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The restorative effects of mental imagery of nature: A study on subjective and physiological responses

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ABSTRACT

Exposure to natural environments, whether real or virtual, has been demonstrated to have restorative effects. However, it is unclear whether these effects depend on the meanings and associations that individuals attribute to different environments. This study explored the restorative effects of mental imagery of nature (i.e., pure top-down processing) following cognitive stress induction. Fifty students participated in a within-subject study where they imagined the contents of nature and urban words for 5 min each. Self-rated measures indicated a stronger sense of subjective restoration following nature imagery compared to urban imagery. The heart rate was slower, and heart rate variability was larger during nature imagery than during urban imagery, suggesting a greater degree of relaxation with nature imagery. Both tonic and phasic electrodermal activity was stronger during the mental imagery of nature than urban contents. This difference was driven by a higher preference for nature over urban words, indicating that imagery of nature was associated with stronger positive arousal than urban imagery. Notably, participants' reported connection to nature moderated some of the physiological responses. In conclusion, top-down processes and individual meanings and associations play a significant role in the positive effects of nature exposure. The results also indirectly support the inclusion of nature imagery as a cost-effective component of therapeutic techniques aimed at promoting relaxation.

1. Introduction

In the modern, fast-paced world, stress and cognitive load have become common issues affecting individuals from all walks of life. Numerous studies have highlighted the remarkable ability of exposure to nature to alleviate stress and promote psychological well-being (Berman et al., 2008; Berto, 2005; Corazon et al., 2019; Hartig et al., 2014; Ross & Mason, 2017). Exposure to natural environments, such as parks, gardens, or even virtual representations of nature in terms of images, videos, or virtual reality, has demonstrated positive outcomes in stress reduction and other psychological and physiological functions (Berto, 2005; Bratman et al., 2021; Frost et al., 2022; Grassini et al., 2019, 2022; Ohly et al., 2016; Spano et al., 2023; Stevenson et al., 2018).

These positive mental effects are most often explained from an evolutionary perspective. The Stress Reduction Theory (SRT) (Ulrich, 1983; Ulrich et al., 1991) assumes that during evolution (non-threatening) nature has provided favorable conditions for biological survival, which have led humans to respond positively to non-threatening nature. The positive emotional responses counteract the negative ones and thus reduce stress. Attention Restoration Theory (ART) (Kaplan, 1995; Kaplan & Kaplan, 1989) states that an urban lifestyle produces stress and mental fatigue associated with a reduced capacity to direct top-down attention. ART assumes that spending time in natural environments enables people to restore their attentional capacity. This occurs, according to ART, because attention to natural environments is dominated by effortless bottom-up attention and because in nature, people are away from stressful urban environments. Recently, also constructivist frameworks have emphasized the importance of the learned associations (Egner et al., 2020) and the meanings (Van Hedger et al., 2019) humans attribute to the physical attributes of nature rather than hard-wired bottom-up tendencies developed during evolution. The constructivist views stress the physical features of nature to a lesser extent. Instead, these emphasize the top-down interpretation that humans make of natural signals and how they are associated with prior situations and emotions.

The experimental studies guided by SRT and ART have most often, with few exceptions (e.g., Korpela et al., 2001; Korpela & Hartig, 1996), exposed participants to physical stimuli, either real or synthetic (e.g.,

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photos or videos), which have led the focus mostly on the stimulus-driven bottom-up processes. However, human-environment interactions are shaped by both bottom-up processing, defined by the physical characteristics of the environment, and top-down factors, such as individuals' environmental preferences, associations, and attributed meanings. Consistent with constructivist views, Haga et al. (2016) and Koivisto et al. (2022) showed that perceptions and restorative effects of nature were influenced by attributing the source of an ambiguous stimulus to nature, suggesting that top-down processing, such as beliefs and interpretations, affect subjective relaxation. Van Hedger et al. (2019) further showed that nature-associated sounds were aesthetically preferred over urban ones only when they were recognized as such, demonstrating the role of recognition and association.

A key example of top-down processing is mental imagery, or 'seeing with the mind's eye' (Kosslyn et al., 2001). Perception and imagery share common cognitive resources and neural activation patterns, suggesting overlapping mechanisms (Baddeley & Andrade, 2000; Ganis et al., 2004; Ishai et al., 2000; Segal & Fusella, 1969). Despite being similar to perception, mental imagery differs from it fundamentally in its lack of external sensory stimuli. Nevertheless, mental imagery is not purely independent of bottom-up processes because it relies on memories from past experiences (Kosslyn et al., 1995; Dijkstra et al., 2019). Mental imagery encompasses our everyday cognitive functions, including thinking (Kosslyn et al., 1995), decision-making (Taylor et al., 1998), and memory use (Keogh & Pearson, 2011). Importantly, our thoughts and mental images can directly influence our emotions. Imagery's tight coupling with emotions can be observed in emotional disorders (Holmes & Mathews, 2010). Mental imagery has sometimes been used in therapeutic techniques to alter negative thought patterns (Beck & Haigh, 2014; Holmes et al., 2006).

Several lines of evidence suggest that mental imagery of nature may produce psychologically beneficial effects. Nguyen and Brymer (2018) found that the inclusion of natural elements in Guided Imagery (GI; Hart, 2008), a therapeutic approach that guides imagery using external instructions, helped to reduce state anxiety more than GI with carefully matched urban elements. However, it may not be necessary to include any guidance in the imagery of nature to obtain positive psychological effects. Although not using instructions to imagine, Menzel and Reese (2022) reported that viewing nature-related words for 10 min led to higher perceived restoration than viewing urban-related words. With explicit instruction to imagine, Koivisto and Grassini (2023) found that participants subjectively experienced more relaxation and positive emotions after having imagined for 30 s themselves being in restorative natural environments (e.g., forest path or seaside) than after having imagined being in restorative urban settings (e.g., library or museum). These effects remained statistically significant even after accounting for individual preferences (i.e., liking the environments).

Individuals vary in the way they feel connected to nature. "Nature connectedness" or "nature connection" is often defined as a sense of relationship or interconnectedness with the natural environment (Mayer et al., 2009; Tam, 2013). Nature connectedness may mediate or moderate the effects of nature exposure on psychological well-being (Mayer et al., 2009; Pensini et al., 2016) and emotions (Koivisto and Grassini, 2023; Koivisto et al., 2022; McMahan et al., 2018). The benefits of nature exposure are typically stronger for individuals with higher levels of nature connectedness. One might expect that the benefits of strong nature connectedness will be evident, especially when top-down processing and personal preferences can influence behavior and emotions, such as mental imagery.

So far, evidence for the benefits of imagining nature has come from studies that have not examined whether imagining nature helps individuals recover from stress, either experimentally induced stress or stress resulting from natural occurrences. Another limitation of these studies is that they have used only subjective, self-reported measures. Thus, it is unclear whether the positive mental effects of imagining nature can be replicated with other types of measures that are less vulnerable to biases (e.g., demand-characteristics or "nature positive bias", Corazon et al., 2019) than subjective measures. Based on the evidence supporting the stress-reducing effects of nature and the efficacy of mental imagery interventions, it is reasonable to hypothesize that mental imagery of nature holds the potential to mitigate stress induced by cognitive load. In the present study, we tested whether imagery of nature-related contents would restore induced cognitive stress more than imagery of urban-related contents. One should note that with imagery of nature, we refer not only to imagery of natural environments (e.g., forest) but to natural objects or elements that can be found in nature (e.g., bee, flower) and are products of nature. Similarly, imagery of urban-related contents includes not only imagery of urban environments (e.g., marketplace) but also man-made objects typically, but not exclusively, found in built urban environments (e.g., street signs, bus).

We hypothesized that imagery of nature promotes stronger restoration from stress than urban-related imagery. In addition, we hypothesized that the effect of imagery of nature vs. urban contents on the subjective experience of restoration and physiological arousal depends on the meaning of nature for the individual, predicting that the stronger the individual's nature connection, the more imagery of nature would influence one's restoration. We purposely did not pre-control for individuals' preferences between nature and urban words because people tend to like (i.e., prefer) nature more than urban environments (Kaplan & Kaplan, 1989; Koivisto Grassini 2022b; Meidenbauer et al., 2020; Ross & Mason, 2017), and this may be one of the reasons why nature exposure has positive psychological influences. Instead, we controlled the familiarity and imageability between nature and urban words (see Methods section). We allowed the preference to vary "naturally" so that the meanings and emotions participants typically associate with nature would express their effects.

We measured restoration from induced cognitive stress and its physiological indices with the subjective Restoration Outcome Scale (ROS) (Korpela et al., 2008, 2010), electrodermal activity (EDA), and heart rate variability (HRV) (Pham et al., 2021; Shaffer & Ginsberg, 2017). EDA is known to reflect arousal of the autonomous nervous system (Boucsein, 2012). Of the EDA recordings, we analyzed the tonic activity (skin conductance level, SCL) and the faster skin conductance responses (SCRs) (Benedek & Kaernbach, 2010). The SCL indexes the general arousal level. The event-related SCRs (ER-SCRs) are phasic and transient changes in skin conductance related to the level of arousal elicited by stimuli about 1–5 s after stimulus onset, whereas the non-specific SCRs (NS-SCRs) occur without any obvious external stimuli. SCRs can be elicited by stimuli with either positive or negative emotional valence (Gross & Levenson, 1997; Kreibig, 2010). Assuming that nature's restorative potential can be revealed during pure mental imagery, we expected that EDA should first increase due to the induction of cognitive stress and then decrease faster during mental imagery of nature than during imagery of urban contents.

In addition, we recorded heart rate (HR) and analyzed typical heart rate variability (HRV) measure Root Mean Square of Successive Differences (RMSSD) (Pham et al., 2021; Shaffer & Ginsberg, 2017). HR is increased under stress or emotional arousal as the sympathetic nervous system is activated. On the other hand, when an individual is relaxed or calm, the parasympathetic nervous system is active, and it slows down the heart rate and increases the HRV. RMSSD reflects high-frequency variability and is primarily influenced by parasympathetic activity. Thus, if the imagery of nature is more restorative from stress than the imagery of urban contents, we should observe during imagery of nature slower HR and increased RMSSD, reflecting increased parasympathetic activity.

In summary, we hypothesized that mere imagery of nature words promotes stronger restoration from stress than imagery of urban words, measured with subjective ratings before and after imagery, steeper reduction of electrodermal activity by nature words than urban words as a function of time during imagery, and higher heart rate variability during imagery of nature than urban words. In addition, we hypothesize that the effect of imagery of nature vs. urban words on physiological arousal and subjective experiences of restoration depends on the meaning of nature for the individual. This account predicts an interaction between condition (nature vs. urban words) and nature connectedness in such way that the higher the nature connectedness, the more restoration in response to nature, compared to urban words, the individuals would show in subjective and physiological measures.

2. Methods

The study was pre-registered using Open Science Framework preregistration at OSF.io, https://osf.io/e9gwt/

The data and analysis scripts are available at https://osf.io/e9gwt/

2.1. Participants

Participants were 50 students (M = 23.4 years, SD = 5.8, min = 19, max = 52; 4 males), recruited from the introductory psychology courses at the University of Turku. They participated to obtain partial course credits. In statistical analyses, we performed Type III Analysis of Variance (ANOVA) on linear mixed effect models, to obtain main effects and interactions in 2 × 5 analyses. However, it is difficult to calculate the power needed in linear mixed effect models, because they require specification of main effects and their interactions as well as the specification of parameters associated with the variance and correlation of random factors (Kumle et al., 2021). Therefore, simulations are the preferred way to calculate the statistical power for mixed effect models (Green & MacLeod, 2016). In lack of suitable pilot data or estimates for power simulation, we estimated the required sample size in 2 × 5 within-participant ANOVA with G*power (Faul et al., 2007) This procedure gave an approximate estimate of the required sample size based on fixed effects, suggesting that the sample size of 50 participants should be sufficient for at least 80% power with small-to-medium effect size at alpha level of 0.05. The main limitation of this approach is that it does not consider the random effects (Bates et al., 2015) that mixed-effects models handle.

The study was conducted in accordance with the Declaration of Helsinki and with the understanding and written consent of each participant. The study was accepted by Ethics Committee for Human Sciences at the University of Turku.

2.2. Stimuli and scales

The word stimuli in the experiment were 20 nature and 20 urban Finnish words, matched for imageability and familiarity based on an online survey ran with Psytoolkit (Stoet, 2010, 2017). The survey was conducted prior to this study and the participants were 51 native Finnish speakers who did not participate in the present experiment. The survey contained 74 candidate words which were presented one-by-one in random order. In the survey, the participants rated the imageability (*How hard or easy is it for you to imagine the thing that the word is referring to?* 1 = *very hard*, 9 = *very easy*) and the familiarity (*How often do you encounter or use the word?* 1 = *very rarely*, 9 = *very often*) of the words in separate blocks. The order of the imageability and familiarity blocks was counterbalanced across the participants. After having rated the words for imageability and familiarity, the words were presented once again in random order and the participants were also asked to categorize them according to whether they were more associated to nature or urban environments (1 = *nature*, 2 = *urban*). We arranged the words in order into two list (nature, urban) based on both imageability and familiarity ratings and chose the nature and urban words for the study in such a way that both the mean imageability (M = 7.89, SD = 0.50 vs. M = 7.70, SD = 0.55, for nature and urban words, respectively), $t(38) = 1.04$, $p = 0.153$, and the mean familiarity (M = 5.55, SD = 1.19 vs. M = 5.93, SD = 1.00, for nature and urban words, respectively), $t(38) = -1.07$, $p = 0.290$, were as similar as possible in the nature and urban categories. The accuracy of categorizing the selected nature words (M = 98.8%, SD = 1.7) and urban words (M = 98.7, SD = 2.3) did not differ statistically significantly, $t(35) = 0.15$, $p = 0.880$. The selected nature words were: "havunneulanen" (*conifer),* "heinäpelto" *(hayfield),* "järvi" *(lake),* "joki" *(river),* "kallio" *(rock),* "kukkanen" *(flower),* "lampi" *(pond),* "linnunlaulu" *(birdsong),* "lintu" *(bird),* "lintuparvi" *(flock of birds),* "luontopolku" *(nature path),* "mehiläinen" *(bee),* "merenranta" *(seaside),* "metsä" *(forest),* "perhonen" *(butterfly),* "puro" *(stream),* "saaristo" *(archipelago),* "sammal" *(moss),* "sateenkaari" *(rainbow),* and "vuoristo" (*mountain)*. Many of the nature words had to be compound words because the urban words typically are compound words. The urban words were: "asfaltti" (*asphalt),* "baari" *(bar),* "huoltoasema" *(gas station),* "katukyltti" *(street sign),* "kirkko" *(church),* "kortteli" *(block),* "kuja" *(alley),* "linja-auto" *(bus),* "linja-autoasema" *(bus station),* "metro" *(subway),* "moottoripyörä" *(motorbike),* "ostoskeskus" *(shopping mall),* "parkkipaikka" *(parking lot),* "raitiovaunu" *(tram),* "rakennustyömaa" *(construction site),* "stadion" *(stadium),* "risteys" *(crosswalk),* "tehdas" *(factory),* "tori" *(marketplace),* and "tornitalo" (*tower block)*.

The words were transformed into audio files with Voicemaker (https://voicemaker.in) using the voice of Heidi, and the vocalization speed and pitch adjusted to −50. After that, the lengths of the auditory words were edited with Audacity 2.3.3 (© 1999–2018 Audacity Team) such that the audio files were, on average, equally long between nature and urban words.

Restoration Outcome Scale (ROS) (Korpela et al., 2008, 2010) was used to measure restoration. ROS consists of six items. Three items reflect relaxation and calmness, one reflects attention restoration, and two reflect clearing one's thoughts. The participants were asked to rate how much they agreed with each item's statement about their feelings at the moment on a scale from 1 (*not at all*) to 7 (*totally*). Cronbach's α for ROS was 0.75, measured before the nature condition, 0.78 before the urban condition, and after the conditions, they were 0.82 and 0.85, respectively.

Extended Inclusion of Nature in Self (EINS) scale (Martin & Czellar, 2016) measured self-nature connectedness. It consists of four pictorial items (overlap, size, distance, centrality), each with seven alternatives (min = 1, max = 7). The participants selected the alternative that best describes their relationship with the natural environment. An *Extended Inclusion of City in Self* (EICS) scale was created for exploratory purposes by changing the word nature in EINS into the word "city". The score in both scales could vary between 4 and 28. In the present study, Cronbach's α for EINS was 0.871 and for EICS it was 0.812.

2.3. Procedure

For recording manual responses and presentation of all auditory stimuli and the ROS scale, the software E-prime2 (Psychology Software Tools, Inc.) was used. During the study, the auditory stimuli were presented via Philips TAH2005BK headphones. The sound volume was the same for each participant. It was adjusted by the experimenter and few colleagues to a comfortable level, where participants without hearing deficit were able to clearly hear the words. The testing occurred in a closed laboratory room which did not contain windows or anything additional in participant's view. Biopac equipment and monitors for physiological recordings were separated from the participants view with a folding screen. The experimenter was in the same room during acquisition of informed consent and background information, and during giving the instructions and preparation of the participant for the physiological measurements. During the tasks, the participants was alone in the room, while the experimenter was in a separate room and was connected to the participants with an audiovisual connection, allowing communication between the participant and experimenter if something unexpected occurred or needed clarification.

Fig. 1 shows a flowchart demonstrating the course of the experiment. The experiment started with a baseline measurement (2-min sitting quietly). It was followed by 3-min stressor tasks which involved speeded

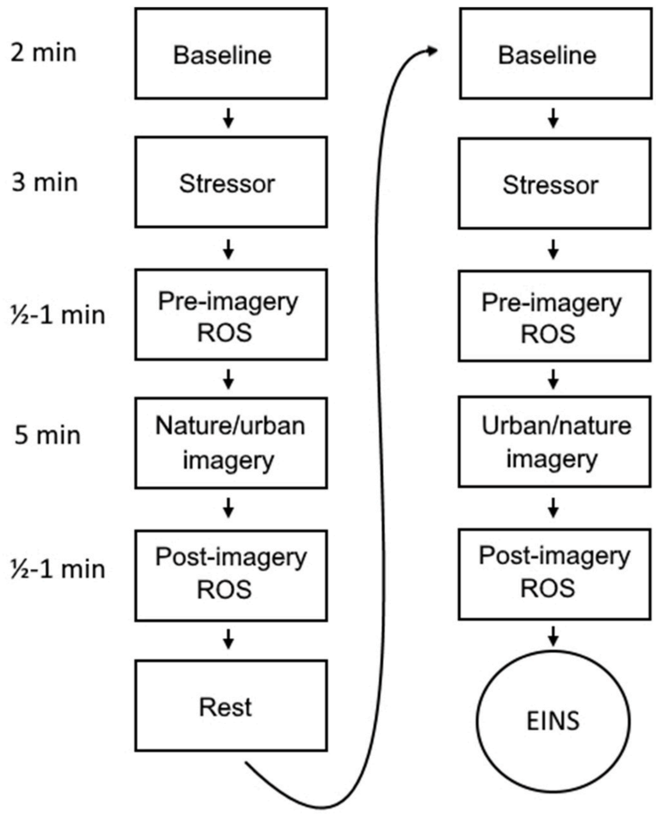

Fig. 1. A flowchart demonstrating how the experiment proceeded.

mental arithmetic. The stressor task began with simple additions (e.g., 10 + 1) and subtractions (e.g., 18–2) and gradually became more difficult, until at the end most of the equations were relatively difficult multiplication (e.g., 4 × 19) or division problems (e.g., 72 : 2). The equations were presented auditorily, and the task was to report the correct result to each equation within 4-sec (after the offset of the equation). All the correct results were within 10–99, and the responses were given with two button presses on the computer numpad. After the 4 s time to respond (during which it was not possible to erase and rewrite the responses), feedback was presented on the screen for 500 ms: "correct", "false", or "too late" (when no response was given within 4 s). It was not possible to erase and rewrite the numbers after the presses were made. The next equation was presented 100 ms after the feedback. This kind of speeded arithmetic tasks, which include feedback, have been shown to effectively induce stress (Alvarsson et al., 2010; Atchley et al., 2017). There were two different sets of equations, counterbalanced across the two stressor conditions (before nature imagery vs. before urban imagery) and nature vs. urban condition orders, so that each participant received different sets in the two stressor conditions.

After the stressor task, the ROS (here *pre-imagery ROS* when presented before the nature or urban imagery phase) was presented on the screen, and the participants gave their ratings. The pre-imagery ROS was followed by the mental imagery phase for 5 min: 20 words (either 20 nature-related words or 20 urban-related words, order counterbalanced across participants) were presented auditorily in random order, with stimulus-asynchrony of 15 s. The participants were asked to close their eyes and imagine that they were in the environment referred to in the word or encounter the thing referred to in the word. After the imagery phase, the ROS scale was filled in again (post-imagery ROS). Also, two additional statements were presented: "*I liked the words I heard*" and "*Imagery required effort*". The ratings were given using the same 7-point scale as in ROS. After the *post-imagery* ROS and the questions about liking and effort, the participants were allowed to rest and freely move their limbs as long as they thought necessary. Then the sequence of tasks started again from the baseline measurement and continued to the stressor task, pre-imagery ROS, 5-min imagery (urban or nature words), and post-imagery ROS. At the end of the test session, the participants filled in the EINS and EICS scales.

2.4. *Physiological measurements*

The electrodermal activity (EDA) was recorded using a Biopac MP150 (Biopac Systems, Inc., Santa Barbara, CA) and AcqKnowledge 5.0 software at a sampling rate of 2000 Hz. The electrodes were placed on the top surfaces of the left forefinger and middle finger. The recorded data was processed in Ledalab 3.4.9 software (Benedek & Kaernbach, 2010), running under MATLAB (v. R2019b) (The MathWorks, Inc., Natick, MA). The data was down sampled to 10 Hz, smoothed adaptively, and Continuous Decomposition Analysis (CDA) was performed on every 15-s segment in nature and urban conditions using two sets of initial values considered in the optimization. CDA separated the phasic (SCR) and tonic (SCL) components from the EDA. A SCR was detected if a local maximum differed ≥0.05 μS from its preceding or following local minimum (Benedek & Kaernbach, 2010). The SCL component was measured during the whole 15-sec segments, whereas the ER-SCRs were measured 1–5 s after the onset of the words, and the NS-SCRs were measured 6–15 s after the onset. The resulting variables were the amplitude (μS) of SCL and the amplitudes of ER-SCRs and NS-SCRs, and the number of ER-SCRs and NS-SCRs. The EDA variables SCL and the number and amplitude of SCR were also used to compare the activity during the stressor task and baseline to confirm the effect of the stressor task.

The heart rate was recorded with photoplethysmography (PPG) from the tip of the ring finger of the non-dominant hand with Biopac MP150 and AcqKnowledge 5.0. Heart rate variability (HRV) variables were obtained by calculating the fluctuation time between heartbeats using the HRVTool (Vollmer, 2019). In anticipating noisy PPG signals, we preregistered the HRV data only to be used as far as the PPG sensor entirely records the data. The major measures extracted from the PPG signal were Heart Rate (HR) and Root Mean Square of Successive Differences (RMSSD). In addition, we report also the less specific Standard Deviation of NN intervals (SDNN) and Low-Frequency power (LP) in Supplementary Materials.

2.5. *Statistical analyses*

For descriptive analyses and correlations, we used Jamovi 2.3.21 (The Jamovi project, 2022). To further analyze the experimental results, we used R (R Core Team, 2018) with linear mixed-effects models (package lme4, Bates et al., 2015, and lmerTest, (Kuznetsova et al., 2017) with Type III Analysis of Variance with Satterthwaite's method for the ROS and EDA amplitude data. The results were visualized with packages ggplot2 (Wickham, 2016) and sjPlot (Lüdecke, 2019). The EDA amplitudes were always log-transformed, but the values in the figures and supplementary tables have been back-transformed to the original scale. The number of SCRs represents count data, so they were analyzed with generalized mixed-effects models with Poisson distribution and Type III Wald Chi-square tests. The continuous variables were always scaled (centered and normalized) before entering them as predictors into the models. One of the participants had exceptionally high SCL (more than 5 SDs higher than the mean) and was therefore excluded from all analyses of SCL.

The ROS summary scores were analyzed following the preregistered analysis plan with Condition (nature vs. urban), Time (pre-imagery ROS vs. post-imagery ROS), EINS, and their interactions as fixed effects. Comparison of models with different random effect structures with the anova function in R indicated that the model with random slopes for Condition and Time fitted the data the best, therefore, we included them as the random effects instead of the preregistered random intercept.

For all EDA measures, the efficiency of the stressor tasks was analyzed with Load (baseline vs. stressor), Condition (before nature condition, before urban condition), and their interaction as fixed effects and a random intercept for participants as the random effect.

The amplitude of EDA during the experimental imagery conditions (nature, urban) was analyzed with Condition, Time (5: 1 min sequences during imagery), EINS, and their interactions as fixed effects. A random intercept for participants served as the random effect in the models on SCL and ER-SCR; the model for NS-SCR included additionally the random intercept for Time as a random effect as these random effects structures fitted the data the best. Two participants did not show any ER-SCRs, so their data were excluded from the analysis of ER-SCRs; data from two participants did not include any NS-SCRs during the nature or urban conditions and thus were excluded from the analyses of the amplitudes of NS-SCR (one of the excluded participants was the same in ER-SCR and NS-SCR analyses).

Heart rate (HR) variables were analyzed with Condition, EINS, and their interactions as fixed effects. Recording of HRV needs a relatively long time-window. Therefore, only Environment, EINS, and their interaction were fixed effects in the analyses of HR variables (extracted from the whole 5-min imagery conditions). A random intercept was the random effect. Due to recording failure, the HR data was not obtained from one of the participants. In addition, the PPG data was noisy, and the used HRVtool did not detect all beat-to-beat RR intervals for 24 participants (for an example data, see Supplementary Materials, Supplementary Fig. 1). Therefore, the HR variables during the 5-min imagery could be entirely derived only for 25 participants whose data were entered into the statistical analyses. As an exploratory analysis, the efficiency of the stressor task was analyzed with the same design as the corresponding EDA data. Here, however, 8 of the above-mentioned 25 participants' data lacked RR intervals in one of the four conditions (nature-baseline, nature load, urban baseline, urban load), and one participant lacked it in two conditions. It was, however, possible to enter their data from the conditions with full data into models examining the effects of the stressor task because linear mixed-effect models can handle data that has empty cells.

Because the analyses of subjective ratings showed that nature words were liked more than urban words, we added Preference as a covariate (or Preference and its interactions, if they were observed and did not show collinearity) into the original analyses if they showed effects related to the condition. In this way, we explored whether the observed differences in response to nature vs. urban words could be observed after controlling for the influence of preference of the words.

Exploratory analyses using EICS or the difference between EINS and EICS instead of EINS in the models (e.g., Condition x Time x EICS) are reported in Supplementary Materials file.

3. Results

3.1. Induced cognitive stress

First, to verify that the stressor task-induced cognitive stress, we compared electrodermal activity and heart rate variables between baselines and the stressor tasks with the Task (baseline vs. stressor), Condition (before nature imagery vs. before urban imagery), and their interaction as fixed effects. The "before nature imagery" vs. "before urban imagery" conditions refer to the baseline and stressor situations performed immediately before the nature or urban imagery, respectively (Fig. 1). Note, however, that the second baseline and stressor conditions (shown on the right side of Fig. 1) followed the preceding imagery condition and related post-imagery ROS, which may have carry-over effects. The observed results are illustrated in Fig. 2. SCL (Fig. 2A) was higher during the cognitive load induced by the stressor tasks ($M = 7.34$, $SD = 4.9$, 95% CI [6.35, 8.33] than during the baseline ($M = 5.52$ μS, $SD = 4.71$, 95% CI [4.58, 6.47], $F(1,144) = 45.84$, $p < 0.001$. No main effect for Condition, $F(1, 144) = 1.52$, $p = 0.220$) or Condition × Load interaction, $F(1,144) = 0.48$, $p = 0.488$, were detected for SCL. The number of SCRs (Fig. 2B) was higher during the stressor tasks ($M = 16.8$, $SD = 5.3$, 95% CI [15.7, 17.8] than during the baseline ($M = 11.7$, $SD = 7.0$, 95% CI [10.3, 13.1], $\chi 2 = 58.50$, $p < 0.001$, but the main effect of Condition, $\chi 2 = 3.61$, $p = 0.058$, and Condition × Load interaction, $\chi 2 = 2.24$, $p = 0.135$, did not reach statistical significance. Similarly, the

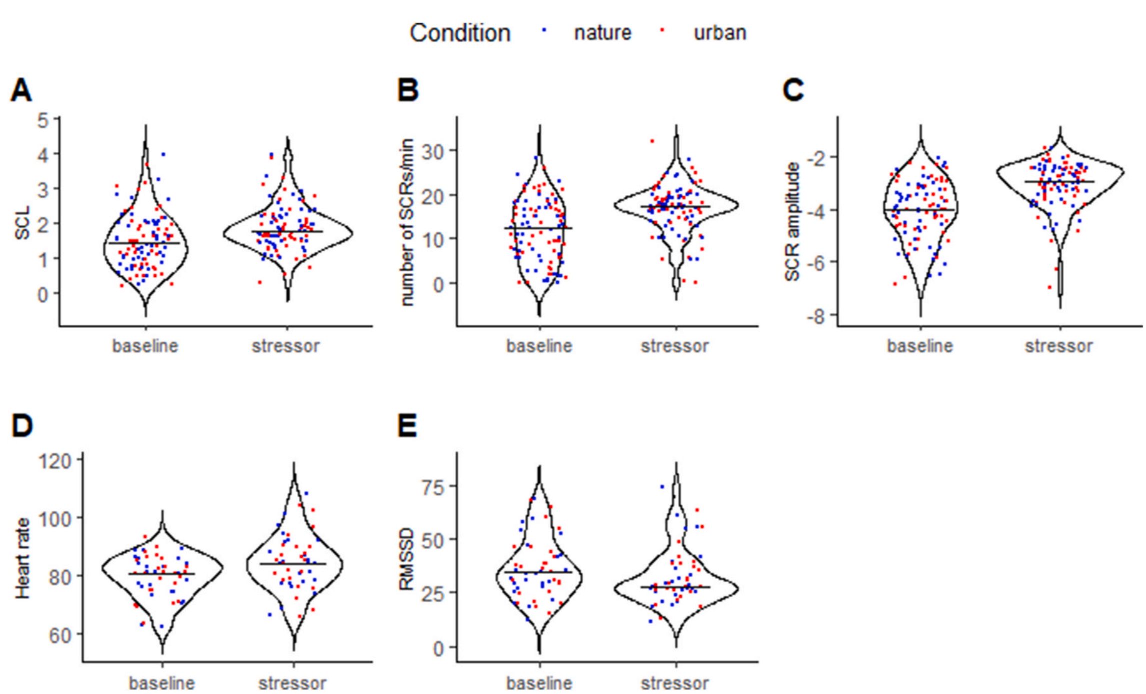

Fig. 2. The observed results of (A) skin conductance level (log(μV)), (B) number of skin conductance responses, (C) amplitude of skin conductance responses (log (μV)), (D) heart rate, and (E) RMSSD during baseline and stressor tasks. The dots represent individual participants' results, with the blue dots referring to measurements before the nature condition and the red dots referring to measurements before the urban condition. The vertical lines inside the violins show the median. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

amplitude of SCRs (Fig. 2C) was higher during the stressor tasks (M = 0.06, SD = 0.04, 95% CI [0.05, 0.07], than during the baseline (M = 0.03 μS, SD = 0.03, 95% CI [0.02, 0.03], F(1,147) = 93.11, p < 0.001. The main effect for Condition, F(1,147) = 0.64, p = 0.4255, and the Condition × Load interaction, F(1,147)<0.001, p = 0.999, were not statistically significant. Thus, all EDA measures showed the effectiveness of the cognitive load manipulation.

Heart rate (Fig. 2D) was higher during the stressor task (M = 84.1, SD = 9.5, 95% CI [81.4, 86.8]]) than during the baseline (M = 79.3, SD = 7.2, 95% CI [77.2, 81.3]), F(1,72) = 40.01, p < 0.001. Similarly, RMSSD (Fig. 2E) was larger during the baseline (M = 36.4, SD = 14.6, 95% CI [32.4, 40.4]) than during the stressor task (M = 32.2, SD = 13.3, 95% CI [28.4, 36.0]), F(1,72) = 14.69, p < 0.001. There were no main effects of Condition (F(1,72) = 0.10, p = 0.757 and F(1,72) = 0.01, p = 0.914, for heart rate and RMSSD, respectively) or Condition × Load interactions (F(1,72) = 0.22, p = 0.642 and F(1,72 = 0.503, p = 0.480, for heart rate and RMSSD, respectively). Thus, the physiological measures were sensitive to the effects of the stressor task. In addition, there were no significant differences in the physiological measures during baseline or stressor task depending on whether they were performed before nature or urban imagery.

3.2. Rating scales

3.2.1. Descriptive statistics of the covariates and correlations

The participants liked the nature words (M = 5.90, SD = 0.84) more than the urban words (M = 4.20, SD = 1.25), t(49) = -8.08, p < 0.001, d = −1.142. However, the effort required in imagery did not statistically differ between nature (M = 2.82, SD = 1.48) and urban (M = 3.06, SD = 1.52) words, t(49) = 1.60, p = 0.116, d = 0.226).

The mean EINS score was 20.9 (SD = 4.12, min = 9, max = 28). It correlated positively with the preference for nature words, r = 0.41, p = 0.003, but not with the preference for urban words, r = 0.07, p = 0.640. EINS correlated negatively with the effort needed in the imagery of nature words, r = −0.33, p = 0.020, but its' negative correlation with the effort in the imagery of urban words did not reach statistical significance, r = −0.22, p = .134.

3.2.2. Restoration Outcome Scale (ROS)

We tested the hypothesis that imagery of natural words promotes stronger restoration from stress than imagery of urban words, measured with subjective ratings before and after imagery, and that this effect would be moderated by nature connectedness (EINS). The ROS summary scores were analyzed with Condition (nature vs. urban), Time (pre-imagery ROS vs. post-imagery ROS), EINS, and their interactions as fixed effects and a random intercept for participants and time as random effects (Fig. 3A). The results showed a main effect for Time, indicating that the post-imagery ROS scores were higher than the pre-imagery ROS scores, F(1,47) = 29.60, p < 0.001. The Condition × Time interaction shows that the increase of ROS scores was higher in the nature condition than in the urban condition, F(1,48) = 5.45, p = .024, and at the post-imagery ROS nature condition was associated with a higher score than the urban condition, B = 1.58, 95% CI [0.48, 2.69], p = 0.007. EINS did not have any main effect, F(1,48) < 0.01, p = 0.991, or higher order interactions, p-values >0.355. Thus, as hypothesized, the imagery of nature had a larger effect on subjective restoration than the imagery of urban content. However, nature connectedness did not moderate this effect.

After including Preference and its interaction with Time as covariates (Fig. 3B), the Condition × Time interaction was no longer statistically significant, F(1,65) = 1.58, p = 0.213. Preference increased ROS scores, F(1,59) = 10.22, p = .002, and more in the post-imagery ROS than in the pre-imagery ROS, F(1,86) = 19.33, p < 0.001. Thus, after controlling for the preference, the conditions no longer differed in their restorative effects, suggesting that the restorative subjective effect of imagining nature depends on preference.

3.3. Electrodermal activity during imagery

3.3.1. SCL

We hypothesized that mere imagery of nature words promotes stronger restoration than imagery of urban words, which should be observed during imagery as steeper reduction of SCL (and SCR) by nature words than by urban words, and this effect would depend on nature connectedness. Nature condition elicited higher SCL (Fig. 4A; Supplementary Table 1) than urban condition, F(1,1893) = 83.65, p < 0.001, and the SCL decreased as a function Time, F(4, 1893) = 105.85, p < 0.001, but the Condition × Time interaction was not statistically significant, F(4, 1893) = 0.64, p = 0.635. In addition, Time and EINS interacted, F(4, 1893) = 4.74, p < 0.001, reflecting a decrease of SCL when the EINS score increased, particularly in the fifth minute, B = −1.09, 95% CI [−1.15, 1.04], t(1893) = -3.27, p = 0.001. The hypothesis that imagery of nature would result in steeper reduction of SCL than imagery of urban words was not supported. By contrast, imagery of nature in general resulted in higher SCL than imagery of urban words, and this effect did not depend on nature connectedness as we expected.

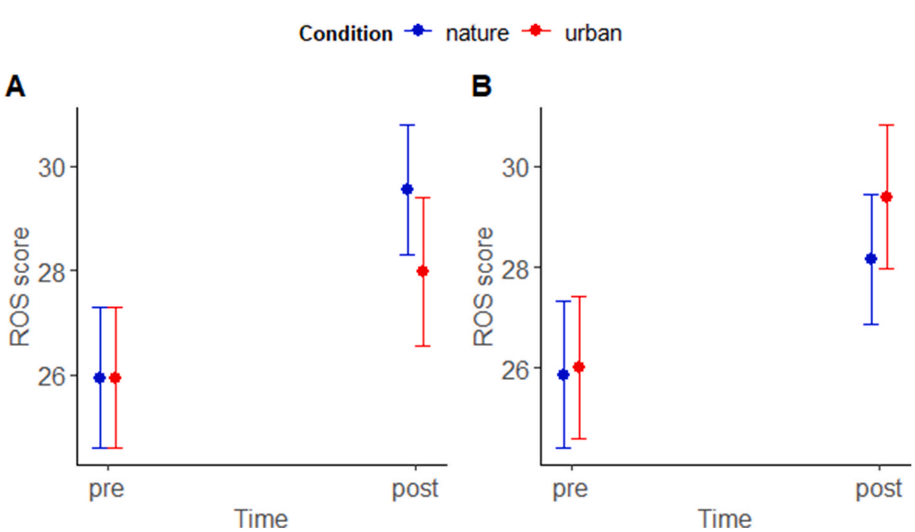

Fig. 3. Modelled results of the Restoration Outcome Scale (ROS) before (pre-imagery) and after (post-imagery) the nature and urban conditions (A) without, and (B) with Preference as the covariate (n = 50).

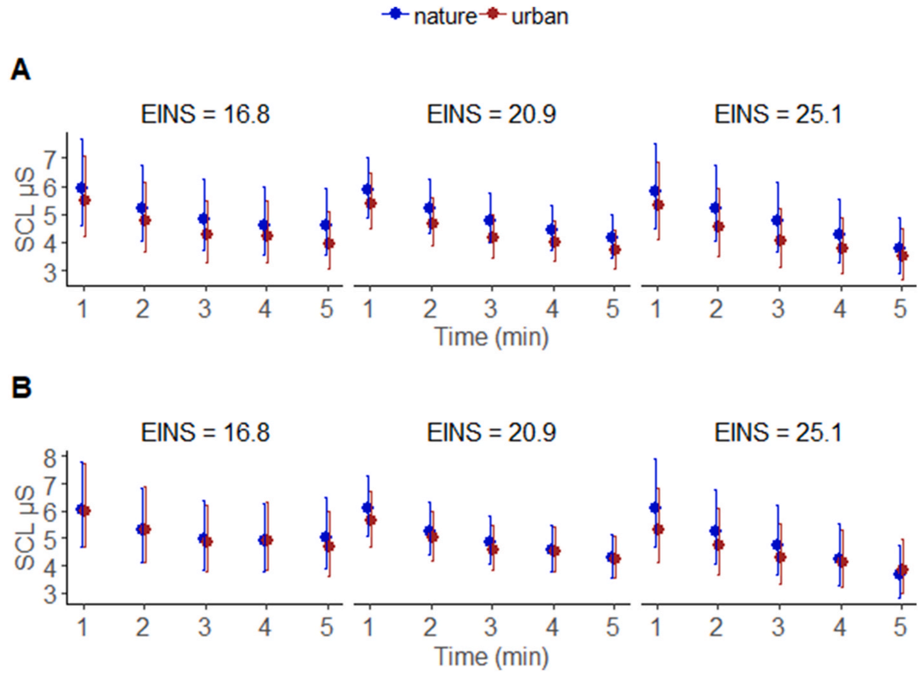

Fig. 4. Modelled skin conductance level (SCL) in nature and urban conditions as a function of time and nature connectedness (EINS) (A) without and (B) with Preference as a covariate. The EINS levels refer to 1 SD below mean, mean, and 1 SD above mean (n = 49).

When Preference with its interactions were added to the model as covariates (Fig. 4B), the SCL amplitudes in the nature condition, on average, were higher than in the urban condition, F(1,1884) = 4.46, p = 0.035. The Time × EINS interaction, F(4, 1873) = 7.66, p < 0.001), and the Condition x Time × EINS interaction were statistically significant, F (4, 1873) = 2.94, p = .019, suggesting that the higher the EINS score, the more the SCL was reduced as time progressed in the nature condition. Analysis of simple effects showed that while participants with mean or high EINS (mean + 1.5 SD) showed higher SCL in the nature condition than in the urban condition during the first minute of imagery (F = 3.87, p = 0.049 and F = 6.97, p = 0.008, respectively), during the last minute the difference between the conditions had vanished (F-values <1, p-values >0.358). Preference increased SCL, F(1,1887) = 9.32, p = .0022, and it interacted with condition, F(1,1891) = 70.44, p < 0.001, showing that while preference did not have an effect in the nature condition, B = −0.05, 95% CI [−0.12, 0.020], t(1879) = -1.39, p = 0.164, it increased SCL in the urban condition, B = 0.12, 95% CI [0.04, 0.21], t(1880) = 2.77, p = 0.006, especially in the 4th and 5th minutes, B = 0.16, 95% CI [0.05, 0.27], p = 0.004, and B = 0.23, 95% CI [0.12, 0.34], p < 0.001, respectively. These results suggest that the higher SCL during nature than urban imagery depended partially on preference (i.e., participants liked nature words more than urban words); when preference was controlled for, participants with medium or high nature connection showed higher arousal of autonomic nervous system for nature than urban words in the beginning of the imagery conditions.

3.3.2. *Event-related skin conductance responses (ER-SCRs)*

Next, we tested whether the presentation of nature vs. urban words differently evoke phasic skin conductance responses. The number of ER-SCRs (Supplementary Table 2) measured 1–5 s after word onset, changed as a function of Time, $\chi^2(4) = 13.53$, p = 0.009. They were the most frequent in response to the words presented during the first minute (M = 0.84/word), after which the frequency decreased to 0.62 - 0.66 per word. Other effects or interactions were not statistically significant (p-values >0.650).

The amplitudes of the ER-SCRs (Supplementary Table 3) did not reveal any difference between nature and urban conditions, F(1,1854) = 0.20, p = .659. Neither were there any effects for Time, F(4, 1854) = 1.81, p = .123, EINS, F(1,46) = 0.15, p = .703, or interactions between any of these variables, p-values >0.201.

3.3.3. *Non-specific skin conductance responses (NS-SCRs)*

The number of NS-SCRs (Supplementary Table 4) measured 6–15 s after the onset of words, decreased after the first minute from about 1.8 responses per word to about 1.3–1.6 responses, $\chi^2(4) = 14.35$, p = 0.006. Other effects for the number of NS-SCRs were not statistically significant.

In contrast to our hypothesis that imagery of nature would reduce arousal more than imagery of urban contents, the amplitudes of NS-SCRs were larger in response to nature words than to urban words, F(1,37) = 5.00, p = .031 (Fig. 5A, Supplementary Table 5). Time, F(4, 1849) = 0.81, p = .519, and EINS, F(1,46) = 0.64, p = .428, did not show main effects. Condition and EINS interacted, F(1,1816) = 5.56, p = .018, showing that the higher the EINS score, the lower the NS-SCR amplitude in the urban condition compared to that in the nature condition. Other interactions were not statistically significant, with p-values >0.610.

The effect of condition on NS-SCRs was no more statistically significant when Preference was added as a covariate (Fig. 5B), F(1,209) = 0.15, p = .704, and the interaction between Condition and EINS was only marginally significant, F(1,1821) = 3.55, p = 0.060. Thus, preference explained why nature words elicited higher NS-SCR amplitude in the previous analysis (without the preference as a covariate): participants were more positively aroused by nature words because they liked them more than urban words. The interactions of Preference could not be added to the model because of high collinearity (e.g., for Condition x Preference, GVIF^(1/(2*Df)) = 4.09, corresponding approximately to standard VIF of 16). The effect of Preference was not statistically significant, F(1,1860) = 1.92, p = 0.166.

3.4. *Heart rate measures during imagery*

The descriptive statistics for heart rate measures are presented in Table 1. Heart rate (HR) was higher in the urban condition than in the nature condition, F(1,23) = 8.87, p = 0.007. RMSSD was higher in the nature condition than in the urban condition, F(1,23) = 10.13, p = 0.004. These results support the hypothesis that imagery of nature

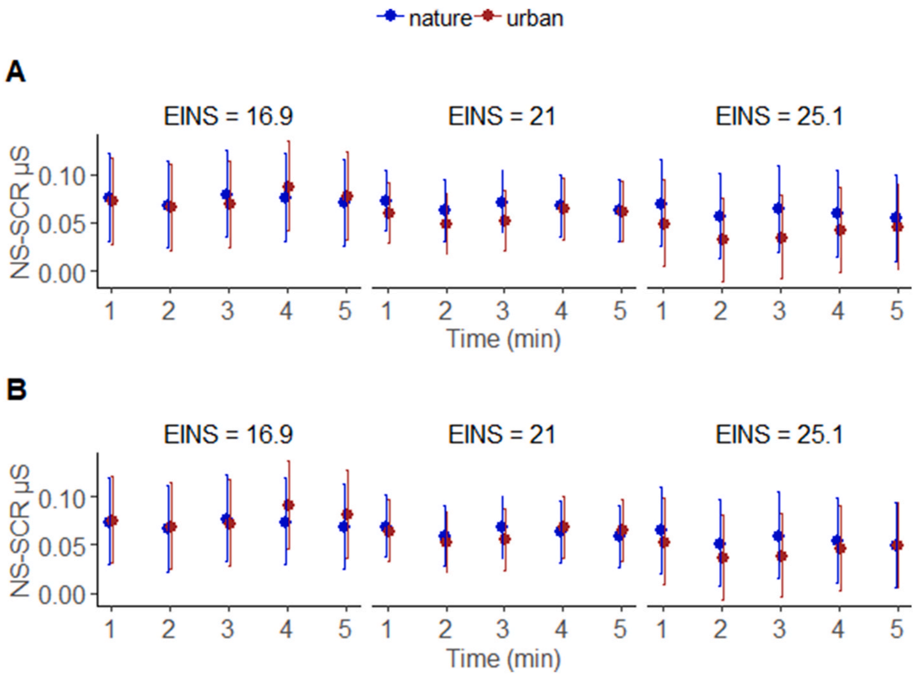

Fig. 5. Modelled non-specific skin conductance responses in nature and urban conditions as a function of time and nature connectedness (EINS) (A) without and (B) with Preference as a covariate. The EINS levels refer to 1 SD blow mean, mean, and 1 SD above mean (n = 48).

Table 1
Descriptive statistics for the heart rate variables during imagery (n = 25).

			95% Confidence Interval				
	Condition	Mean	Lower	Upper	SD	Minimum	Maximum
HR	nature	79.5	76.5	82.5	7.32	67	93
	urban	80.9	77.8	83.9	7.41	67	96
RMSSD	nature	34.1	28.2	40.1	14.44	12.5	72.0
	urban	31.8	26.8	36.8	12.19	14.7	62.6

Note. HR = heart rate, RMSSD = root mean square of the successive differences.

results in stronger restoration than imagery of urban words.

The effect of EINS was not statistically significant for HR, $F(1,23) = 1.05$, $p = 0.316$, or for RMSSD, $F(1,23) = 2.40$, $p = 0.135$. EINS and Condition did not interact in any of the heart rate measures (all p-values >0.24).

When Preference was added to the model examining HR, the effect of HR was statistically significant, $F(1,23) = 5.68$, $p = .026$, but the main effect of preference on heart rate was not statistically significant, $F(1,24) = 0.67$, $p = 0.422$). However, the effect of condition on RMSSD was no more statistically significant after adding preference to the model (1, 23) = 0.6921, $p = .414$, although the main effect of Preference was not significant, $F(1,23) = 1.71$, $p = 0.204$. These results suggest that, independent of nature connectedness, imagery of nature results in stronger restoration than imagery of urban words because nature words are liked more than urban words.

4. Discussion

The present study aimed to test whether the imagery of nature, relying on top-down cognitive processing, has restorative subjective and physiological effects after the induction of cognitive stress and whether such effects depend on individual factors. The results of the study provide support for some of our hypotheses while challenging others.

As hypothesized, we found that the imagery of nature promoted stronger restoration compared to the imagery of urban contents, as measured with subjective ratings by the Restorative Outcome Scale (ROS). This result aligns with the top-down hypothesis that mental imagery can influence emotional states and stress levels, suggesting that mental imagery of nature can induce restorative effects similarly as actual exposure to nature does. This extends previous evidence, which indicated that mental imagery of being in natural environments produces self-reported positive effects and relaxation (Koivisto & Grassini, 2023), to the imagery of a wider variant of natural elements.

Heart rate measures also supported the top-down hypothesis. The main finding of the heart rate recordings was that the heart rate decreased and RMSSD, as a marker of parasympathetic function, increased during imagery of nature, compared to imagery of urban contents. These findings suggest that the participants were more relaxed during the imagery of nature than during the imagery of urban contents.

The results of the electrodermal recordings are complex to interpret because they can reflect either positive or negative emotional arousal (Gross & Levenson, 1997; Kreibig, 2010). The comparison of baseline activity with that during the stressor task indicated that SCL and SCRs increased due to the induced cognitive stress. We expected that if the imagery of nature promotes better restorative effects than the imagery of urban contents, the electrodermal activity should decrease after induced cognitive stress more steeply during the imagery of nature than the imagery of urban contents. To test this, we divided the imagery conditions into 5-min segments. This hypothesis was not, however, supported as none of the EDA variables showed an interaction between the condition and time.

The EDA SCL index measures a person's general level of physiological arousal. We found that the nature condition elicited higher SCL than the urban condition, and that this activity decreased over time similarly in both conditions. Additionally, the amplitudes of non-specific skin conductance responses (NS-SCRs) were larger in response to nature words than to urban words, but time did not influence their amplitudes.

The finding that the amplitudes of EDA increased when imagining nature compared to that during imagining urban contents is not entirely unexpected. EDA may reflect either negative or positive arousal, such as happiness or pleasure (Gross & Levenson, 1997; Kreibig, 2010). Nature was preferred more than urban contents in the present study, and a previous study (Koivisto and Grassini, 2023) has shown that preference predicts relaxation and positive emotional valence and arousal during mental imagery. In the present study, the amplitudes of SCL and to some extent the non-specific SCRs were influenced by participants' preference (i.e., liking) of the to-be-imagined words. Thus, regarding ART (Kaplan, 1995; Kaplan & Kaplan, 1989), the high EDA during imagery of nature may be interpreted as reflecting the phenomenon often referred as "soft fascination" (Kaplan, 1995) or something alike that may be associated with positive emotions toward nature. It could also be related to a higher interest level when producing mental images of natural elements, as natural elements may be perceived as more aesthetically pleasing (Meidenbauer et al., 2020). In the context of the SRT (Ulrich, 1981; Ulrich et al., 1991), the enhanced EDA amplitudes during imagery of nature may reflect the more positive emotions evoked by nature than urban words.

Event-Related Skin Conductance Responses (ER-SCR) represent phasic changes in skin conductance in response to specific events or stimuli. ER-SCRs can be influenced by many factors, including emotional valence, emotional arousal, attention, cognitive load, and surprise or novelty (Boucsein, 2012). In the present study, the number of ER-SCRs (amplitude $\geq$0.05 μS) or their amplitudes were not sensitive to any differences between imagining nature or urban contents. However, the number of ER-SCRs decreased during the time course of the 5-min imagery periods. Repetition of the same stimulus causes habituation and a decrease in SCRs (Dawson et al., 2007). It can be speculated that the reduction in the number of ER-SCRs might be due to habituation, that is, a reduction in response to repeated exposure to words from the same category, or to reduction of attention over time. This might have led to a reduction in physiological arousal and fewer ER-SCRs. Similarly, the number of NS-SCRs decreased over time, but their amplitudes stayed constant. The finding that the amplitudes of NS-SCRs remained stable over time suggests that when NS-SCRs were triggered, their intensity remained constant, whereas the decrease in the frequency of NS-SCRs may have reflected increased fluctuation of attention over time.

The general pattern of results from the subjective and physiological measures supports the hypothesis that mental imagery of nature has restorative effects. Additionally, we hypothesized that the meanings of nature for individuals moderate the effects of imagery, predicting that the stronger the individual's connection to nature, the more the imagery of nature would influence one's restoration. However, this hypothesis is only partially supported by our data. The effect of nature imagery on self-reported restoration (ROS) was not moderated by individual differences in nature connectedness, as measured by the EINS scale. This result contradicts our hypothesis and suggests that individual differences may not influence the restorative effects of nature imagery to the extent we anticipated. Similarly, in a source attribution study (Koivisto et al., 2022), subjective experiences favoring the attribution of an ambiguous sound to nature more than attribution to an industrial environment were not moderated by nature connectedness, although physiological EDA was. However, another study (Koivisto and Grassini, 2023) found that the self-reported positive emotions and relaxation were higher when the participants imagined themselves being in restorative nature environments (e.g., nature park, mountain lake) than in restorative-built environments (e.g., spa, museum), and this effect was larger, the higher the nature connectedness.

The analysis of non-specific skin conductance responses showed that the higher the nature connectedness, the stronger the NS-SCR amplitude in the nature condition compared to that in the urban condition. This finding goes against the prediction that imagery of nature would results in *lower* NS-SCR than imagery of urban contents in highly connected participants. Despite that, the observed effect suggests that individuals' nature connection moderates the top-down effects of nature. It is also in line with a similar top-down effect observed in a previous study (Koivisto et al., 2022) which found that nature connectedness moderates the SCL and SCRs such that the higher the connectedness, the higher the skin conductance was when an ambiguous stimulus was attributed to nature, compared to attribution to a non-natural environment or baseline level. In the present study, the tonic SCL decreased as a function of time, indicating that the autonomic nervous system was becoming less aroused towards the end of the 5-min imagery periods. This reduction in SCL was more pronounced in people who felt a stronger connection to nature. However, when taking personal preferences into account, the link between feeling connected to nature and SCL became clearer: the participants with high or average connection to nature showed in the first minute of imagery larger SCL in response to nature words, compared to urban words, but in the last minutes this difference disappeared. This pattern suggests that the participants with average or higher connection with nature were more (positively) aroused by the nature words than urban words in the early phase of the imagery period, but this effect did not last to the end of the 5-min imagery condition. The other physiological outcome variables which were sensitive to the difference between nature and urban conditions, the heart rate and RMSSD outcome variables, were not influenced by nature connectedness. However, these null effects must be considered cautiously due to the relatively small sample size ($n = 25$) used in the analyses. In addition, the heart rate variables, as well as the subjective ROS, did not allow to track the responses minute-by-minute during imagery, which may explain why they were not sensitive to the effects of nature connection which showed its effects on electrodermal activity most clearly in the beginning of the imagery period.

Interestingly, we found that the restorative effects of nature imagery were due to participants preferring (i.e., liking) the nature words more than the urban ones. When we controlled for this preference, the self-reported restorative effects of the nature and urban conditions did not differ statistically significantly. Similarly, the physiological differences between the imagery of nature versus urban contents were weakened (SCL, HR) or were no longer detected (NS-SCR amplitudes, RMSSD). These findings align with those of Meidenbauer et al. (2020), who, in a large series of experiments, showed that the affective benefits of viewing nature are explained by preference. When the preference or beauty was controlled between nature and urban images, nature's affective benefits disappeared. On the other hand, a previous study on mental imagery of nature (Koivisto and Grassini, 2023) still detected differences, albeit weakened ones, between restorative nature and built environments after accounting for nature connectedness and preference. These findings, along with the present ones, suggest that the restorative effects of viewing or imagining nature are at least partly driven by individual preferences for nature, which is consistent with the constructionist views positing that the meanings and attitudes associated with nature play a significant role in their restorative potential. This does not exclude the possibility that non-threatening nature is intrinsically preferred for evolutionary motives (Ulrich, 1981), leaving room for an evolutionary-constructivist view (Koivisto and Grassini, 2023) in which the preference for nature is based on evolutionary underpinnings, but the environmental preferences, especially related to build or urban environments, can be shaped by individual factors such as meanings and associations grounded on personal experiences.

The generalizability of the results is limitation in the present study. We could not balance the gender distribution, and the sample consisted mostly of females. Thus, we cannot know whether the effects of imagining or of the moderating effects of nature connectedness can be generalized across genders. In addition, the sample of participants was limited mostly to young adults who were university students in a medium-sized Nordic city. Thus, future work is important with more diverse samples to understand replicability of the results across a broader population. One must keep in mind also that in the present study, imagery of nature refers not only to imagery of natural places (e.g., *forest*) but also to particular natural elements which are only a part of natural environments (e.g., *river, rainbow*) and which can be encountered also in some urban settings. The urban words referred to man-made places or objects, which might also be found in nature (e.g., a *factory* can be in the middle of a field on countryside). The words were, however, selected so that the participants in the survey agreed that nature words were more related to nature and the urban words to urban settings. A methodological limitation was that we measured heart rate with photoplethysmography (PPG), a simple, non-invasive, and low-cost optical technique that can detect blood volume changes in the microvascular bed of tissue. However, PPG signal is associated with several weaknesses (Schäfer & Vagedes, 2013), and in the present study, we were able to record a signal of an acceptable quality only from about half of the participants. Despite the extracted indices of HRV from PPG signal have been found to be similar to the same indices when extracted from electrocardiogram signal, the use of electrocardiography could be considered in future studies to obtain a higher quality signal (Pinheiro et al., 2016).

In conclusion, our findings support the role of top-down processes in the restorative effects of nature exposure. To our knowledge, this is the first study to suggest that mental imagery of natural places or other natural elements is associated with higher subjective restoration and physiological benefits compared to the imagery of urban or man-made environments or elements. These findings have practical implications, for example, for psychological therapies. Some applications of therapeutic techniques, such as guided imagery (Nguyen & Brymer, 2018), have successfully included mental imagery of nature or natural elements as part of the therapeutic process. The present results suggest that when access to nature is not possible, the incorporation of nature imagery instead of actual visits to nature may be a potentially valid alternative.

Conflict of interest

We have no conflict of interest to disclose.

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CRediT authorship contribution statement

Mika Koivisto: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Simone Grassini:** Writing – review & editing, Methodology, Conceptualization.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvp.2024.102346.

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