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Assessing the objective and subjective impacts of nature for reducing cognitive fatigue

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ABSTRACT
Exposure to nature can help recover cognitive fatigue by enhancing working memory, attention control, and cognitive flexibility. However, these effects may be impacted by multiple confounding variables, including engagement level and baseline differences. Additionally, it remains unclear whether changes in objective restoration measures may extend to perceived fatigue as well. This study examined whether nature could reduce cognitive fatigue while controlling for initial fatigue levels and using a set of objective and subjective outcomes. Participants performed working memory and attention control tasks at pretest and posttest. Between these tests, they went through a cognitive fatigue task, followed by exposure to either nature or urban pictures on a computer. Measures of subjective fatigue, performance, and prefrontal cerebral activity were collected. While performance and neurophysiological measures were similar across conditions, nature exposure improved subjective fatigue reports, unlike urban exposure. This finding highlights how subjective and objective experiences of attention restoration may differ.

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Attention restoration; fatigue; attention control; working memory; fNIRS

Introduction

Attention is a resource involved in various high-level processes, including executive functioning and self-regulation (Kaplan & Berman, 2010). However, attentional resources are limited and susceptible to depletion when sustained cognitive effort is required. This phenomenon—known as cognitive fatigue—is a frequent challenge experienced in many real-life situations. Operators from high-stake domains such as aviation (Dehais et al., 2014), command and control (Hodgetts et al., 2017), and defence (Cooke et al., 2004), as well as workers in more clerical jobs (Jett & George, 2003; Mak & Lui, 2012), can be vulnerable to attention depletion due to the cognitive demands incurred by their work. The resulting cognitive fatigue may increase likelihood of errors and, in high-risk domains, pose threats to human safety and infrastructure.

Exposure to nature stimuli can represent an effective intervention to help recover depleted attention resources. Such a restorative effect has been demonstrated both in the lab and in real-life settings (e.g. Atchley et al., 2012; Berman et al., 2008; Berto, 2005; Duvall, 2011). According to the attention restoration theory (ART; Kaplan, 1995), four properties particularly present in nature could explain how natural environments can help recover attention. First, the environment must provide a sense of *being away*—a psychological or physical distance from distractions, stressors, or demanding situations of daily life. Second, it must offer *compatibility*, meaning the setting aligns with an individual's intentions, purposes and inclinations. Third, stimuli in the environment should evoke *fascination*, drawing attention automatically/effortlessly through inherently interesting or engaging features. Fourth, it should possess *extent*—a richness and coherence that sustain attention over time. Recent findings suggest that nature's restorative effects on attention may not arise solely from effortless attentional capture, but rather from its capacity to foster a calibrated interplay between involuntary attention and active engagement (Marois et al., 2021; Szolosi et al., 2014).

The restorative effects of nature on attention also have practical implications, particularly as a potential

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means to replenish attentional resources and mitigate the negative effects of cognitive fatigue (Marois, 2020). Some studies have already documented the benefits of integrating natural elements or interventions into academic and professional settings (e.g. Craig et al., 2021; Gbetoglo, 2021). The current study aims to further explore whether nature, compared to urban environments, can provide benefits to cognitive functioning at both objective and subjective levels following the exposure to either nature or urban pictures, focusing on cognitive capacities and cognitive fatigue[1] as an intervention and outcome. Despite growing evidence of the benefits of nature on cognition, findings remain inconsistent, especially regarding its effects on cognitive fatigue and functions like working memory and sustained attention. The next section reviews key empirical findings in this area.

Nature's effects on attention

A large body of research has investigated how nature exposure can positively influence a series of psychological and health-related variables (see, e.g. Jimenez et al., 2021, for a review). Several studies also reported cognitive performance improvements associated with exposure to natural settings—whether real or virtual (e.g. photographs or videos of nature)—including improvements in problem solving (Atchley et al., 2012), attentional control (Berman et al., 2008; Charbonneau et al., 2024; Chung et al., 2018), memory (Berman et al., 2012; Shin et al., 2011; Szolosi et al., 2014), and sustained attention (Berto, 2005; Berto et al., 2010; Pasanen et al., 2018). Yet, recent work has yielded mixed results regarding possible improvements in cognitive performance following exposure to nature. For instance, both Bratman et al. (2015) and Scott et al. (2023) examined changes in working memory capacity following walks in a nature or in an urban environment using the operation span task. While Bratman et al. found evidence of post-task improvements on working memory capacity for the nature group, Scott et al. failed to observe such effects for both conditions.

Recent reviews and meta-analyses provide a more nuanced picture of the actual effects of nature exposure on cognitive functioning, and they emphasise how context and specific types of measures may play a moderating role. Bowler et al. (2010) conducted a meta-analysis on 25 studies to evaluate positive outcomes ensuing from nature exposure. They reported clear evidence that nature could improve levels of health and well-being (e.g. on energy level, anxiety and mood), but raised questions as to the benefits on attention functions. Across the eight included studies, gains over attentional outcomes (i.e. on the proofreading task, digit span backward, combined digit span backward/forward, Necker cube pattern control, and self-reported ADHD symptoms) disappeared after controlling for pretest effect sizes.

Stevenson et al. (2018) conducted a meta-analysis that evaluated the different attentional processes that can be restored by nature and the tasks that showed potential for such restoration while considering aspects related to pre-intervention fatigue, baseline individual differences, and type of exposure. They revealed that attentional control (via the Necker Cube Pattern Control, Attention Network Task [ANT], Multi-Source Interference Task, and Stroop Task), working memory (using the digit span backward task, digit span forward task, forward spatial span, and reading span task), and cognitive flexibility (measured with the Trail Making Task B and Stroop Task) were the most responsive to nature exposure. They further highlighted the importance of active engagement with the environment (e.g. exposure to real environments, potentially driven by exposure duration/level of engagement; see, e.g. Browning et al., 2020; Duvall, 2011; Lin et al., 2014; Pasanen et al., 2018; Szolosi et al., 2014) as a key factor enhancing restoration effects, especially for attentional control and cognitive flexibility. Stevenson et al. also outlined that controlling for baseline differences, when comparing nature and urban exposure conditions, reduced restoration effects over attentional control and working memory, but only when a period of cognitive fatigue preceded the intervention. Therefore, while attentional control, working memory and cognitive flexibility appear to benefit from nature exposure, some confounding variables including baseline cognitive states and exposure conditions must be considered.

Research gaps on attention restoration and cognitive fatigue

According to ART, cognitive benefits ensue from nature exposure because of the opportunities that nature

[1]Cognitive fatigue, from a theoretical perspective, may possess important overlap with other conceptually similar phenomena such as self-regulation, ego-depletion, and even boredom, sleepiness and hypovigilance. As raised by Goodman et al. (2025), this phenomenon remains elusive due to a variety of inter-related constructs and manifestations (see also Hassan et al., 2024). Generally, these different concepts can be distinguished (MacMahon et al., 2023; Marois et al., 2023), and some authors offer perspectives on whether and how they reflect common or separate phenomena (Brown et al., 2019; Forestier & Chalabaev, 2020; Habay et al., 2023; Pickering, 2023). From an ART perspective, cognitive fatigue is rarely defined clearly (Joye & Dewitte, 2018). For the purpose of this study, we view cognitive fatigue as any transient behavioural manifestation of attention performance depletion (including slower response, reduced accuracy and disengagement) that might ensue from sustained (active or passive) cognitive activity over time.

provides to replenish attentional resources. These benefits on attention would in fact be driven by the low demands in executive-based attention that nature imposes upon the system, which in turn allows attention to rest and ultimately recover (Kaplan, 1995, 2001; Pearson & Craig, 2014). From this perspective, replenished resources should improve feelings—and behavioural evidence of—cognitive fatigue. However, very few studies have focused specifically on measuring cognitive fatigue or other related outcomes (e.g. vigilance, including measures of reaction time, alerting or self-perceived fatigue evaluations; Berman et al., 2008; Berto, 2005; Imamura et al., 2022; Johnson et al., 2022; Sun et al., 2022). As discussed by Joye and Dewitte (2018), ART possesses many vague theoretical notions and conceptual shortcomings. Among their criticisms, they outlined that cognitive fatigue should be better considered in future studies and suggested a standardised method for inducing fatigue prior to environmental exposure. The authors also proposed that measures of fatigue should be integrated into experimental designs.

Besides the role of cognitive fatigue—both as an outcome and as a pre-exposure state—there is also a need to clarify the distinctions between objective and subjective measures. Although studies often combine objective indicators of emotional and attentional/cognitive functioning with subjective (self-report) assessments (e.g. Joye et al., 2013), direct comparisons between these two types of measures in the context of cognitive fatigue remain scarce. Johnson et al. (2022) suggested that subjective reports of restoration as well as markers of cognitive alertness could be improved by exposure to nature environments. Reports of restored state were higher for participants exposed to nature compared with urban exposure. Markers of cognitive alertness (i.e. performance on the sustained attention to response task and pupillary dilation), however, did not improve. Nonetheless, the study lacked subjective measures of fatigue, which may have been more sensitive and appropriate for assessing the subjective impact of nature. Studies that did incorporate subjective markers of fatigue have similarly failed to observe any advantages of nature exposure over urban settings (e.g. Imamura et al., 2022; Johnson et al., 2022; Sun et al., 2022).

These inconsistencies highlight a broader issue: the need for more integrative and methodologically diverse approaches to evaluating the cognitive impact of nature exposure. This includes not only typical behavioural pre- vs. posttest evaluations, but also other sets of methods including subjective reporting and neurophysiological measures that provide direct or indirect insights into cognitive functioning. Different neurophysiological measures such as electroencephalography (EEG), functional near infrared spectroscopy (fNIRS), electrocardiography and oculometry (e.g. Chen et al., 2016; Hopman et al., 2020; Imamura et al., 2022; Marois et al., 2021; Olszewska-Guizzo et al., 2018; Scott et al., 2020; see Norwood et al., 2019, for a review) have been employed to assess attentional processes. Similarly, self-report methods (e.g. Berry et al., 2015; Jiang et al., 2016; Johnson et al., 2022; Li & Sullivan, 2015) have sometimes been used to assess different cognitive states. Yet, to our knowledge, no study focused on a comprehensive set of cognitive functioning measures combining such a variety of methods while also trying to control for differences in pre-exposure baseline levels. Besides, methods favoured for nature exposure (e.g. types of exposure, exposure duration, task during exposure) differ considerably across studies, as highlighted in previous reviews (Bratman et al., 2012; Browning et al., 2020).

Per Jenkins' (1979) tetrahedral model for organising scientific research for cognitive psychology, four components should be focused on by researchers when contributing to the growing body of research on a given topic: (a) materials; (b) outcomes; (c) participants; and (d) context. Therefore, a more holistic approach for studying the impact of nature exposure on cognitive functioning—more specifically on cognitive fatigue—should aim at considering these components (cf. Watson et al., 2025).

Study goal

The present study represents a first step towards a more holistic assessment of the relationship between cognitive fatigue and nature exposure. More precisely, the goal is to examine the impact of a nature intervention on cognitive fatigue following a period of cognitive resource depletion by collecting a combination of objective and subjective outcomes. Such depletion serves to control for any difference in baseline, ensuring that all participants are facing cognitive fatigue before being exposed to the intervention (cf. Joye & Dewitte, 2018; Stevenson et al., 2018). In coherence with Jenkins (1979) we focused specifically on addressing three of the four aspects of the tetrahedral model, namely control over the material (i.e. type of stimulus used for the intervention), outcomes (i.e. through a mix of methods to evaluate nature's effects on cognition), and context (i.e. by ensuring similar pre-exposure states via a cognitive fatigue period).

Participants performed a pretest measure of their working memory (AOSPAN task) and attention control abilities (ANT) before carrying out a repetitive task to induce cognitive fatigue. Such cognitive abilities were specifically chosen given Stevenson et al.'s (2018) conclusions that nature could mostly benefit attentional control, working memory and cognitive flexibility. Following the fatigue stage (Jenkins' context component), participants were exposed to either nature or urban pictures that were carefully chosen to match different visual properties (Jenkins' control over material component). After the intervention, they performed a posttest measure using the same set of tests used at pretest. Across all these steps, they were asked approximately every 10 min to report their subjective fatigue level using the Karolinska sleepiness scale (KSS; Åkerstedt & Gillberg, 1990). Throughout the experiment, participants' cerebral activity was also measured using fNIRS to provide a complementary tool that allowed us to explore evidence of cognitive engagement as a proxy for cognitive fatigue (cf. Imamura et al., 2022; Jenkin's outcomes component). fNIRS is a non-invasive brain-imaging technique that relies on cerebral oxygenation and blood flow. It allows for measuring changes in tissue hemodynamics (blood perfusion) and oxygenation on the human head (Karmakar et al., 2023). The total hemoglobin (tHb) signal was measured, and the following features were extracted: signal mean value, amplitude, slope, kurtosis, skewness, polarity and standard deviation (*SD*). These features have previously been associated with cognitive fatigue and engagement (cf. Aghajani et al., 2017; Holper et al., 2012; Naseer & Hong, 2015; Varandas et al., 2022). Specifically, past studies have linked higher activity measures (i.e. mean, slope, polarity) to lower engagement and drowsiness (e.g. Khan & Hong, 2015; Reddy et al., 2022) whereas higher variability measures (i.e. *SD*, kurtosis, skewness, amplitude) were typically reported in low-performance situations such as those characterised by fatigue (e.g. Angsuwatanakul et al., 2015; Garrett et al., 2013).

We hypothesised that following the nature intervention, participants exposed to nature, as opposed to those exposed to urban settings, would: H1) experience improvements on the AOSPAN scores; H2) present reduced reaction times on the ANT; H3) demonstrate neurophysiological evidence of reduced fatigue with the fNIRS, that is lower tHb activity measures (mean, slope, polarity) and variability measures (*SD*, kurtosis, skewness, amplitude); and H4) report lower subjective fatigue on the KSS.

Method

Participants

Sixty-one participants (17 men, 44 women, $M_{age} = 25.67$, $SD_{age} = 7.32$) took part in the study. Sample size analysis performed in GPower was related to Johnson et al.'s (2022) effect size measure of self-reported variations in perceived restoration across nature and urban conditions using a $\eta_p^2 = 0.20$, with an α level of .05 and statistical power of .95 for two-tailed between-group differences ($n = 54$, with the addition of 6 participants to compensate for data loss of ~10% of the sample, and of another to compensate for one participant withdrawal). All participants reported normal or corrected-to-normal vision and audition. The study was approved by the Université Laval Research Ethics Committee (2022-352 / 22-09-2022).

Apparatus and material

Participants performed the experiment in a dimly lit room. A PC computer running E-Prime 3.0 (Psychology Software Tools) was used for presenting the instructions, controlling the tasks and measures, and presenting the intervention.

Pretest and posttest assessments

At the beginning of the experiment (pretest) and at the end (posttest), measures of working memory capacity and attention control were collected.

Working memory task. Working memory capacity was assessed using the Automated Operation Span task (AOSPAN; Unsworth et al., 2005). Many studies interested in the nature effects on working memory focused on other tasks such as the backward digit span task (e.g. Stenfors et al., 2019; see also Stevenson et al., 2018). The AOSPAN however provides a stronger test for assessing the impact of nature on working memory given its high internal consistency and strong test-retest reliability (cf. Bratman et al., 2015). The AOSPAN engages more complex working memory ability components, including inhibitory control, which are not required in simpler span tasks (Kane et al., 2007). This makes it particularly valuable for testing whether the cognitive benefits of exposure to nature extend beyond basic storage to more demanding working memory tasks, a question that remains open given the mixed findings reported by Bratman et al. (2015) and Scott et al. (2023).

As shown in Figure 1A, participants were shown series of letters of various lengths with each letter being interleaved with simple mathematical operations (e.g. $[2 + 4] - 2 = 4$). Each letter was presented for 1,000 ms. For each mathematical operation, participants were asked to indicate whether the outcome depicted was true or false within a maximum of 3,000 ms. Once all the letters of the series were presented, participants were asked to

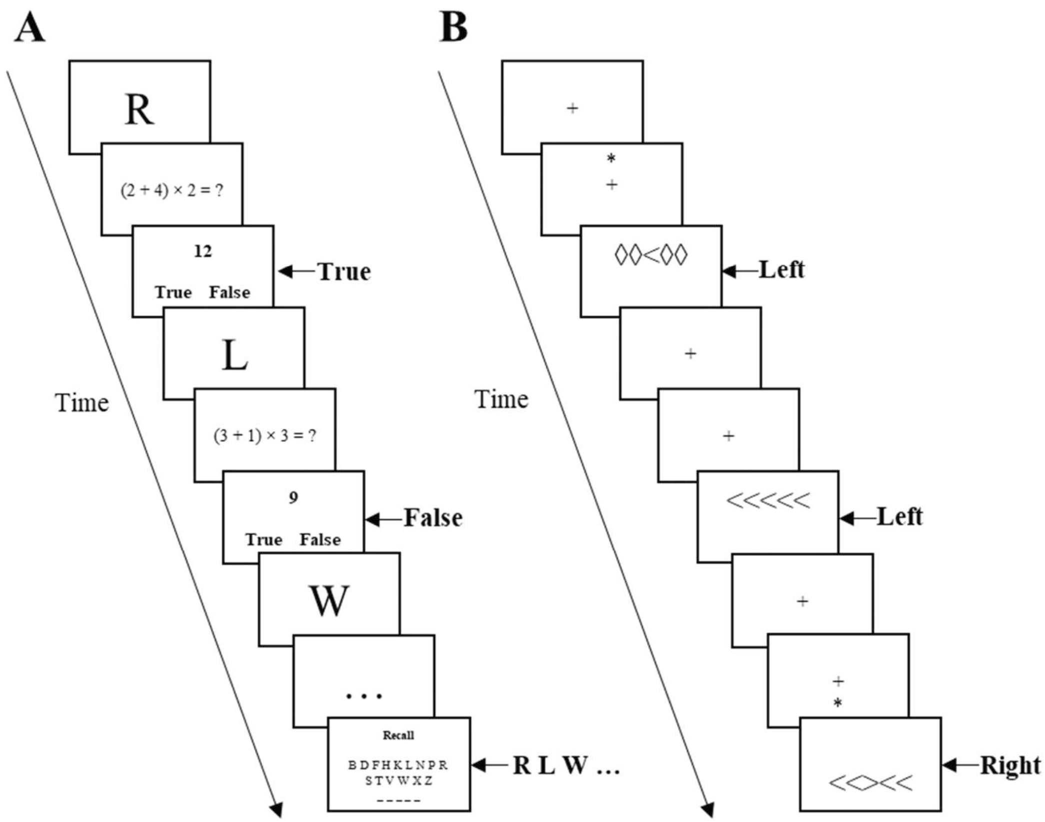

Figure 1. Depiction of the AOSPAN task (A) and the ANT (B). Both tasks were performed at pretest and posttesst.

recall them in their presentation order using the computer mouse. Two performance measures were produced: (a) the AOSPAN absolute score, representing the sum of all perfectly recalled sets for the 15 trials; (b) and the AOSPAN partial score, representing the sum of all items that were correctly recalled.

Attention control task. To measure attention control capacities, the Attention Network Test (ANT; Fan et al., 2002; Wang et al., 2014) was used. This task was specifically selected due to its demonstrated sensitivity in detecting attention control restoration (cf. Stevenson et al., 2018) and for its capacity to assess additional cognitive processes including processing speed and visual attention.

As depicted in Figure 1B, on each trial ($n = 120$), following the presentation of a 1,000-ms fixation cross, a cue could be presented either at the centre, on the upper part or the lower part of the screen for 1,000 ms. After a 1,000-ms delay, the target (an arrow pointing either left or right) appeared where the cue was presented or appeared at random either above or below the fixation cross if no cue was presented. The target was surrounded by flankers (either neutral or pointing to a congruent or incongruent direction with respect to the target, i.e. left or right). Participants were asked to indicate the direction of the target using the keyboard within 2,000 ms, depending on its direction.

Following Fan et al.'s (2002) method, and per previous studies on attention restoration (cf. Berman et al., 2008), three main variables were generated: (a) the alerting effect, that is, the difference in mean response time (RT) between centre-cue trials and no-cue trials, averaged over all target types (i.e. congruent and incongruent targets); (b) the orienting effect, that is, the difference in mean RT between spatial-cue trials and centre-cue trials, averaged over all target types (i.e. congruent and incongruent targets); and (c) the conflict effect, which is the difference in mean RT between congruent and incongruent targets, averaged over all cue types (i.e. no cue, central cue, spatial cue). A recent study conducted by Wang et al. (2014) however raised many problems with Fan et al.'s method for computing ANT scores. As such, we also relied on Wang et al.'s (2014, Equations 1–7) method using new ways of measuring these effects and controlling for their interaction. These variables go as follows: (a) the alerting effect; (b) the orienting effect; (c) the conflicting effect; (d) the alerting effect while controlling for the conflict effect (alerting with conflicting); (e) the orienting effect while controlling for the conflict effect (orienting with conflicting); (f) the conflicting effect while controlling for the alerting effect (conflicting with alerting); and (g) the conflicting effect while controlling for the orienting effect (conflicting with orienting). A higher (positive) score for each effect suggests more efficient processing. Note that all analyses focused only on the correctly answered trials and that all RTs < 200 ms and > 1,200 ms were removed, as they were considered outliers by Wang et al. (2014).

Cognitive fatigue task

The AX-Continuous Performance task (AX-CPT) was used to induce cognitive fatigue (Servan-Schreiber et al., 1996). The AX-CPT can be performed for long periods of time, and although it can be related to cognitive control (Cooper et al., 2017), it is deemed to only require low levels of cognitive activity and processing (O'Keefe et al., 2020). Such a task is thus often used to induce cognitive fatigue while allowing to prevent any confounding effect arising from an increase in cognitive load (e.g. Goodman et al., 2025; Hassan et al., 2024). Therefore, we chose to use this task as a cognitive fatigue intervention.

As depicted in Figure 2, participants were shown at the centre of the screen a 1,000-ms fixation cross, followed by a letter (the cue) for 200 ms. Then, another fixation cross was presented for 1,000 ms, followed by another letter (the potential target). Participants had to press a specific key only when the cue was an *A*, followed by the target letter (an *X*). In other cases (e.g. *AY* cues or *YY* cues, where *Y* can be any letter), they had to press another key. All 324 trials (comprised of the two fixation crosses, the cue and the letter), split into three blocks, were followed by an interstimulus interval of either 1,500, 2,000 or 2,500 ms, randomly generated. Participants took on average 28.99 min ($SD = 0.94$) to perform the AX-CPT. Accuracy as well as mean RT on the three types of trials (*AX*, *AY*, and *YY*) were analysed for the three blocks of trials as a manipulation check for the cognitive fatigue induced by the task.

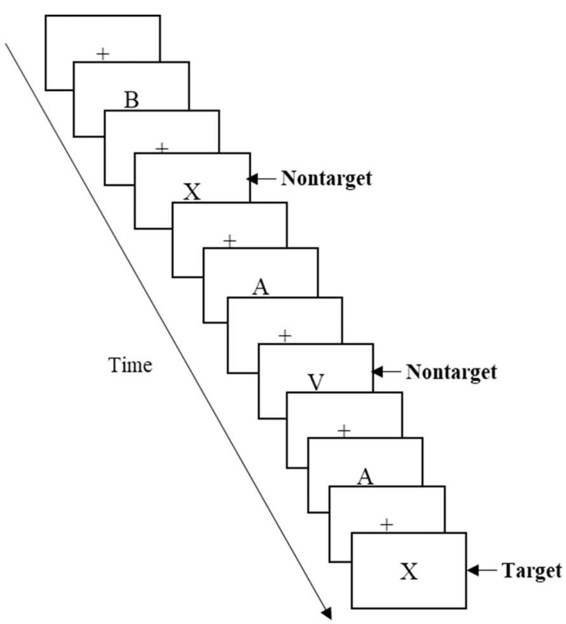

Figure 2. Depiction of the AX-CPT task. The task was used as a cognitive fatigue task prior to the intervention.

Restoration intervention

After the fatigue task, participants were exposed to the restoration intervention (see Figure 3). Half of the participants were assigned to the Nature condition whereas the other half was assigned to the Urban condition. They were presented with a series of 30 pictures, each presented for 20 s, split into two blocks of 15 pictures (see Supplementary Materials for the pictures). The 20-s presentation length was chosen as it allowed participants to take enough time to picture themselves in the settings presented to answer the Perceived Restorativeness Scale (PRS; see below). In addition, Szolosi et al. (2014) found that longer presentation durations were associated with greater cognitive benefits. Stevenson et al. (2018) similarly outlined that longer durations and real nature exposures were both linked to stronger effects, although the two were often confounded in existing studies.

In the Nature condition, nature landscapes were presented, whereas pictures of cities were presented in the Urban condition (pictures selected from royalty-free websites https://isorepublic.com/ and https://unsplash.com/fr). Pictures across both conditions were controlled for the following properties: the season (Summer, Fall or Winter), the type of view (straight, from above or from below), the orientation (portrait vs. landscape) and the type of visual modifications made (visual effects or not). This was to ensure that visual features would not impact their restorative properties differently across groups, as previously shown (Berman et al., 2014; Celikors & Wells, 2022; Kardan et al., 2015; Schertz et al., 2020; Schertz & Berman, 2019; but see Menzel & Reese, 2022). Appendix A provides a description of the full procedure to select pictures as well as the analyses of the low-level visual properties, discussing characteristics of both set of pictures and impacts of said properties.

Following the presentation of each image, participants completed the Fascination subscale of the Shortened Perceived Restorativeness Scale (Hartig et al., 1996). It contained the following statements, freely translated in French: "*This place has qualities that fascinate me*", "*I would like to spend more time looking at the surroundings here*", and "*My attention is drawn to many interesting things here*". Participants had to choose on a Likert scale to what extent they agreed with the statement, from "Not at all" (1) to "Totally" (6).

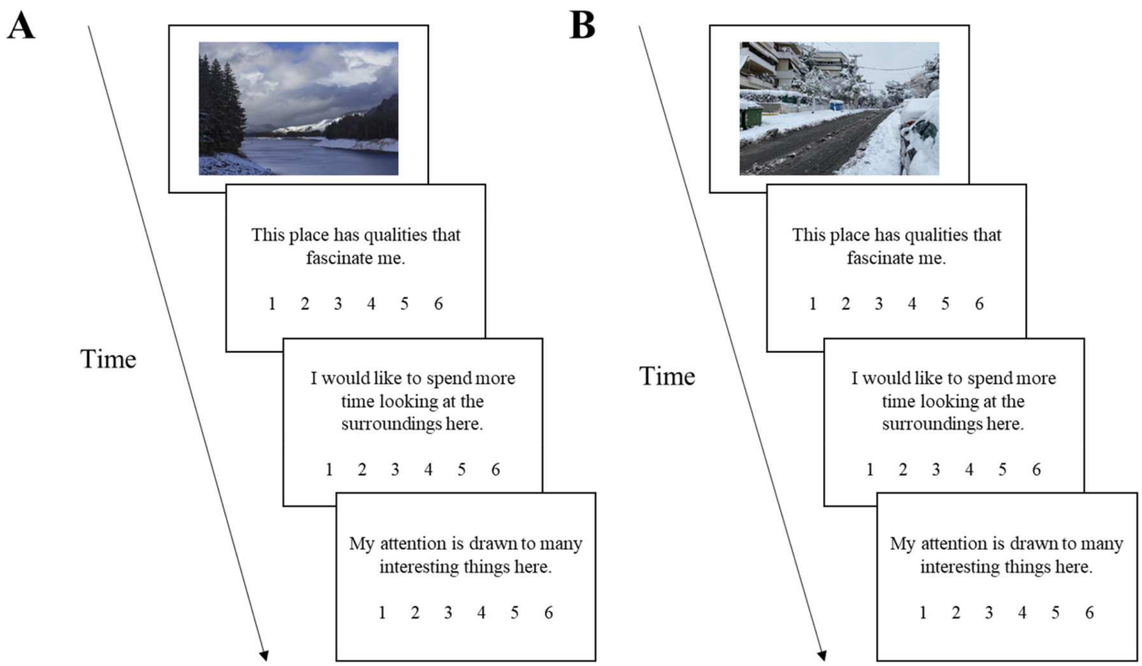

Figure 3. Depiction of the attention restoration intervention with the PRS questions (A: Nature intervention; B: Urban intervention).

Participants could take the time they wanted to answer each question, and the question changed automatically after participants answered them. Typically, higher scores on the PRS are linked with restorative nature while lower scores are associated with low restorative or nonrestorative environments (Korpela, 2013).

Fatigue measures

Throughout the experiment, participants were measured on their fatigue level using objective and subjective methods.

Objective measures of fatigue. An fNIRS device was used to collect neurophysiological measures of attention engagement. fNIRS uses near infrared light of 650–900 nm to determine the increase and decrease of cerebral oxygenation (Kamran et al., 2015). It is based on the principle that human tissues are transparent to light in a specific spectral window (650-1000 nm; Ferrari & Quaresima, 2012). The device used was the Octamon + (Artinis Medical Systems), which consists of eight light-emitting diodes (Tx) at wavelengths of 760 and 850 nm, along with two receptors (Rx) with proprietary ambient light protection. The sampling rate was set to 10 Hz. The device enables collection of raw data on oxyhemoglobin (O_2Hb) and deoxyhemoglobin (HHb). The optode placement used the standard template for dorsolateral, ventrolateral, orbitofrontal and ventromedial measurement (see Figure 4), with the left emitter (Rx1) placed on the prefrontal cortex region over Fp1 in the international EEG 10–20 system, and the right emitter (Rx2) placed over Fp2.

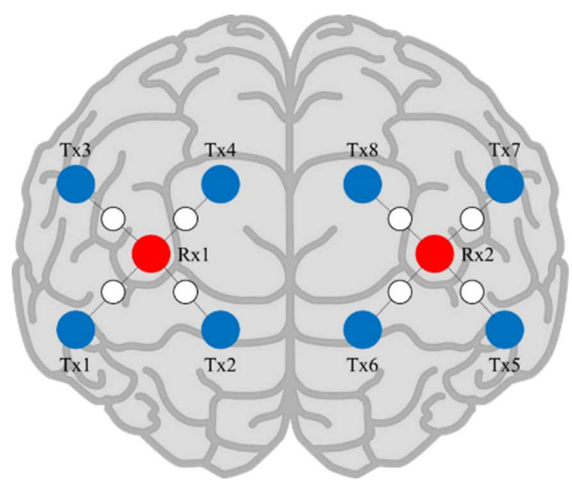

Figure 4. Optode template placement for the transmitters (Tx) and receivers (Rx).

Analysis of the fNIRS signal went as follows.[2] Data from the fNIRS device was segmented into different time windows representative of all the main steps of the experiments, aligned with the 10 KSS measurement points (i.e. between Tl and T2, T2 and T3, and so forth). Signal from the fNIRS was time-locked to the KSS questionnaires using the time clock of the computer collected on each key period. In line with previous studies

[2]See the following link for the script used for the analysis: https://github.com/LEILAHUL/Objective-and-Subjective-Effects-of-Nature-on-Fatigue_fNIRS-Analysis

focusing on cognitive fatigue (see Dehais et al., 2018; Varandas et al., 2022), we then conducted preprocessing of the signal following the recommendations of Bizzego et al. (2020). The raw signal collected by the optodes was transformed using a modified Beer–Lambert law by the Oxysoft software (Artinis in-house data collection software), allowing to obtain changes in hemoglobin concentrations for O_2Hb, HHb and total hemoglobin (tHb). A visual quality check was then conducted across all participants for O_2Hb, HHb and tHb to remove channels that were characterised by too much noise, artifacts, or missing data (Ahn et al., 2016). Artifact removal was then performed using a high-variance detection algorithm, followed by a spline interpolation (Dehais et al., 2018; Gao et al., 2022; Scholkmann et al., 2010). This algorithm identifies data points exhibiting abrupt changes in amplitude or standard deviation, exceeding predefined thresholds (i.e. 5 units for both properties). These points were then eliminated from the signal and missing values were reconstructed through spline interpolation. Additionally, transitions between the unmodified signal segments and the interpolated regions were smoothed to ensure continuity in the signal (Scholkmann et al., 2010). Finally, noise from other sources of variation in the signal was removed using a zero-phase Butterworth band-pass filter with a low-pass cutoff frequency of 0.01 Hz (order 3) and a high-pass cut-off frequency of 0.5 Hz (order 5; Dehais et al., 2018; Pinti et al., 2019).

Following preprocessing, the tHb signal was chosen for the analysis as it allows covering both variations of O_2Hb and HHb and because it is deemed more strongly correlated to actual exchanges in oxygenated hemoglobin as measured by blood-oxygen-level-dependent (BOLD) functional magnetic resonance imaging (fMRI) signal (Moriguchi et al., 2017). A baseline was extracted from this signal following the completion of the first KSS (prior to the pretest) up to the next 25 s after (Parchment et al., 2016). Using this baseline, we corrected the tHb signal for each of the eight channels of the fNIRS device and multiple features were extracted. To extract these features, the fNIRS signal was segmented into time-windows time-locked on each KSS question. Then, five 5-s segments with no overlap were generated, locked on each KSS question. Five-second time-windows were selected given previous demonstration that this duration effectively captures alertness-related hemodynamic responses (Khan & Hong, 2015). Features were extracted from the signal within each of these segments and averaged across each of the time-windows, following the approach described by Varandas et al. (2022). The following features were extracted: signal mean value, amplitude, slope, kurtosis, skewness, polarity (defined as the ratio of the segment's maximum to minimum) and *SD*.

Subjective measures of fatigue. Participants were asked to answer the Karolinska Sleepiness Scale (KSS), a 10-point sleepiness subjective scale (Åkerstedt & Gillberg, 1990). Scoring goes from (1) "*Extremely alert*" to (10) "*Extremely sleepy, can't keep awake*", freely translated in French. Higher KSS values indicate higher fatigue levels. This scale was chosen given its frequent use in the literature on cognitive fatigue and other related constructs (cf. Marois et al., 2023; Shahid et al., 2010; see also multiple studies from the special topic on cognitive fatigue from Peigneux & Lorist, 2017) as well as its ability to assess "the changes in response to environmental factors" (Shahid et al., 2012, p. 209). The KSS was completed at the following moments: (T1) prior to the pretest; (T2) after the first task of the pretest; (T3) following the second task of the pretest; (T4) after the first block of the cognitive fatigue task; (T5) after the second block of the cognitive fatigue task; (T6) after the last block of the fatigue task; (T7) after the first block of the intervention; (T8) after the second block of the intervention; (T9) following the first task of the posttest; and (T10) after the second task of the posttest.

Procedure

After having provided informed consent, participants were explained the procedure. A research assistant helped them install the fNIRS system and started collecting the data. Then, participants were asked to go through the pretest tasks (i.e. the ANT and AOSPAN) in a counterbalanced order across participants. After, they performed the cognitive fatigue task (AX-CPT), followed by the intervention, either with nature or urban pictures. After the intervention, participants performed the posttest tasks (counterbalanced order). At the end of the experiment, participants were debriefed, thanked and received monetary compensation for their participation. Figure 5 summarises the flow of the study.

Statistical analyses

All alpha levels were set at .05 and Bonferroni corrections were used for multiple comparisons. When sphericity assumptions were violated, Greenhouse-Geisser corrections were applied and corrected *p*-values were reported. Two participants were removed due to missing data, resulting in 31 participants in the Nature condition and 29 in the Urban condition. Univariate

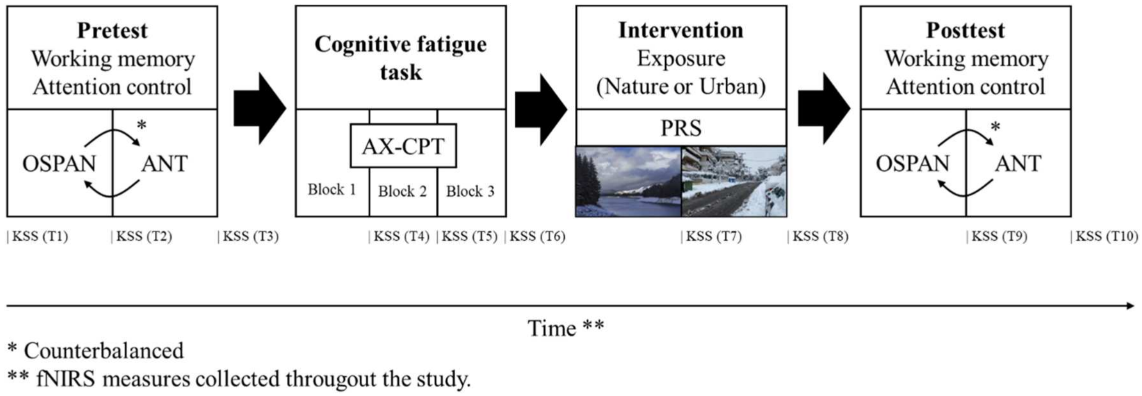

Figure 5. Flow of the study with the different tasks and measures collected. Note that participants were either assigned to the nature or urban condition for the intervention step.

outliers with a distance of ± 4 *SD* from the mean (condition-dependent) were also removed.

Two manipulation checks were conducted. The first one concerned performance on the AX-CPT, which was analysed with a 3 × 3 repeated-measures analysis of variance (ANOVA) with the factor Block (Blocks 1-3) and Type of trial (AX, AY and YY) to see whether performance varied as a function of type of trial and time (i.e. throughout the blocks), suggesting that participants experienced fatigue as the time unfolded. Note that the restoration condition effect (i.e. Nature vs. Urban) was not included given that, up to this step, both Nature and Urban conditions went through the same tasks. The second manipulation check focused on comparing the mean PRS scores collected in both Restorative conditions (Nature vs. Urban) using an independent samples *t*-test to assess whether nature pictures provided more perceived restoration.

Performance measures on the AOSPAN and ANT were also compared between groups and between pretest and posttest using a 2 × 2 mixed ANOVA with the between-subjects factor Restorative condition (Nature vs. Urban) and the within-subject factor Time of measurement (pretest vs. posttest). Reports of fatigue on the KSS were compared between restorative conditions and across times of reporting. More specifically, baseline-corrected KSS scores were used (i.e. corrected from the first KSS level prior to the pretest) using a 2 × 10 mixed ANOVA with the between-subjects factor Restorative condition (Nature vs. Urban) and the within-subject factor Time of measurement (T1 to T10).

Finally, the features extracted from the fNIRS corrected tHb signal were compared across three different moments: at baseline (T1), after the AX-CPT task before the intervention (T6) and after the intervention (T8). Channels Tx1 to Tx4 were averaged together to form a right prefrontal cortex channel while channels Tx5 to Tx8 formed the left prefrontal cortex channel. This decision was based on the poor spatial resolution of the fNIRS signal and the absence of specific hypotheses regarding differences across prefrontal regions. A 2 (Restorative condition: Nature vs. Urban) × 3 (Time of measurement: T1, T6 and T8) × 2 (Channel laterality: Right vs. Left) mixed ANOVA was then performed to test for differences across the seven features extracted from the tHb signal. These features were also related to subjective reports of fatigue using a Spearman correlation analysis, similar to what was reported by Imamura et al. (2022).

Bayesian-equivalent analyses were also performed with JASP (van den Bergh et al., 2020) to ensure that effects and absence thereof were not due to limitations of frequentist tests (see Appendix B). We report the probability of observing different models containing specific factors or combinations of factors given the data under H_0 as well as $BF_{inclusion}$ values, that is, comparison of all models that include given effects (i.e. each factor and their interaction) to models that do not include the effect to observe the current data.

Results

Manipulation check

Fatigue manipulation

Table 1 depicts the mean RT and mean accuracy across types of trials (AX, AY and YY trials) and blocks (Blocks 1 to 3), averaged across conditions, for the AX-CPT. The 3 × 3 repeated-measures ANOVA carried out on the RT data raised a significant main effect of Type of trial, $F(2, 88) = 30.70$, $p < .001$, $\eta^2_p = .41$, but no main effect of Block, $F(2, 88) = 1.39$, $p = .255$, $\eta^2_p = .03$, nor interaction, $F(4, 176) = 0.55$, $p = .616$, $\eta^2_p = .01$. Mean RT was lower for the YY trials as opposed to both AX and

Table 1. Mean RT (in ms) and accuracy (and SD) for AX, AY and YY trials across Blocks 1, 2 and 3, averaged across conditions.

	AX trials		AY trials		YY trials		Mean	
Block	RT (ms)	Accuracy (%)	RT (ms)	Accuracy (%)	RT (ms)	Accuracy (%)	RT (ms)	Accuracy (%)
1	478.34 (116.81)	74.62 (39.83)	492.38 (118.87)	89.30 (25.17)	503.83 (109.10)	78.91 (31.82)	460.64 (93.03)	80.95 (20.28)
2	501.75 (78.90)	71.21 (38.75)	498.59 (76.14)	86.86 (27.66)	508.16 (80.81)	75.93 (32.81)	460.59 (90.00)	78.00 (21.47)
3	422.32 (132.52)	70.83 (38.69)	426.09 (123.43)	84.11 (30.66)	432.93 (124.81)	71.94 (35.32)	472.57 (97.10)	75.63 (24.28)
Mean	487.81 (98.96)	72.22 (38.81)	494.14 (72.17)	86.76 (24.91)	412.51 (171.74)	76.03 (30.91)	462.53 (87.08)	78.19 (20.41)

AY trials ($ps < .001$). AX and AY trials did not differ ($p = .469$). The 3 × 3 repeated-measures ANOVA carried out on accuracy measures revealed a significant effect of Type of trial, $F(2, 188) = 3.80$, $p = 044$, $\eta_p^2 = .06$, as well as a main effect of Block, $F(2, 188) = 4.03$, $p = .028$, $\eta_p^2 = .06$, but no interaction, $F(4, 236) = 0.63$, $p = .543$, $\eta_p^2 = .01$. Multiple comparisons showed that accuracy at Block 3 was marginally lower than that of Block 1 ($p = .056$), suggesting a reduction in performance with time. Accuracy for AY trials was marginally higher than that of AX trials ($p = .059$).

Attention restoration intervention

On average, nature pictures were rated at a level of 3.59 points out of 6 ($SD = 1.08$) while urban pictures reached a mean level of 2.47 ($SD = 0.79$). An independent samples *t*-test confirmed that nature pictures were considered significantly more restorative than urban pictures, $t(57) = 4.53$, $p < .001$, Cohen's $d = 1.18$.

Pretest and posttest performance measures

Working memory

Figure 6 shows the mean scores for the Nature and Urban conditions at pretest and posttest for both absolute and partial scores of the AOSPAN task. The mixed ANOVA performed on the absolute score revealed a main effect of Time of measurement, $F(1, 57) = 37.79$, $p < .001$, $\eta_p^2 = .40$, but no effect of Restorative condition nor any two-way interaction ($Fs < 2.07$, $ps > .155$, $\eta_p^2 < .04$). Significant improvements from pre- to post-test were observed, regardless of Restorative condition. The same pattern of results was observed for the partial score, with a significant main effect of Time of measurement, $F(1, 57) = 28.03$, $p < .001$, $\eta_p^2 = .33$, but with no main effect of Restorative condition, $F(1, 57) = 0.08$, $p = .781$, $\eta_p^2 < .01$, and no interaction, $F(1, 57) = 0.06$, $p = .801$, $\eta_p^2 < .01$.

Attention control

Participants showed similar response accuracy across restorative conditions and times of measurement on the ANT. At pretest, mean accuracy for the Nature condition was 97.82% ($SD = 0.57$) and 96.67% for the Urban condition ($SD = 0.97$). These scores changed to 97.15% ($SD = 0.65$) and 97.08% ($SD = 0.66$) at posttest for the Nature and Urban conditions, respectively.

Figures 7 and 8 respectively depicts the rest of the ANT scores generated using both Fan et al.'s (2002) and Wang et al.'s (2014) methods. Table 2 presents the results of the mixed ANOVA carried out to assess differences across conditions and times of measurement for all the scores generated from the ANT. As shown in Table 2, only two significant effects could be found. The first effect was found for Wang et al.'s orienting effect where the impact of Restorative condition reached significance ($F = 9.11$, $p = .004$). Multiple comparisons indicated that the Urban group had an orienting effect significantly lower than that of the Nature condition (Cohen's $d = 0.62$), regardless of the time of measurement. The second significant effect was found in Wang et al.'s conflict with orienting effect ($F = 6.53$, $p = .013$). The Nature group had a conflict with orienting effect significantly lower than that of the Urban group (Cohen's $d = -0.53$), regardless of the time of measurement. All other effects across ANT scores failed to reach significance. This suggested that the Nature group, compared with the Urban group, showed improved orienting effect but poorer conflicting with orienting effect at both pre- and post-test, that is regardless of the manipulation.

Fatigue measures

Objective measures

Ten more participants were specifically removed from the fNIRS analyses due to device malfunction or to excessive interpolated data (> 50% within analysed time-windows), resulting in 25 participants in the Nature condition and 24 in the Urban condition. Table 3 presents the means for each feature extracted from the corrected tHb signal as a function of Restorative condition, Time of measurement (either baseline [T1], pre-intervention [T6] or post-intervention [T8]) and

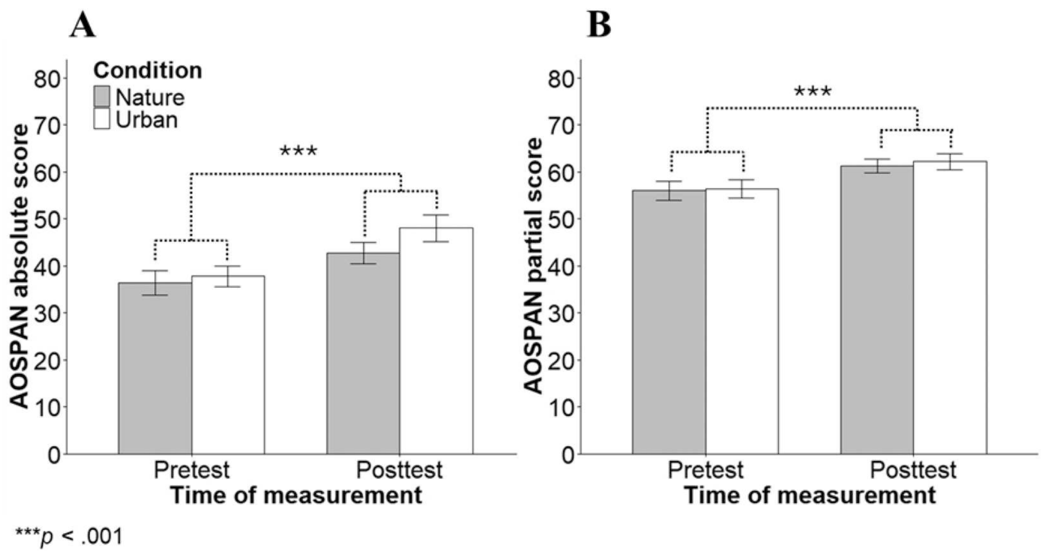

Figure 6. AOSPAN absolute (A) and partial (B) scores as a function of Time of measurement (pretest vs. posttest) and Restorative condition (Nature vs. Urban). Error bars represent the standard errors of the mean.

Channel laterality. For the amplitude, kurtosis, skewness and *SD* features of the signal, significant main effects of Time of measurement emerged (*ps* $< .05$). However, the effect of Time of measurement failed to reach significance for the other features and, across almost all features, the effects of Restorative condition, of Channel laterality and interactions failed to reach significance. An effect of Restorative condition emerged for the polarity feature ($p = .031$).

Multiple comparisons showed that the amplitude of the signal increased significantly from baseline to pre-intervention ($p = .017$), regardless of the condition and channel laterality. The amplitude was also higher at post-intervention compared to baseline ($p = .022$), and similar between pre-intervention and post-intervention ($p > .999$). Kurtosis of the tHb signal was lower at baseline compared with pre-intervention ($p = .010$), but other differences failed to reach significance (*ps* $> .197$). Polarity levels were generally higher in the Nature condition compared to the Urban condition ($p = .031$). A brief look at the data indicates that both conditions differed at pre-intervention (Nature: 1.41; Urban: −2.82) and post-intervention (Nature: 2.39; Urban: −1.77), which may be mostly driven by individual differences across conditions given that, at pre-intervention, both conditions had performed the same set of tasks up to that moment. The difference in skewness of the signal was significant between pre- and post-intervention ($p = .048$), with skewness values being lower for the latter. Skewness did not vary between other times of measurement (*ps* $> .120$). As for the *SD* of the tHb signal, it was significantly higher at pre-intervention compared with baseline ($p = .024$) and with post-intervention ($p = .021$), regardless of the condition and channel laterality. *SD* of the tHb signal was similar between pre- and post-intervention ($p = .644$).

Spearman correlation analyses were performed between all the tHb features extracted and the corrected reports of fatigue on the KSS to assess any relationship between objective and subjective measures at pre- and post-intervention. Given the absence of effect of laterality reported above, we averaged the tHb features across both right and left regions. At pre-intervention, a significant positive correlation was found between the amplitude and the *SD* of the tHb frontal signal with the corrected KSS level (with $r_s = .42$, $p = .005$, and $r_s = .33$, $p = .027$, respectively). All other features failed to significantly correlate to KSS measures (*ps* $> .05$). At post-intervention, no significant correlation was found across all tHb features (*ps* $> .05$).

Subjective measures

Figure 9 presents the corrected KSS scores from T1 (i.e. baseline, score = 0) to T10. A mixed ANOVA with the factors Time of measurement (T1 to T10) and Restorative condition (Nature vs. Urban) raised a significant main effect of Time of measurement, $F(9, 504) = 26.19$, $p < .001$, $\eta_p^2 = .32$, no main effect of Restorative condition, $F(1, 56) = 2.91$, $p = .094$, $\eta_p^2 = .05$, and a significant interaction, $F(9, 504) = 2.33$, $p = .014$, $\eta_p^2 = .04$.

Simple effect tests for the interaction raised significant differences across Times of measurement within the Nature and Urban conditions (*Fs* > 10.07, *ps* $< .001$). Decomposition of the interaction showed that, within the Nature condition, a significant increase in baseline-corrected KSS scores was observed. In fact, T1 and T2,

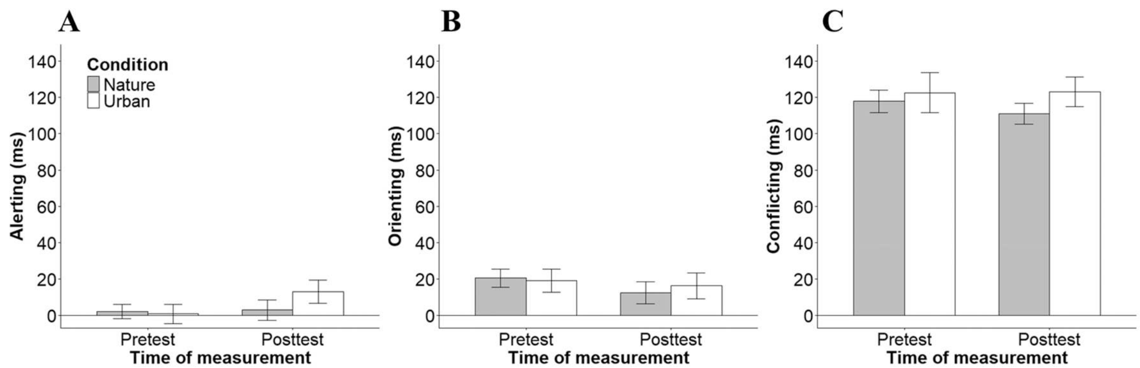

Figure 7. ANT scores (A: Alerting; B: Orienting; and C: Conflicting), in ms, computed from Fan et al.'s (2002) method as a function of Time of measurement (pretest vs. posttest) and Condition (Nature vs. Urban). Error bars represent the standard errors of the mean.

characterised by similar levels ($p > .999$), were significantly lower than the measures collected at T3, T4, T5, T6 and T7 ($ps < .018$). Within this condition, the intervention also induced an incremental reduction in KSS score as evidenced by the statistical difference between T6 (collected before the intervention) and T7, T8 and T9 ($ps < .002$), which were all statistically equivalent ($ps > .999$). The scores collected at T9 were also similar to T1 and T2 ($ps > .090$). Within the Urban condition, a similar pattern of KSS score increase was observed from T1 and T2 up to T6 ($ps < .016$). However, following the intervention, no significant decrease in KSS score was observed as supported by the absence of difference between scores at T6 with those collected at T7, T8, T9 and T10 ($ps > 0.999$). Further simple effects tests showed significant differences across both conditions at T10. The baseline corrected KSS score was indeed significantly lower in the Nature condition than in the Urban condition ($p = .005$). Due to Dunn's procedure (corrected critical α level = .0125), all other comparisons (from T1 to T9) failed to reach significance, although the difference across conditions at T9 was of 1.17 points on the KSS ($p = .026$).

Discussion

As an initial step towards a more holistic evaluation of the potential of nature-based interventions to alleviate cognitive fatigue, this study examined the effects of

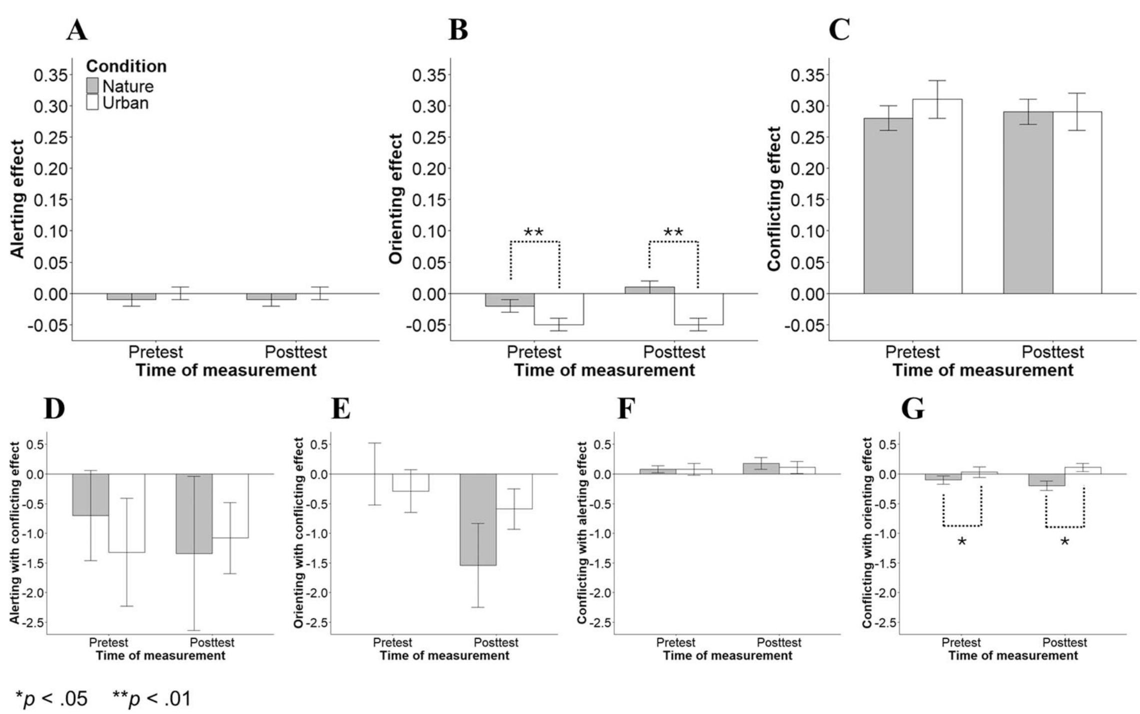

Figure 8. ANT effects (A: Alerting; B: Orienting; C: Conflicting; D: Alerting with conflicting; E: Orienting with conflicting; F: Conflicting with alerting; and G: Conflicting with orienting) computed from Wang et al.'s (2014) method as a function of Time of measurement (pretest vs. posttest) and Condition (Nature vs. Urban). Error bars represent the standard errors of the mean.

Table 2. Results of the mixed ANOVAs performed on the different ANT scores as a function of Time of measurement and Condition generated following Fan et al.'s (2002) and Wang et al.'s (2014) methods.

ANT scores	Time of measurement	Condition	Time of measurement × Condition
Mean accuracy	$F(1, 57) = 0.07$, $p = .798$, $\eta_p^2 < .01$	$F(1, 57) = 0.48$, $p = .491$, $\eta_p^2 = .01$	$F(1, 57) = 1.21$, $p = .276$, $\eta_p^2 = .02$
Fan et al.'s (2002) method			
Alerting	$F(1, 56) = 1.95$, $p = .168$, $\eta_p^2 = .03$	$F(1, 56) = 0.54$, $p = .465$, $\eta_p^2 = .01$	$F(1, 56) = 1.47$, $p = .230$, $\eta_p^2 = .03$
Orienting	$F(1, 56) = 0.99$, $p = .324$, $\eta_p^2 = .02$	$F(1, 56) = 0.04$, $p = .848$, $\eta_p^2 < .01$	$F(1, 56) = 0.24$, $p = .626$, $\eta_p^2 < .01$
Conflict	$F(1, 54) = 0.44$, $p = .512$, $\eta_p^2 = .01$	$F(1, 54) = 0.71$, $p = .404$, $\eta_p^2 = .01$	$F(1, 54) = 0.57$, $p = .456$, $\eta_p^2 = .01$
Wang et al.'s (2014) method			
Alerting	$F(1, 57) < 0.01$, $p = .976$, $\eta_p^2 < .01$	$F(1, 57) = 1.04$, $p = .311$, $\eta_p^2 = .02$	$F(1, 57) = 0.08$, $p = .781$, $\eta_p^2 < .01$
Orienting	$F(1, 57) = 2.31$, $p = .134$, $\eta_p^2 = .04$	**$F(1, 57) = 9.11$, $p = .004$, $\eta_p^2 = .14$**	$F(1, 57) = 2.72$, $p = .105$, $\eta_p^2 = .05$
Conflict	$F(1, 57) < 0.01$, $p = .994$, $\eta_p^2 < .01$	$F(1, 57) = 0.39$, $p = .536$, $\eta_p^2 = .01$	$F(1, 57) = 0.92$, $p = .343$, $\eta_p^2 < .02$
Alerting with conflict	$F(1, 54) = 0.05$, $p = .827$, $\eta_p^2 < .01$	$F(1, 54) = 0.03$, $p = .853$, $\eta_p^2 < .01$	$F(1, 54) = 0.23$, $p = .631$, $\eta_p^2 < .01$
Orienting with conflict	$F(1, 53) = 3.15$, $p = .082$, $\eta_p^2 = .06$	$F(1, 53) = 0.42$, $p = .518$, $\eta_p^2 = .01$	$F(1, 54) = 1.44$, $p = .235$, $\eta_p^2 = .03$
Conflict with alerting	$F(1, 56) = 0.56$, $p = .458$, $\eta_p^2 = .01$	$F(1, 56) = 0.15$, $p = .700$, $\eta_p^2 < .01$	$F(1, 56) = 0.15$, $p = .704$, $\eta_p^2 < .01$
Conflict with orienting	$F(1, 55) = 0.03$, $p = .868$, $\eta_p^2 < .01$	**$F(1, 55) = 6.53$, $p = .013$, $\eta_p^2 = .11$**	$F(1, 55) = 1.85$, $p = .179$, $\eta_p^2 = .03$

Note. Significant effects are depicted in bold font.

viewing images of nature—compared to urban images matched over certain visual properties—on objective and subjective markers of cognitive fatigue following a fatigue-inducing period. Pre–post differences over working memory and attention control were also assessed. Despite being perceived as more restorative and contrary to H1, H2 and H3, nature images did not yield measurable improvements on objective indicators of cognitive functioning, including working memory, attention control performance, or fNIRS-derived tHb signals. Yet, consistent with H4, exposure to nature images significantly reduced subjective cognitive fatigue, as measured by the KSS, compared to urban images. Notably, following the intervention, fatigue levels remained at high levels in the Urban condition, but they returned to pre-fatigue task levels for the Nature condition.

Objective measures of attention restoration

The absence of restoration condition effect on working memory and attention control, along with the absence of pre–post effects on fNIRS features, suggests that nature pictures failed to produce objective restorative effects. Such findings are not unheard of (Johnson et al., 2022; Kimura et al., 2021; Ohly et al., 2016; Scott et al., 2023; Yap et al., 2022). For instance, Charbonneau et al. (2024) found that nature images, compared to urban ones, improved performance on an attention control task, namely the Flanker Deadline, but had no impact on other working memory components of primary and secondary memory. According to Stevenson et al. (2018), nature exposure can improve performance on working memory tasks such as the digit span backward and forward tasks, as well as attention control effects on the ANT. Yet, these effects may be moderated by multiple factors. Stevenson et al.'s meta-analysis showed that higher engagement and pre-intervention cognitive fatigue tend to augment restorative impacts. However, in the present study, participants were not given any specific task during exposure, aside from completing the PRS after each 20-s picture. One could perhaps contend that this low-engagement format likely reduced the potential for restoration, especially compared to immersive interventions (e.g. walking in real natural settings; Berman et al., 2008; Browning et al., 2020) or interventions that promote increased engagement toward the setting (Duvall, 2011; Lin et al., 2014; Macaulay et al., 2022). The 20-s presentation duration of the images may also have played a role in the absence of effect. While some evidence suggests that longer exposures can increase cognitive benefits of nature (cf. Szolosi et al., 2014), they may also induce fatigue, disengagement or even boredom (see Berman et al., 2021, on the failed replication of their past study by Johnson et al., 2021, which they explained because of the presentation lengths of their images). Overall, the combination of exposure duration, static images and relatively passive viewing may have been insufficient to elicit objective behavioural restorative effects.

An alternative explanation could be that the tasks used were not sensitive enough to capture effects related to cognitive fatigue or that the fatigue manipulation itself was too weak. Although some AX-CPT performance decrement and changes in fatigue-related fNIRS features were observed, the AX-CPT may not have induced a strong enough fatigue effect to yield measurable pre–post intervention differences. Furthermore, the ANT and AOSPAN tasks may not be suited to detect short-term variations in cognitive fatigue. Despite Stevenson et al.'s (2018) suggestions that the ANT and that working memory tasks such as the digit span backward task and the digit span forward task can benefit from nature exposure, such tasks may be insensitive to fatigue effects. This might be specifically

Table 3. Corrected values and ANOVA results (F-value) for the fNIRS tHb features extracted for each restorative condition as a function of the Channel laterality (right or left) and Time of measurement (baseline [T1], pre-intervention [T6] or post-intervention [T8]).

			Corrected value			*F*-value						
Feature	Cond.	Chan.	T1	T6	T8	Cond.	Chan.	T.	T. × Cond.	T. × Chan.	Con. × Chan.	Con × T. × Ch.
Mean	Nature	Right	0.00	−0.23	−0.11	0.41	0.83	0.02	1.12	2.29	0.01	0.32
		Left	0.00	−0.22	0.20							
	Urban	Right	0.00	0.28	−0.29							
		Left	0.00	0.04	0.20							
Amplitude	Nature	Right	0.00	0.88	0.85	0.37	0.01	**5.60****	0.40	0.04	0.45	0.26
		Left	0.00	0.78	0.74							
	Urban	Right	0.00	0.69	0.36							
		Left	0.00	0.81	0.41							
Kurtosis	Nature	Right	0.00	0.45	0.01	0.01	<0.01	**5.86****	0.78	1.03	0.24	0.93
		Left	0.00	0.28	0.11							
	Urban	Right	0.00	0.22	0.14							
		Left	0.00	0.26	0.18							
Polarity	Nature	Right	0.00	1.05	4.28	**5.05***	1.29	0.53	2.90	2.81	0.11	0.13
		Left	0.00	1.77	0.49							
	Urban	Right	0.00	−2.20	0.44							
		Left	0.00	−3.43	−3.97							
Skewness	Nature	Right	0.00	0.13	−0.01	2.13	1.85	**4.50***	0.71	1.17	2.43	1.21
		Left	0.00	0.11	0.03							
	Urban	Right	0.00	0.13	−0.01							
		Left	0.00	−0.04	−0.15							
Slope	Nature	Right	0.00	0.00	0.00	0.02	0.18	1.08	1.76	0.10	<0.01	0.14
		Left	0.00	0.00	0.00							
	Urban	Right	0.00	0.00	0.00							
		Left	0.00	0.00	0.00							
Standard deviation	Nature	Right	0.00	0.39	0.25	0.78	0.19	**5.36***	0.35	0.60	0.13	0.11
		Left	0.00	0.42	0.22							
	Urban	Right	0.00	0.22	0.12							
		Left	0.00	0.27	0.14							

* $p < .05$ ** $p < .01$

Note: Cond.: Restorative condition; Chan.: Channel; T.: Time of measurement; T1: Baseline; T6: Pre-intervention; T8: Post-intervention. Significant effects are depicted in bold font. Scores at T1 all present a 0-value given the baseline correction. Comparisons with other times of measurement allow to evaluate whether the fNIRS features significantly differed from the baseline while considering effects of the condition, laterality, and interactions.

the case with the AOSPAN task. While Bratman et al. (2015) showed that nature exposure could positively impact the AOSPAN score, Scott et al. (2023) failed to replicate this outcome. The AOSPAN task is often considered a trait (complex) working memory capacity measure rather than a "purer" and "simpler" span task —as opposed to the *n*-back, digit span forward and backward tasks—given its high test-retest reliability and its specific association with other trait-like cognitive abilities such as fluid intelligence and attention control (Bratman et al., 2015; Kane et al., 2007; Redick & Lindsey, 2013; Unsworth et al., 2005; but for an alternative view on the AOPSAN and complex working memory capacity, see Ecker et al., 2010; Wilhelm et al., 2013). Future studies should consider alternative tasks that rely on similar cognitive mechanisms (i.e. working memory and attentional control) but with less overlap and/or confounding variability with other cognitive abilities. The improvement in posttest performance on the AOSPAN task for both conditions is also noteworthy. This likely reflects that participants were still learning the task, and additional practice might naturally lead to better performance at posttest, despite the increased fatigue induced by the AX-CPT. Such practice-related gains may have masked the detrimental effects of fatigue. Greater familiarity with the tasks could potentially increase sensitivity to fatigue effects (as is the case for tasks performed in real-world situations where fatigue may have more noticeable impacts). This should be considered in future studies.

Regarding the fNIRS measures, the tHb signal appeared to be mainly influenced by the time of measurement rather than the restoration condition. Indeed, differences in amplitude, kurtosis, skewness and *SD* in the tHb signal were found between the three time points analysed (T1, T6 and T8, that is at the beginning of the pretest, after the fatigue task and after the intervention). These variations suggest that the fatigue task induced higher cognitive engagement, with more variability in oxygen exchange across participants in periods of higher fatigue (i.e. at T6). Such increased variability of cerebral blood oxygenation in frontal cerebral regions under fatigue has been previously reported (e.g. Angsuwatanakul et al., 2015; Garrett et al., 2013; Holper et al., 2012), and may reflect individual differences in cognitive resource management. This aligns with the higher fatigue reported by participants after the AX-CPT, and with the correlation

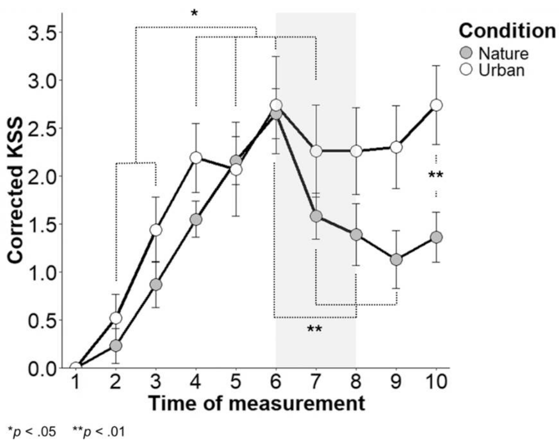

Figure 9. Baseline-corrected KSS scores as a function of Time of measurement and Restorative condition (Nature vs. Urban). Error bars represent the standard errors of the mean. The light grey region highlighted represents the period where the intervention was presented. The KSS was completed at the following periods: (T1) prior to the pretest; (T2) after the first task of the pretest; (T3) following the second task of the pretest; (T4) after the first block of the cognitive fatigue task; (T5) after the second block of the cognitive fatigue task; (T6) after the last block of the fatigue task; (T7) after the first block of the intervention; (T8) after the second block of the intervention; (T9) following the first task of the posttest; and (T10) after the second task of the posttest.

between self-reports of fatigue and both tHb amplitude and *SD* observed at T6 (i.e. at the pre-intervention stage). It also speaks to Imamura et al.'s (2022) results, which showed a significant relationship between frontal oxygenated hemoglobin exchange and self-reports of fatigue. Yet, the type of intervention (either nature or urban) hardly influenced the fNIRS signal collected after the intervention and no effect of channel laterality (either right or left prefrontal cortex) was observed. This absence of an intervention effect on the fNIRS signal was also evidenced by the lack of correlation between self-reports of fatigue and all tHb features at T8, after the intervention, as opposed to T6. Although some results provide evidence of a fatigued state, the fNIRS analysis only concerned a small set of features that may lack specificity with respect to other low-performance cognitive states such as cognitive (over)load. Therefore, other neurophysiological monitoring techniques should be explored. For instance, fNIRS-based functional connectivity network analysis, focusing on the intertwined relationships across different cerebral regions, has been shown to be sensitive to changes in cognitive fatigue (e.g. Borragan et al., 2019; Peng et al., 2022). EEG is also often used to assess how nature exposure may modulate cognitive processing and brain activity (Chen et al., 2016; Collins et al., 2025; Hopman et al., 2020; LoTemplio et al., 2020; McDonnell et al., 2025; Olszewska-Guizzo et al., 2018). Such methods could be explored in future studies.

Subjective measures of fatigue

The higher restorative ratings for nature pictures, along with the positive effects observed on the KSS, align with previous studies on subjective measures of attention restoration including perceived restoration (e.g. Chung et al., 2018; Yap et al., 2022; for a meta-analysis, see Menardo et al., 2021), and mood and affect (e.g. Hartig et al., 2003; Meidenbauer et al., 2020; for a meta-analysis, see McMahan & Estes, 2015). However, to our knowledge, self-reported improvements in fatigue following nature exposure have scarcely been observed. For instance, Johnson et al. (2022) found no difference in KSS reports between participants exposed to either urban, meadow or ocean pictures. All groups reported increased fatigue from pre- to post-exposure. Similarly, Sun et al. (2022) reported no difference in subjective fatigue, measured by the visual analog scale (VAS; Ahearn, 1997), across participants being exposed to a 12-min viewing of natural scenes compared with urban photos. Imamura et al. (2022) reported improvements in the VAS for participants performing cognitive tasks in a room full of plants vs. a control room containing no natural green features, but the difference failed to reach significance. These findings provide novel evidence suggesting that perceived fatigue may benefit from exposure to nature.

Several factors may explain the discrepancy between our pattern of results and that of other studies. In Johnson et al. (2022), participants were not fatigued prior to the intervention, potentially reducing opportunities for feeling subjective restoration. In contrast, both Imamura et al. (2022) and Sun et al. (2022) exposed participants to a fatigue task and reported significant increases in fatigue after its completion, as we did. Yet, in Imamura et al. (2022), participants performed fatigue task *while* being exposed to either indoor forest bathing or a control (nonrestorative) environment, potentially confounding restorative effects with ongoing cognitive depletion. As for Sun et al. (2022), the absence of between-conditions differences after the intervention is more puzzling. One explanation could be that the exposure durations used in their study—approximately 4.17, 8.33 min, or 12.50 min—were insufficient. Previous studies emphasised the importance of engagement and exposure duration for nature benefits to emerge (cf. Browning et al., 2020; Duvall, 2011; Lin et al., 2014; Pasanen et al., 2018; Szolosi et al., 2014; but see Berman et al., 2021). In our case, the intervention lasted approximately 16.14 min, which may have been appropriate for inducing subjective effects. The specific role of exposure duration on one's subjective experience of restoration, however, remains to be tested.

The reduction in perceived fatigue observed for the nature intervention is coherent with how restorative nature can engage one's attention without necessarily imposing further demands (Duvall, 2011; Marois et al., 2021; Szolosi et al., 2014). Nature may encourage active exploration and engagement toward the setting, while properties inherent to nature (e.g. soft fascination; see Berman et al., 2008; Kaplan & Berman, 2010) may facilitate this engagement. Unlike urban environments, which often contain bottom-up stimulation that demand directed attention to resist, nature draws attention "gently" in a way that does not incur resistance nor inhibition as it aligns with top-down intentions (Kaplan, 1995; Pearson & Craig, 2014). This lack of effortful inhibition to "compete" with attraction driven by nature may promote restoration of cognitive resources, in turn improving self-reported measures and experience of fatigue.

An alternative explanation could be that exposure reduced participants' stress levels, in turn improving their perceived fatigue. According to the stress reduction theory (Ulrich et al., 1991), exposure to nature environments can lower physiological and psychological stress as evidenced by recent reviews and meta-analyses (e.g. Berto, 2014; Jimenez et al., 2021; Kondo et al., 2018; Shuda et al., 2020; Song et al., 2016; Yao et al., 2021). Given the close relationship between stress and feelings of fatigue, even for daily fluctuations (cf. Åkerstedt et al., 2014), it is plausible that nature pictures reduced stress, in turn reducing the subjective experience of fatigue. Alternatively, other subjective and arbitrary components may also play a role. More precisely, the difference in PRS score across nature and urban nature may be responsible for the reduction in fatigue. The items of the PRS that participants completed focused solely on the fascination properties, that is the extent to which each image tended to attract attention and spend time in the different surroundings presented. Such questions may have primed participants in considering the nature images to be restorative and calming, thus impacting self-perceived fatigue. While perceived fascination—as a prerequisite to restoration—and perceived fatigue both correspond to distinct concepts, some overlap can still be found, especially regarding the feeling they may induce on participants and the arbitrary experience they represent. Similarly, preference could also have played a role. Meidenbauer et al. (2020) suggested that aesthetic preference mainly impacts affective responses to nature images, demonstrating that urban images equally preferred to nature images induced similar positive states. From the Conditioned Restoration Theory perspective (Egner et al., 2020), the restorative and relaxing effects experienced from nature exposure could even result from a two-step process that mostly originates from conditioning and associative learning. Taken together, these alternative views outline that the differences in subjective fatigue may not only/necessarily be driven by actual restorative properties of the images, but potentially by other confounding factors such as stress and preference. It could even be the result of a biased or conditioned response. Again, the current data cannot delineate these effects, but future studies should explore these alternatives.

Tetrahedral perspective for studying nature's effects on attention

The present article brings many contributions for improving our understanding of nature's influence on attention, more specifically from the perspective of Jenkins' (1979) tetrahedral model for organising scientific research for cognitive psychology. First, our study provided better control over the material studied, that is, the type of stimulus used for the intervention. We tried to equate the nature and urban pictures on several key characteristics, such as the season displayed (Summer, Fall or Winter), the type of view (straight, from above or from below), the orientation (portrait vs. landscape), and the type of visual editions made on the picture (visual effects or not). However, some low-level visual properties are inherent to the type of image presented (e.g. built settings such as those that can be found in urban environments typically possess straighter edges). As discussed in Appendix A, natural and urban settings can vary on multiple visual features, but it remains to be determined whether such variation can contribute to how attention may be restored (Berman et al., 2014; Celikors & Wells, 2022; Kardan et al., 2015; Schertz et al., 2020; Schertz & Berman, 2019; but see Menzel & Reese, 2022). In the absence of complete control over these features, it remains difficult to determine whether these aspects could have influenced the effectiveness of the intervention to induce cognitive benefits. While great effort was made to render the two sets of pictures equivalent on most visual features, some features (i.e. colour saturation, variability in hue, and edges) were particularly difficult to control. Future studies should aim to disentangle the impact of these low-level visual features from broader effects of environmental content. Images controlled on their different visual properties, for instance displaying only low-level features or overt semantic information (e.g. Schertz & Berman, 2019) could represent a great tool for such a purpose.

Second, our study contributes to a better understanding of the outcomes used to investigate nature's effects on attention. Indeed, we favoured a mix of methods to evaluate how nature could potentially affect cognitive fatigue combining subjective self-reports of fatigue, behavioural pre- vs. post-task differences in working memory and attentional control performance, and brain activity measures through a set of fNIRS features. Such an approach offers a more holistic and nuanced view of nature's (potential) restorative effects. In our case, this mix of measures and the different pattern of results observed across subjective and objective measures helped us raise questions regarding fundamental principles of restoration, specifically whether this effect is objective or importantly driven by perception and subjectivity. Such questions should be investigated in future studies.

Finally, our study also helped improve our knowledge of the role of context by ensuring similar pre-exposure states through the induction of cognitive fatigue. The use of the AX-CPT ensured that all participants experienced similar fatigue levels before exposure, providing enough "space" for restoration to occur. As discussed by Stevenson et al. (2018), such pre-intervention state may affect how nature restores attention. Analysis of the KSS ratings, AX-CPT accuracy and fNIRS features supported that participants from both conditions were indeed fatigued before the intervention, and, most importantly, to a similar level. Thanks to this manipulation, we could conclude that the absence of difference between the Nature and Urban conditions was not due to pre-intervention differences in the fatigue level. Future studies should systematically include a fatigue task to better control for pre-intervention states and guarantee validity of the conclusions about the effectiveness of nature interventions.

Limitations

Our study offers a novel perspective on the impact of nature exposure on cognitive fatigue and, more particularly, on how this effect may differ across objective and subjective markers. However, some limitations must be acknowledged. First, the study draws upon a large range of psychological constructs that, while conceptually distinct, overlap in both theory and measurement. The focus of the paper is cognitive fatigue, a construct frequently used in ART literature to describe how attention (more specifically directed attention) needs to be replenished after being depleted. Yet, we also incorporated a variety of additional measures including the AX-CPT (attention control and passive fatigue), the AOSPAN (working memory trait and complex working memory) and the ANT (attention control and inhibition). These different concepts and phenomena are difficult to reconcile with specific theoretical perspectives, an issue previously raised regarding ART (cf. Joye & Dewitte, 2018).

Second, we used the KSS to assess self-perceived (cognitive) fatigue, which also relates to larger, biological and homeostasis-driven states—including hypovigilance, sleepiness, drowsiness and boredom—that share common behavioural manifestations yet differ conceptually (see, e.g. Neu et al., 2010; Pickering, 2023; Shahid et al., 2010). This conceptual ambiguity reduces the internal validity of our fatigue measures. According to the circumplex model of affect (Russell, 1980; see also Posner et al., 2005), all affective states (including stress, boredom and even alertness) can be mapped along two dimensions depending on their valence (pleasure-displeasure continuum) and their level of arousal (activation–deactivation continuum). Higher self-perceived fatigue ratings on the KSS may reflect unpleasant and high-arousal states of mental overload and tensity on the circumplex model of affect but may also imply boredom (unpleasant-deactivation) or even calmness (pleasant-deactivation). As such, the KSS scale lacks the specificity needed to distinguish these various states. Consequently, the lower fatigue reported across the Nature condition may not necessarily represent a restored state, even if this interpretation aligns with ART and with the differences in PRS scores. Future research is needed to characterise more precisely the affective state underlying the lower fatigue reported and to anchor this to a clearer theoretical framework.

Finally, although our experimental design allowed control for pre-intervention fatigue levels, some improvements could enhance the evaluation of nature's restorative effects. In particular, AOSPAN and ANT measures could have been collected after the fatigue period, before the intervention. Currently, these measures were only administered at the beginning and end of the experiment, preventing us to understand how attention control and working memory assessed *after* fatigue may be restored by nature exposure. Moreover, the absence of a condition without any fatigue limits interpretability (cf. Joye & Dewitte, 2018). In fact, a more comprehensive design would involve a condition in which participants follow the same steps without performing the AX-CPT. Taken together, these two manipulations would provide a more complete picture of the interplay between cognitive fatigue and the capacity of nature images to restore attention.

Conclusion

The current study provides a comprehensive assessment of how nature interventions impact cognitive fatigue by considering a mix of behavioural, self-reported and neurophysiological methods. It also shows how better control over the pre-intervention state and over the pictures used for the intervention could be applied. The presentation of nature pictures, relative to urban pictures, reduced self-reported fatigue levels but failed to impact pre–post performance differences for the cognitive tasks and prefrontal brain activity. In addition to the methodological contributions this study brings with respect to Jenkins' tetrahedral model, our study helped raise questions as to the conceptual principle of cognitive fatigue and attention restoration given the discrepancy between subjective vs. objective measurements. The fact that the pattern of cognitive fatigue measures can vary depending on whether they are objective or subjective helps refine our view of attention restoration. Future studies should focus more on understanding how these experiences vary and to what extent this may affect the numerous benefits that nature is expected to bring.

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article supplementary materials.

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