

Fig. 3. Intervention sound ratings across condition for liking, sound quality, and naturalness.
Note: Error bars represent ±1 standard error of the mean. Violin plots depicting the distribution of responses are additionally represented.

Nature sounds were liked more, $F(1, 223) = 228.02, p < .001, \eta^2 = 0.51$, rated as higher quality, $F(1, 223) = 51.35, p < .001, \eta^2 = 0.19$, and were rated as more natural compared to urban sounds, $F(1, 223) = 702.68, p < .001, \eta^2 = 0.76$, as evidenced by significant main effects of Environment. Furthermore, unaltered sounds were liked more, $F(1, 223) = 16.30, p < .001, \eta^2 = 0.07$, and were rated as higher quality, $F(1, 223) = 83.34, p < .001, \eta^2 = 0.27$, compared to degraded sounds, as evidenced by significant main effects of Quality. Unaltered sounds did not significantly differ from degraded sounds in terms of naturalness ratings. The interactions between Environment and Quality were nonsignificant for how much participants liked the sounds and participants' perceived quality of the sounds; however, there was a significant interaction between Environment and Quality for naturalness ratings, characterized by an attenuated difference between degraded nature and urban sounds compared to unaltered nature and urban sounds, $F(1,223) = 4.32, p = .039, \eta^2 = 0.02$. Mean liking ratings of the sounds was positively correlated with changes in positive affect, $r(225) = .34, p < .001$ and was negatively correlated with changes in negative affect, $r(225) = -.25, p < .001$.

2.2. Auditory N-back

For 2-back performance (Fig. 4, top), there were no main effects of Environment, $F(1, 222) = 0.44, p = .508, \eta^2 = 0.002$, or Quality, $F(1, 222) = 0.06, p = .813$ $\eta^2 < 0.001$, nor was there an interaction between Environment and Quality, $F(1, 222) = 0.87, p = .353, \eta^2 = 0.004$. In the model including aesthetic and affective covariates, there were similarly no main effects of Environment, $F(1, 219) = 0.20, p = .653, \eta^2 < 0.001$, or Quality, $F(1, 219) = 0.16, p = .685, \eta^2 < 0.001$, nor was there an interaction between Environment and Quality, $F(1, 219) = 0.32, p = .569, \eta^2 = 0.001$. There was, however, a significant effect of liking ratings as a covariate, $F(1, 219) = 5.05, p = .026, \eta^2 = 0.023$. However, this effect was not straightforward, as the simple association between liking and 2-back improvement was nominally negative and nonsignificant, $r(225) = -.06, p = .341$.

For 3-back performance (Fig. 4, middle), there was a significant effect of Environment, $F(1, 222) = 8.76, p = .003, \eta^2 = 0.038$, characterized by overall larger improvement scores for participants listening to nature sounds ($M = 0.17, SD = 0.69$) compared to participants listening to urban sounds ($M = -0.05, SD = 0.55$). The main effect of Quality was not significant, $F(1, 222) = 0.38, p = .538, \eta^2 = 0.002$, nor was there a significant interaction between Environment and Quality, $F(1, 222) = 2.91, p = .089, \eta^2 = 0.013$. Including the aesthetic and affective covariates did not change the significance of the model terms as the main effect of Environment was still significant, $F(1, 219) = 5.22, p = .023, \eta^2 = 0.023$. Sound liking ratings, changes in positive affect, and changes in negative affect were all nonsignificant in the model (*ps* > .319).

2.3. Self-reported mental fatigue

For self-reported mental fatigue (Fig. 4, bottom), listening to nature sounds showed significantly attenuated changes in fatigue scores ($M = 0.19, SD = 1.00$) compared to participants listening to urban sounds ($M = 0.55, SD = 0.97$), as evidenced by a main effect of Environment, $F(1, 222) = 8.42, p = .004, \eta^2 = 0.037$. There was no main effect of Quality, $F(1, 222) = 0.82, p = .365, \eta^2 = 0.004$, nor was there an interaction between Environment and Quality, $F(1, 222) = 1.24, p = .267, \eta^2 = 0.006$. Including the aesthetic and affective covariates did not change the significance of the model terms as the main effect of Environment was still significant, $F(1, 219) = 4.88, p = .028, \eta^2 = 0.022$. Sound liking ratings, changes in positive affect, and changes in negative affect were all nonsignificant in the model (*ps* > .175).

2.4. Perceived restoration

2.4.1. Perceived Restorativeness Scale

Mean ratings across condition for the PRS are plotted in Fig. 5. We found a significant main effect of Environment, $F(3, 221) = 6.94, p < .001$, with nature sounds eliciting higher scores on the PRS compared to urban sounds. There were no significant main effects of Quality, $F(3, 221) = 0.82, p = .482$, nor were there significant interactions between Quality and Environment, $F(3, 221) = 0.06, p = .982$.

When including the aesthetic and affective covariates, the main effect of Environment was no longer significant, $F(3, 218) = 1.99, p = .116$. Instead, we observed strong main effects of sound liking, $F(3, 218) = 27.21, p < .001$, and changes in positive affect, $F(3, 221) = 6.54, p < .001$. This suggests that the effects of Environment for the PRS were best explained by how much participants liked the sounds they heard and how much their positive affect increased, not something about nature sounds per se (Fig. 6).

2.4.2. Mental Bandwidth Scale

For the MBS, there were no significant main effects of Environment, $F(3, 221) = 1.47, p = .222$, or Quality, $F(3, 221) = 0.99, p = .398$, nor was there an interaction of Environment and Quality, $F(3, 221) = 1.12, p = .341$. In the model containing the liking and affective measures as covariates, there was a significant effect of liking, $F(3, 218) = 7.61, p < .001$. suggesting that similar to the PRS, variance in the MBS was best

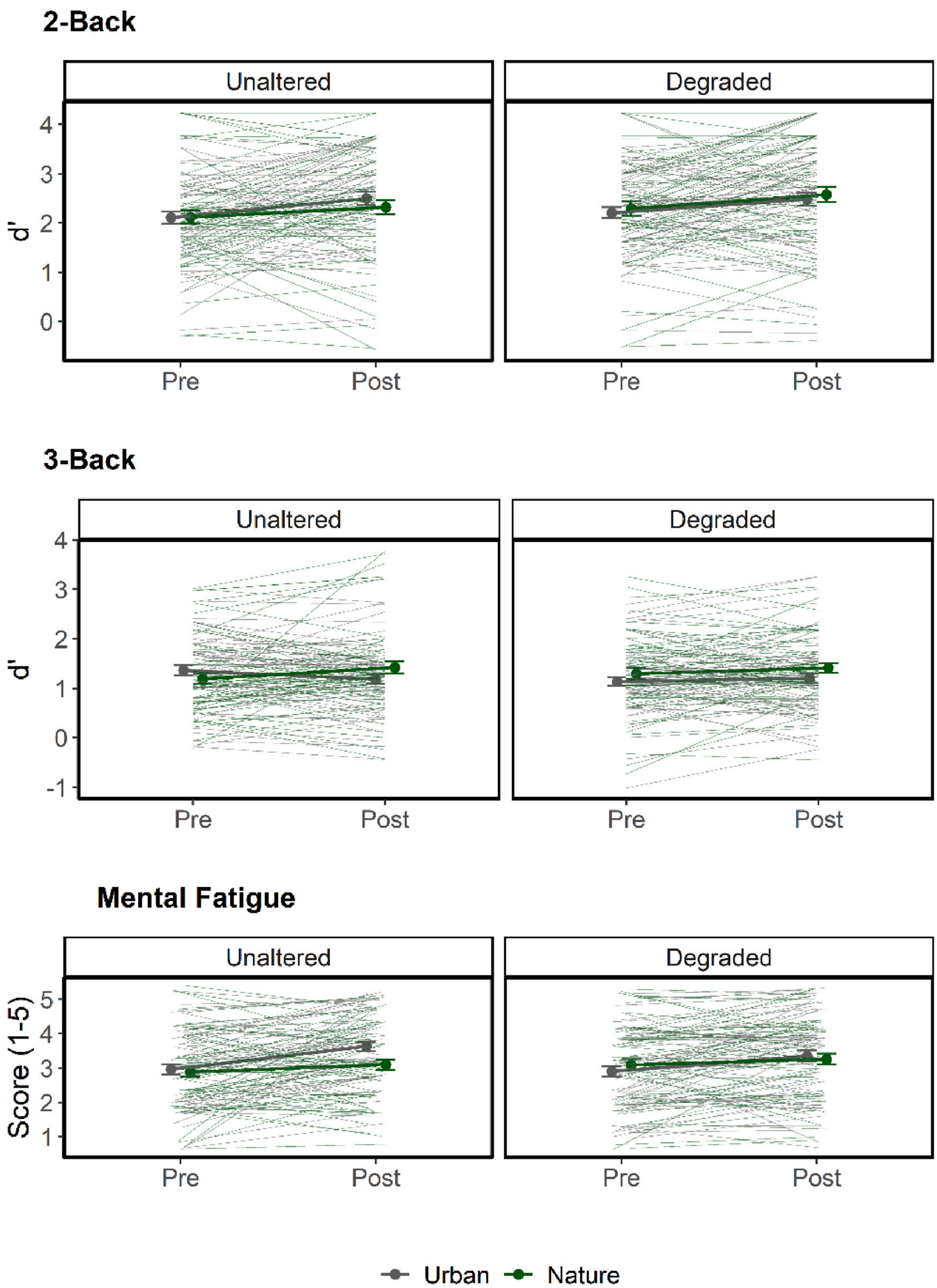

Fig. 4. 2-Back Scores (top), 3-Back Scores (middle), and Self-Reported Mental Fatigue Scores (bottom) as a function of Environment (nature, urban), Quality (unaltered, degraded), and Time (pre-intervention versus post-intervention).
Note: Error bars represent ± 1 standard error of the mean. Individual participant lines are plotted alongside group means. Although the dimension of Time is shown for visualization purposes, the analyses used the change score (i.e., post-minus pre-intervention) while including pre-intervention score as a covariate. Individual values for the mental fatigue measure were jittered to better show individual responses.

explained by how much participants liked the sounds they heard, not the environmental category or perceptual quality of the sounds they heard.

2.5. Correlations among restoration measures and sound liking

Correlations among the measures of restoration and sound liking ratings are reported in Table 2 for participants across all conditions. Overall, we found that *n*-back performance and mental fatigue were correlated, with higher *n*-back performance relating to lower mental fatigue ratings. We also found significant correlations between the MBS and both *n*-back and mental fatigue measures, with lower MBS scores being associated with better *n*-back performance and lower mental fatigue ratings. MBS and PRS were moderately correlated, and interestingly both PRS and MBS positively correlated with sound preference.

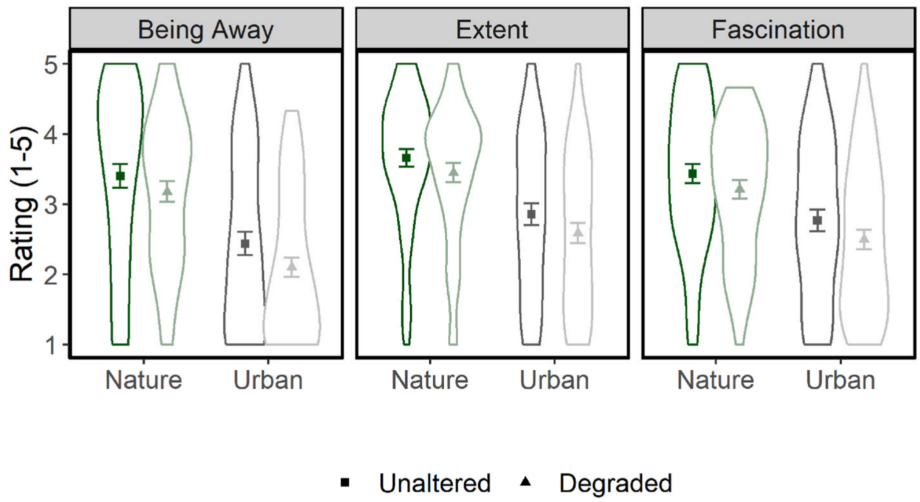

Fig. 5. Ratings across the dimensions of the Perceived Restorativeness Scale (PRS) as a function of Environment and Quality.
Note: Error bars represent ± 1 standard error of the mean. Violin plots depicting the distribution of responses are additionally represented.

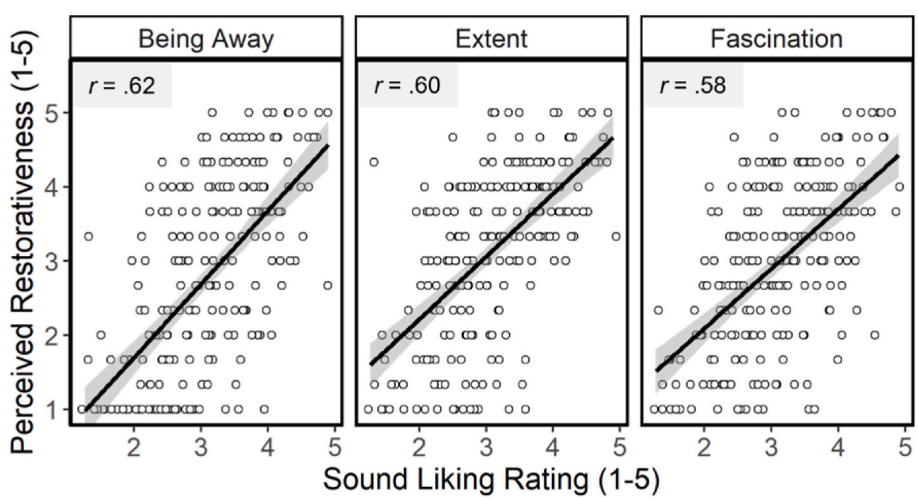

Fig. 6. Correlations between sound liking ratings and each dimension of the Perceived Restorativeness Scale (PRS).
Note: Error ribbons represent 95 % confidence intervals.

Table 2
Correlation matrix of restoration measures and sound liking ratings.

	2-Back	3-Back	Fatigue	PRS	MBS
2-Back	–				
3-Back	.61***	–			
Fatigue	−.20**	−.15*	–		
PRS	−.07	.02	.01	–	
MBS	−.36***	−.17*	.23***	.31***	–
Liking	−.14*	.07	−.05	.64***	.30***

Note: PRS = Perceived Restorativeness Scale; MBS = Mental Bandwidth Scale. Correlations were derived from post-intervention scores for measures that were administered twice (2-Back, 3-Back, and Mental Fatigue). ***$p < .001$ **$p < .01$ * $p < .05$.

2.6. Comparing the correlation strength of different restoration measures with sound preference

The correlation strength between sound liking and the PRS was significantly stronger than the correlations between sound liking and all measures associated with the n-back. For the 2-back [.63, .93], 3-back [.42, .72], and mental fatigue measure [.43, .74], the 95 % Confidence Interval of the correlation difference did not include zero. Similarly, the correlation strength between sound liking and the MBS was significantly stronger than the correlations between sound liking and all measures associated with the n-back. For the 2-back [.23, .63], 3-back [.17, .55], and mental fatigue measure [.08, .40], the 95 % Confidence Interval of the correlation difference did not include zero. These results suggest that the significant associations between PRS and MBS and sound liking, reported in the previous section, were significantly stronger than any of the correlations observed between the performance-based n-back measures or mental fatigue and sound liking.

3. Discussion

The current study examined whether the perceptual quality of nature and urban sound interventions have an influence on cognitive performance and nature-related restorative benefits. Here we find evidence that listening to nature sounds improved cognitive performance relative to urban sounds, with no statistical attenuations in performance as a function of perceptual quality. Although several measures (performance on an auditory 3-back task, self-reported mental fatigue, and self-reported restoration via the PRS) showed nature-related improvements, in line with ART, one notable finding was that responses on the

PRS appeared to be driven primarily by liking (aesthetic preference) and positive affect rather than by the nature versus urban distinction specifically. These findings suggest a potential dissociation of the mechanisms underlying self-reported benefits of nature that focus on the restorative experience (such as the PRS) versus those that focus on the cognitive performance and current cognitive state of the participant (such as the *n*-back and mental fatigue measure).

3.1. Implications of manipulating sound quality

The manipulation of sound quality in the present experiment has both practical and theoretical importance for understanding sound-based restorative effects. In practice, although sound quality is carefully controlled in research contexts, there are many potential sources of sound quality variability when individuals listen to environmental recordings outside of experimental contexts (e.g., variability in recording quality, speaker or headphone quality, room acoustics, and the extent of ambient noise in the environment). Importantly, similar to the manipulation of sound quality in the present experiment, these potential sources of variability would not be expected to substantially attenuate sound identification. For example, even if one listened to a low-quality recording of birdsong over low-quality speakers, one would still be expected to identify the recording as containing birdsong. In this sense, the present manipulation of sound quality provides an initial indication of how well nature-based restorative effects might generalize to a wider variety of ecologically valid listening contexts (although some caution needs to be exercised in this generalization, given the fact that the present experiment only used a single form of spectral manipulation and at one level of variation).

Beyond these practical considerations, the manipulation of sound quality provides a means of disentangling restorative effects from aesthetic evaluations, or more specifically, helps to disentangle preference from environment (i.e., natural sounds tend to be more liked than urban sounds). We had hypothesized that degraded sounds might lead to reduced ratings of *soft fascination*, *extent*, and *being away*, which could have been one possible path through which cognitive restoration was attenuated. This, however, did not appear to be the case, as evidenced by the analyses of the Perceived Restorativeness Scale (PRS). However, in line with our predictions, we did find that degraded sounds were significantly less liked than their unaltered counterparts. Thus, perceptual degradation offers an intriguing approach for disentangling restorative effects from aesthetic preferences – which is of particular importance in the context of nature-based restoration work, as nature stimuli are consistently more liked than urban stimuli in non-degraded formats among adult raters (Ibarra et al., 2017; Kaplan et al., 1972; Meidenbauer et al., 2020; Van Hedger, Nusbaum, Heald, et al., 2019). The approach of perceptual degradation – at least the form used in the present experiment – offers a means of systematically varying both aesthetic preference and source identification (i.e., what environment is depicted), allowing for a more nuanced understanding of how aesthetics relate to environmental aspects of restoration.

3.2. Cognitive benefits of listening to nature soundscapes

The improvements in cognitive performance following experiences with nature sounds relative to urban sounds conceptually replicate prior work using both visual (e.g., Berman et al., 2008; Tennessen & Cimprich, 1995) and auditory (Van Hedger, Nusbaum, Clohisy, et al., 2019) nature interventions. To our knowledge this is the first online replication of a performance-based nature sound intervention (Van Hedger, Nusbaum, Clohisy et al., 2019). However, this prior work has not systematically manipulated the perceptual quality of the intervention, which is important for understanding how specific aspects of the experience (e.g., presence of specific perceptual features, aesthetic evaluations of the stimuli) might relate to cognitive restoration. Despite participants liking the degraded sounds less and rating them as overall lower in quality, degraded nature sounds statistically showed comparable effects as unaltered nature sounds in terms of all restorative measures. Although this goes against our hypothesis that degraded sounds might attenuate restorative benefits of nature sounds, one potential explanation of these results lies in the specific degradation implemented in the present study. Specifically, we used bandpass filtering, which was expected to degrade perceived quality *without* significantly impairing sound identification. Indeed, based on the "naturalness" ratings obtained during the sound intervention, the degraded nature and urban sounds were still strongly differentiated by participants based on naturalness ratings. Given that prior work has shown that sound identification is a critical factor in the aesthetic evaluation of nature and urban sounds (Van Hedger, Nusbaum, Heald, et al., 2019), this might explain why the PRS did not show any attenuation based on sound quality (as the PRS ultimately was best explained by how much participants liked the sounds in the intervention). The fact that degraded sounds did not statistically attenuate the performance-based and self-reported cognitive fatigue measures holds initial promise in terms of application, as these findings suggest that less-than-ideal perceptual experiences with nature sounds can still yield cognitive benefits.

The nature-related improvements in cognitive performance and self-reported mental fatigue were still observed when controlling for how much participants liked the intervention sounds, as well as participant changes in both positive and negative affect after listening to the intervention sounds. This finding is consistent with prior work examining performance-based measures of cognitive restoration. For example, Berman et al. (2008) found that the changes in positive and negative affect from viewing nature or urban pictures was unrelated to nature-related cognitive performance gains using a backward digit span task, and Van Hedger, Nusbaum, Clohisy et al. (2019) found nature-related cognitive improvements in a composite cognitive measure even when controlling for changes in positive and negative affect. These findings thus suggest that nature-related changes to affect are theoretically dissociable from nature-related changes to cognition (cf. Stenfors et al., 2019).

Although the current experiment found performance-based cognitive improvements following unaltered nature exposure, it should be noted that these effects were only observed for the more difficult 3-back assessment. In contrast, the 2-back assessment did not show any evidence of nature-based improvement above urban sounds. Two potential explanations of this discrepancy are (1) that the 2-back was not sufficiently demanding to show nature-based effects, or (2) given that the 2-back always preceded the 3-back, participants were not yet sufficiently mentally fatigued when completing the 2-back. The present findings suggest that researchers must consider cognitive assessments that are appropriately difficult. This point was also noted by Schertz et al. (2022), who used a dual *n*-back paradigm and reported performance that was ostensibly too low to observe any performance-based effects of nature but was observed when only focusing on the 2-back trials of the dual *n*-back. Recent work has suggested that nature benefits are best observed when tasks include working memory and cognitive flexibility components (Stevenson et al., 2018), making the *n*-back a well-suited task for examining nature-related cognitive performance benefits. Nevertheless, given the heterogeneity of tasks used to assess cognitive restoration following nature interventions (Stevenson et al., 2018), future work should consider the relative design and placement of cognitive assessments to maximize sensitivity to detect effects.

Another consideration in interpreting the present findings is that the observed nature-based cognitive benefits for the 3-back had a relatively small effect size, particularly when compared to previous work. This finding is unlikely to be due to the specific nature of the *n*-back, given that the *n*-back is a widely used measure of working memory (e.g., Owen et al., 2005) and thus should be suitable for assessing nature-related improvements in cognitive performance (e.g., Stevenson et al., 2018). Another possibility is that performance-based assessments of cognition are not as amenable to online paradigms. This could be because participants in an online context, who cannot be monitored by the experimenters, may not fully engage with the intervention or may not fully understand how to perform the cognitive assessments (and not have an easy means of clarifying instructions in the moment). In support of this idea, a recent online study (Stobbe et al., 2022) found robust nature-related effects on self-reported mood (e.g., reductions in anxiety), but no effects of performance-based cognitive changes, despite using a large sample size ($n = 295$). However, in-person follow-up work by this same group found stronger evidence in support of nature-based cognitive improvements using both behavioral (Stobbe et al., 2023) and neuroimaging (Stobbe et al., 2024) measures. Although more work is clearly needed to determine the conditions under which online paradigms are suitable for measuring performance-based cognitive improvements, one intriguing finding from the current experiment is that self-reported mental fatigue also showed nature-related improvements and additionally was not associated with how much the soundscapes were liked. These findings suggest that assessments of mental fatigue (e.g., following a cognitively demanding task) may be a promising way of measuring cognitive restoration in future work, particularly in online contexts.

3.3. Perceived restorativeness depends on aesthetic preference

In contrast to the cognitive performance measure, the self-reported measures that focused on restorative aspects of the experience (i.e., the PRS and MBS) showed a distinct and consistent pattern of results. For the PRS, the present experiment found a main effect of environment (i.e., greater restoration following nature interventions compared to urban interventions, regardless of sound quality), similar to the cognitive performance and mental fatigue measure. For the MBS, there was surprisingly no effect of environment. Yet, for both the PRS and MBS, the added covariate of sound liking was highly significant, and in the case of the PRS, resulted in a complete attenuation of the main effect of nature. Follow-up analyses demonstrated that the association between sound liking and PRS was significantly stronger than either of the cognitive measures that showed nature-related changes (i.e., 3-back performance and mental fatigue ratings). Thus, what seems to explain the most variance in these measures of restoration is how much participants *liked* the intervention (e.g., see Fig. 6), not necessarily whether the sound intervention contained sounds of nature or urban environments. This finding conceptually aligns with previous work (Meidenbauer et al., 2020), which has found that the affective benefits of interacting with nature are completely attenuated when matching nature and urban interventions in terms of preference, but that the cognitive effects of interacting with nature might not be reliant on stimulus preference (Gonzalez-Espinar et al., 2023; Stenfors et al., 2019; Berman et al., 2008, 2012). Although Meidenbauer et al. (2020) focused on affective rather than cognitive restoration, it is notable that their study also used a self-report measure. Based on the present experiment, it is reasonable to expect that self-reported measure of restoration – particularly those that frame questions in terms of evaluating the restorative experience – might be best explained in terms of stimulus preference, rather than the depicted environment.

The current findings have potentially important implications for research using nature-based restoration paradigms, as well as for the theoretical understanding of how nature might confer restorative benefits. Given the robust findings across decades of research that nature environments are preferred over urban or manmade environments (e.g., Ibarra et al., 2017; Kaplan et al., 1972; Kaplan & Kaplan, 1989; Van Den Berg et al., 2007; Van Hedger, Nusbaum; Heald et al., 2019; Wilson, 1984), it is not surprising that aesthetic preference factors into many theories of nature-based restoration, including Stress Reduction Theory (e.g., Ulrich et al., 1991) and Biophilia (Kellert & Wilson, 1993). The present results suggest that aesthetic preference may influence both affective and cognitive aspects of restoration, at least in cases where responses are given as self-report and questions are focused on the restorative experience. Additionally, the fact that both the performance-based measure of cognition and the self-reported mental fatigue measure showed significant effects of environment even when controlling for sound liking supports ART, which posits that attentional restoration is not inherently tied to preference or affect.

3.4. Limitations

There are several limitations that need to be considered when interpreting the findings of the present experiment. First, as alluded to in the previous paragraph, data collection for this study was conducted online, and as such there is inherently greater variability in factors such as hardware (e.g., computer and headphone specifications) and testing environment compared to an in-person setting. To address this limitation, participants for this study were recruited through a vetted platform (CloudResearch) that has demonstrated higher data quality than other online sources (Hauser et al., 2023). Additionally, this study involved several attention checks and assessments of task compliance throughout the study to remove low-effort participants. Second, the type of sound degradation applied in the current study was not intended to impair sounds recognition; however, this limits the generalizability of the findings in contexts where sound degradation results in sounds being unrecognizable. It is also possible that other forms of degradation – even those that preserve sound identification to some degree (e.g., time-domain scrambling) – might influence restoration differently, or that with even more extreme degradation the benefits of nature may be removed. Future work could examine where those breakpoints may occur and if they align with lack of sound identification (i.e., maybe nature sounds would not yield cognitive benefits if they cannot be identified). Other future work could also greatly alter the perceptual qualities of nature but tell participants that the original source was from nature to see if that would yield benefits, and if so, for which measures of restoration. Such an approach would provide important information about how important source versus perceptual information is on cognitive restoration, and the present study demonstrates that perceptual degradation is a promising approach for assessing this question. Third, the present experiment was not adequately powered to detect small effects for interactions of sound quality and environment type (see Supplemental Material), which is particularly relevant in the present context given the relatively subtle manipulation of sound degradation. Finally, the intervention used in this study provided auditory stimuli only and it is not guaranteed that the present results would generalize to visual representations, or more naturalistic multimodal depictions of nature and urban environments (e.g., Brancato et al., 2022). Future work is needed to consider the impact of perceptual degradation in other modalities on restoration effects, and there is certainly potential for independent effects of modality-specific degradation in multimodal contexts.

Despite the limitations, the present study offers an important contribution to the literature, namely that perceptual degradation of nature sounds, which reduces how much those sounds are liked but does not impair how well these sounds are categorized, does not appear to attenuate measures of restoration following a sound intervention. Although no measure showed attenuated restorative effects as a function of degradation, the present study found that measures such as the PRS and MBS are best explained by aesthetic preference of the restorative experience, whereas performance-based and self-reported cognitive measures are not explained by preference. This means that these effects have more to do with the links between the properties of nature stimuli and attention and working memory, rather than relationships to affect or preference.

4. Conclusion

The present experiment assessed whether listening to perceptually degraded nature sounds – which were hypothesized to be less liked –

could nevertheless elicit cognitive restoration, as measured via both cognitive performance and self-report. As hypothesized, degraded nature sounds were less liked compared to unaltered sounds; however, we did not find any evidence that degraded nature sounds attenuated measures of cognitive restoration. Critically, we found that the relationship between sound aesthetics and subjective restoration depended strongly on the measure used. In particular, the PRS showed a strong, positive association with sound liking, whereas objective cognitive performance and self-reported mental fatigue did not associate with sound liking. Taken together, these findings suggest that there are important differences in the relative influence of stimulus preference and affect on measures of restoration. For measures that directly and objectively measure cognitive performance and focus on participants' current mental fatigue, stimulus preference and affect do not significantly relate to observed restorative benefits of nature. In contrast, for measures that assess the perceived restorativeness of the intervention, which require participants to reflect on their experiences with the stimuli used in the intervention, stimulus preference and affect appear to entirely drive responses. This is consistent with other theorizing and other empirical results that objective changes in cognitive performance due to interactions with nature, are not driven by environmental preference (Berman et al., 2008, 2012; Gonzalez-Espinar et al., 2023; Kaplan & Berman, 2010; Stenfors et al., 2019) but are instead related to how these stimuli are processed and how cognitively taxing that processing may be. It is possible that if the sounds were even more disliked or even more degraded that these objective cognitive benefits would be eliminated, but at the present levels, those effects persisted, suggesting, again, that the cognitive benefits from interacting with nature are not simply due to environmental preference.

CRediT authorship contribution statement

Huda Ahmed: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kathryne Van Hedger:** Writing – review & editing, Writing – original draft, Supervision. **Marc G. Berman:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Stephen C. Van Hedger:** Writing – original draft, Supervision, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Open science statement

All data and materials associated with this manuscript are available on Open Science Framework (https://osf.io/5urta/). The study was not preregistered. The manuscript reports all measures that were collected as a part of this study, as well as all exclusion criteria for the study. Sample size was determined by consideration of prior web-based research using similar paradigms and availability of funds to the corresponding author.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvp.2025.102608.

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