Received: 27 March 2023 | Accepted: 14 October 2023

DOI: 10.1002/pan3.10564

PEOPLE AND NATURE | BRITISH ECOLOGICAL SOCIETY

RESEARCH ARTICLE

# The more the merrier? Perceived forest biodiversity promotes short-term mental health and well-being—A multicentre study

Kevin Rozario[1,2,3,4] | Rachel Rui Ying Oh[2,3] | Melissa Marselle[5] | Erich Schröger[4] | Loïc Gillerot[6,7] | Quentin Ponette[8] | Douglas Godbold[9,10] | Daniela Haluza[11] | Katriina Kilpi[12] | Dagmar Müller[4] | Urte Roeber[4] | Kris Verheyen[6] | Bart Muys[7] | Sandra Müller[13] | Taylor Shaw[13] | Aletta Bonn[1,2,3]

[1]Institute of Biodiversity, Friedrich Schiller University Jena, Jena, Germany; [2]Department of Ecosystem Services, Helmholtz Centre for Environmental Research—UFZ, Leipzig, Germany; [3]German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Leipzig, Germany; [4]Wilhelm Wundt Institute for Psychology, Leipzig University, Leipzig, Germany; [5]School of Psychology, Environmental Psychology Research Group, University of Surrey, Guilford, UK; [6]Forest & Nature Lab, Department of Environment, Ghent University, Ghent, Belgium; [7]Division of Forest, Nature and Landscape, Department of Earth and Environmental Sciences, KU Leuven, Leuven, Belgium; [8]Department of Environmental Science, Earth and Life Institute, Université catholique de Louvain, Louvain-la-Neuve, Belgium; [9]Institute of Forest Ecology, University of Natural Resources and Life Sciences (BOKU), Vienna, Austria; [10]Department of Forest Protection and Wildlife Management, Mendel University in Brno, Brno, Czech Republic; [11]Department of Environmental Health, Center for Public Health, Medical University of Vienna, Vienna, Austria; [12]BOS+, Melle, Belgium and [13]Faculty of Biology, Chair of Geobotany, University of Freiburg, Freiburg, Germany

**Correspondence**
Kevin Rozario
Email: kevin.rozario@idiv.de

**Funding information**
Biodiversa+, Grant/Award Number: DFG 428795724; German Research Foundation

**Handling Editor:** Kathryn Williams

## Abstract

1. Forests can foster mental health and well-being. Yet, the contribution of forest biodiversity remains unclear, and experimental research is needed to unravel pathways of biodiversity–health linkages. Here, we assess the role of tree species richness, both actual and perceived, and how stress reduction and attention restoration can serve as potential mediating pathways to achieve positive mental health and well-being outcomes.
2. We conducted an experimental, multicentric field study in three peri-urban forests in Europe, employing a mixed design with 223 participants, that comprised 20-min stays in forests with either low, medium or high tree species richness or a built control. Participants' short-term mental health and well-being and saliva cortisol as a biomarker of stress were measured before and after the intervention.
3. Forest visits for 20 min were found to be beneficial for participants' short-term mental health, short-term mental well-being, subjective stress, subjective directed attention and perceived restorativeness compared with a built environment. No differences were found for the physiological stress indicator saliva cortisol, which decreased in both the forest and the built environments.
4. Increased perceived biodiversity—possibly linked to structural forest attributes—was significantly associated with well-being outcomes, while no association was found for differences in actual tree species richness. Structural equation

modelling indicates that higher levels of perceived biodiversity had an indirect effect on short-term mental health and well-being through enhancing perceived restorativeness.

5. While we found no evidence of actual tree species richness effects, perceived biodiversity was associated with positive short-term mental health and well-being outcomes. Understanding these biodiversity–health linkages can inform conservation management and help develop effective nature-based interventions for promoting public health through nature visits.

**KEYWORDS**

attention restoration, Dr. FOREST, forest diversity, mental health and well-being, perceived biodiversity, stress reduction, structural equation modelling, tree species richness

## 1 | INTRODUCTION

Nature experiences can confer a suite of mental health and well-being benefits through reducing many of the stresses associated with urban living (Bowler et al., 2010; Keniger et al., 2013; Marselle, Warber, & Irvine, 2019). Studies suggest that time spent in forests promotes mental health, that is the absence of symptoms associated with psychological conditions such as anxiety or depression (Bielinis et al., 2020; Wen et al., 2019; Zabini et al., 2020), as well as mental well-being, that is a person's emotional state (Cervinka et al., 2020; Nghiem et al., 2021). More recently, studies conducted during the global COVID-19 pandemic have demonstrated that nature visits are an effective nature-based coping mechanism (Berdejo-Espinola et al., 2021). In the German city of Bonn, for instance, strong increases in the number of forest visits were observed during the first COVID-19 lockdown (Derks et al., 2020), while a study from the United Kingdom found that perceived access to green spaces and private gardens emerged as protective factors for self-reported psychological and physical well-being (Poortinga et al., 2021). Natural environments high in biodiversity, that is the variability among living organisms within species, between species and of ecosystems (United Nations, 1992), provide additional benefits for people's mental health and well-being compared with those lower in biodiversity (see reviews by Hedin et al., 2022; Lovell et al., 2014; Marselle, Martens, et al., 2019). Previous studies, however, have been largely correlational, challenging the ability to draw causal conclusions about the effects of biodiversity. We therefore need to clarify whether more biodiverse environments provide greater mental health and well-being benefits and the pathways through which this might occur.

There are two ways to measure biodiversity when assessing its effect on mental states: actual and perceived biodiversity. Actual biodiversity refers to the empirical measurement of biological variations in a specific location (e.g. species richness, metrics of structural or functional diversity). Perceived biodiversity is a person's subjective assessment of the biodiversity they think is present in an environment (e.g. Fuller et al., 2007), and is commonly captured through self-report measures (e.g. Dallimer et al., 2012; Fuller et al., 2007; Marselle et al., 2016). Studies report a good, general concordance between actual and perceived biodiversity (Fuller et al., 2007; Gao et al., 2019; Gonçalves et al., 2021; Johansson et al., 2014; Lindemann-Matthies et al., 2010; Meyer-Grandbastien et al., 2020; Simkin et al., 2021; Southon et al., 2018), yet the accuracy of lay people's biodiversity assessments does not allow for conflating both constructs (Austen et al., 2021; Dallimer et al., 2012). Compared with actual biodiversity, perceived biodiversity has been shown to be a stronger predictor of mental well-being (Cameron et al., 2020; Dallimer et al., 2012; Schebella et al., 2019).

For forest ecosystems, several studies addressed the relationship between biodiversity and mental health and well-being. These studies assessed the influence of actual forest biodiversity (Chiang et al., 2017; Foo, 2016; Johansson et al., 2014; Lee et al., 2018; Simkin et al., 2020; Wei et al., 2022; Wolf et al., 2017), perceived forest biodiversity (Nghiem et al., 2021) or a combined assessment of both (Johansson et al., 2014). Even though there were positive forest biodiversity effects in most of these studies, evidence is yet insufficient to identify decisive forest biodiversity indicators that drive mental health and well-being benefits. This is because of the heterogeneity in methodological approaches (experimental vs. correlational, field vs. laboratory), study designs (between-subjects vs. within-subjects), measurements of forest biodiversity (actual vs. perceived biodiversity) as well as the operationalisation of forest biodiversity (single biodiversity indicators such as species richness vs. holistic biodiversity inventories; Beute et al., 2020; Hedin et al., 2022; Nguyen et al., 2021). In natural settings other than forests, positive effects of actual species richness on mental health and well-being were found (e.g. Cox et al., 2017; Dallimer et al., 2012; Mavoa et al., 2019; Methorst et al., 2021), rendering species richness the most likely candidate in explaining psychological benefits through biodiversity. The particular role of species richness in forests, however, is largely unknown.

### 1.1 | Mediating pathways linking forest biodiversity to mental health and well-being

*How* contact with biodiversity leads to better mental health and well-being outcomes is not yet well understood. Marselle et al. (2021)

proposed that contact with biodiversity can deliver health benefits or risks through four mechanistic pathways: reducing harm, increasing harm, restoring capacities and building capacities. Of particular interest for this study is the 'restoring capacities' domain, which refers to the recovery of adaptive capabilities that may have been diminished through the demands of dealing with everyday life (Marselle et al., 2021). Over time, the lack of restoring these adaptive capacities can result in poor mental and physical health (von Lindern et al., 2017). Environments that facilitate restoration of these capacities are called restorative environments. There are two main theories of restorative environments: Stress Recovery Theory (SRT; Ulrich, 1983; Ulrich et al., 1991) and Attention Restoration Theory (ART; Kaplan, 1995; see Box 1). With regard to SRT, studies have found that stress recovery is strongest when people are exposed to medium (Chiang et al., 2017; Lindemann-Matthies & Matthies, 2018) or high biodiversity environments (Lee et al., 2018; Pettersson et al., 2021; Schebella et al., 2019). Effects were found for both subjective (Schebella et al., 2019) and physiological stress (e.g. Pettersson et al., 2021). Yet, studies on the mediating effect of stress on the relationship between biodiversity and mental health and well-being are lacking. Regarding ART, there is evidence suggesting that biodiversity increases perceived restorativeness (Gonçalves et al., 2021; Scopelliti et al., 2012; Simkin et al., 2020) and restores directed attention (Chiang et al., 2017). Both actual (Carrus et al., 2015) as well as perceived biodiversity (Fisher et al., 2021; Marselle et al., 2016; Nghiem et al., 2021) have been found to indirectly promote mental well-being by increasing perceived restorativeness. Of these studies, only Nghiem et al. (2021) focussed on a forest setting: Perceived animal species richness indirectly increased mental well-being, by elevating perceived restorativeness, though no significant effects were reported for perceived plant diversity (Nghiem et al., 2021). One central question, however, remains unaddressed with ART: While perceived restorativeness as a mediating pathway was investigated by some studies (e.g. Nghiem et al., 2021), no study has tested whether biodiversity indirectly increases mental health and well-being via directed attention. In addition, in the light of the particular importance of perceived biodiversity in fostering mental health and well-being, a double mediation model (i.e. actual biodiversity → perceived biodiversity → stress recovery/attention restoration → mental health and well-being) might be most accurate in describing biodiversity—mental health and well-being relationships. No study, to date, looked

**BOX 1 SRT and ART and their relation to mental health, mental well-being and biodiversity**

SRT (Ulrich, 1983; Ulrich et al., 1991) states that natural environments with certain visual properties benefit mental health by facilitating recovery from stress, measured as reduced physiological and psychological stress (Ulrich, 1983; Ulrich et al., 1991). Stress and mental health and well-being are highly correlated (e.g. Fiksdal et al., 2019; Qi et al., 2016) with excess stress deteriorating mental health (e.g. Larsson et al., 2008). Visual properties of nature that foster stress recovery are moderate-to-high levels of complexity, a focal point, moderate-to-high levels of depth, a rather homogeneous surface texture, deflected vista, water and the lack of threat (Ulrich, 1983). In the SRT, biodiversity is considered an aspect of complexity (Ulrich, 1983).

According to ART (Kaplan, 1995), certain environmental experiences foster restoration of the ability to direct attention (Kaplan, 1995). Attention and mental health and well-being are inevitably intertwined, with attentional deficits being listed among core symptoms of, for example attention deficit hyperactivity disorder (ICD-11; World Health Organization, 2022), and a cause of, for example anxiety (McNally, 2019; Mogg & Bradley, 2018). Two counterparts of attention have to be distinguished, namely directed attention and involuntary attention (James, 1890). Directed attention is effortful, requiring cognitive effort to focus and concentrate. As such, directed attention is a limited cognitive resource, which can become depleted through demands in our everyday lives. In contrast, involuntary attention does not require top-down control mechanisms, making it limitless. Engaging effortless, involuntary attention enables restoration of effortful, directed attention through the reciprocal nature of these attentional subsystems (Kaplan, 1995). Four experiential qualities of nature, referred to as perceived restorativeness, are said to encourage effortless, involuntary attention (Kaplan, 1995):

1. *fascination*, evoked by nature's attracting sensory cues that hold the viewer's attention without cognitive effort,
2. a sense of *being away*, both physically and mentally, from the cognitive demands of everyday life,
3. *extent*, that is an environment is perceived as a coherently organised while providing a sufficient scope to invite for further exploration and
4. *compatibility* between environmental characteristics and a person's needs.

Perceived restorativeness is intermediate in character, occurring between one's experience of an environment and restored directed attention (Hartig, 2011). Accordingly, increases in perceived restorativeness have previously been shown to align with better directed attention (Barbiero et al., 2021; Berto, 2005). Biodiversity may benefit attention restoration as it contains stimuli likely to support all four experiential qualities of perceived restorativeness (Marselle et al., 2016, 2021; Marselle, Warber, et al., 2019). For instance, higher species richness might lead to increased experience of fascination by offering a variation of sensory cues.

at mediating effects of perceived biodiversity in linking actual biodiversity and mental health and well-being.

### 1.2 | Aim of the present study

The present study investigates the effect of actual and perceived forest diversity on short-term mental health and well-being according to the conceptual framework by Marselle et al. (2021). We followed an experimental approach across three study sites in three countries (Austria, Belgium and Germany) and exposed participants to stands of differing tree species richness, which operationalised different levels of biodiversity. We also tested the association of tree species richness and measures of perceived forest biodiversity to assess the relatedness of the two constructs. We hypothesise that:

1. Exposure to forest environments promotes short-term mental health, short-term mental well-being, stress recovery and attention restoration in comparison to exposure to a built environment.
2. Higher levels of actual forest diversity, that is tree species richness, elicit increased short-term mental health and well-being, stress recovery and attention restoration.
3. There is a positive relationship between actual tree species richness and perceived forest biodiversity.
4. Higher levels of perceived biodiversity elicit increased short-term mental health and well-being, stress recovery and attention restoration.
5. The effect of actual tree species richness on short-term mental health and well-being is mediated by perceived forest biodiversity and stress recovery, as well as attention restoration.

## 2 | MATERIALS AND METHODS

### 2.1 | Study design

We conducted a multicentre study in three cities across Europe in September 2021: Leipzig (Germany, $n=70$ participants), Vienna (Austria, $n=66$) and Louvain-la-Neuve (Belgium, $n=87$). The study aimed to clarify how forest diversity (*i*) influences mental health and well-being (see the present study) and subjective thermal comfort (see Gillerot et al., 2024). A total of 223 participants (72% females) between 18 and 60 years of age ($M=35.58$, $SD=12.67$) took part. Prior to the study, we conducted a power analysis for small- and medium-sized effects using G-Power (Faul et al., 2007). This indicated that a sample size of 136–824 participants is required to detect medium- or small-sized effects with a statistical power of 0.80 using mixed ANOVAs ($\alpha=0.05$). The study was conducted in accordance with the Declaration of Helsinki and approved by the institutional ethical committees of Leipzig University (reference: 2021.05.13_eb_91), the Medical University Vienna (reference: 01509146/2021) and the University of Louvain (reference: 2021-30).

Participants were recruited through the social media platforms Facebook and Instagram as well as word of mouth. Prior to participation, all participants were subjected to a phone screening. Eligibility criteria were good physical and mental health, normal or corrected-to-normal vision and hearing, a body mass index between 18 and 30, and no consumption of medication targeted at the central nervous system (e.g. antidepressants). As we measured saliva cortisol as a biomarker of stress, we asked participants to refrain from smoking and consuming caffeinated beverages on the day of data collection. Participants were also instructed not to eat, drink or brush their teeth 30 min prior to the study. We compensated participants with a forest bathing workshop upon conclusion of the study and/or course credits. Each participant had the option to complete the survey either in German, English, French or Dutch, and written informed consent was provided prior to participation.

### 2.2 | Study sites

Forest patches with differing tree species richness (1, 2 and >4 species) were selected with the help of local forest management agencies, resulting in low, medium and high tree species richness conditions. Study sites were considered eligible if they contained a visual scenery of the targeted tree species richness from the participants' point of view on their seats (see Figure 1). The monoculture species differed among cities and were chosen according to their local dominance: *Fraxinus americana* (white ash, Leipzig), *Fagus sylvatica* (common beech, Vienna) and *Pinus sylvestris* (Scots pine, Louvain-la-Neuve). The species composition for the medium and high diversity patches is presented in Table 1. Patches in each of the three sites were within the same forest complex; that is, all patches were within a radius of approximately 2 km. Differences in altitude were avoided with only the monospecific patch in Vienna being situated at a slight descending slope. Access permissions to forests were given by local authorities. Built control sites contained no trees and as little vegetation as possible (see Figure 1).

### 2.3 | Procedure

Data collection took place on three weekends in September 2021 (one weekend per city). To control for light conditions, we invited participants between 09:15 AM and 1:30 PM with an average study duration of 2 h. A maximum of 20 participants were invited per time slot (two time slots in the morning (9:15 and 10:15 AM) and in the afternoon (12:30 and 1:30 PM)). We first asked participants to assemble at a central meeting point (CMP) outside the forest (see Figure 2 for an overview of the study flow). CMPs had to be (i) a neutral space wherein neither urban greenery nor urban infrastructure was dominant over the other and (ii) equidistant from the forest and built patches. At the CMP, participants were welcomed, baseline paper–pencil questionnaires were completed and a saliva sample was taken. Participants were randomly assigned


FIGURE 1 Visual sceneries at Louvain-la-Neuve (Belgium). From left to right and top to bottom: low (a), medium (b), high (c) forest diversity and built control (d).

to one of the three forest conditions (low, medium and high) or a built control condition. Between-subject ANOVAs satisfied expectations of group equivalence in preintervention measures, indicating that randomisation was successful (all $p$ ranging between 0.14 and 0.84). Participants were brought to the study sites by a van, the windows of which were covered with opaque, yet slightly transparent tablecloth to avoid pre-exposure to the forest or built environments. Upon arrival at the study sites, participants were invited to sit on a chair and to concentrate on what could be *seen* and *heard*, but not to focus exclusively on either one. No further instructions were given. Chairs were positioned so that participants could best capture the tree species or built scenario representative of the experimental condition. The duration of the intervention was 20 min (Kotera et al., 2020; Nghiem et al., 2021). Immediately after the intervention, participants completed the second set of paper–pencil questionnaires on site (see Supporting Information S9 for the entire pre and postintervention survey). A second saliva sample was taken 15 min after the intervention ended. Participants were then debriefed about the study objectives.

## 2.4 | Measures

For a detailed overview of all measures with definitions and potential values, see Table 2.

### 2.4.1 | Predictor variables

*Forest diversity*

*Actual forest diversity* was operationalised using tree species richness (i.e. the number of tree species within the participant's visual scenery).

*Perceived forest biodiversity* was assessed through three subjective measures in the postintervention questionnaire. First, perceived tree, plant and bird species richness were assessed with one item each, following the methodology of Fuller et al. (2007) (i). Second, the Biodiversity Experience Index (BEI; Gyllin & Grahn, 2005), a compound value that encompasses participant's judgements of plant and animal species richness and how wild and varied an environment is perceived as, was assessed (ii). Third,

**TABLE 1** Tree species compositions of the forest patches in the visual sceneries from the participant's perspective.

| | Biodiversity condition | | | |
|---|---|---|---|---|
| | Tree species richness | | | |
| | Built (control) | Low (mono) | Medium (2 species) | High (4–5 species) |
| *Leipzig, Germany*: Leipziger Auwald | –– | *Fraxinus americana* | *Fraxinus excelsior*<br>*Acer pseudoplatanus* | *Fraxinus excelsior*<br>*Acer pseudoplatanus*<br>*Quercus robur*<br>*Tilia cordata* |
| *Vienna, Austria*: Wienerwald | –– | *Fagus sylvatica* | *Fagus sylvatica*<br>*Pseudotsuga menziesii* | *Fagus sylvatica*<br>*Carpinus betulus*<br>*Fraxinus excelsior*<br>*Quercus robur*<br>*Larix decidua* |
| *Louvain-la-Neuve, Belgium*: Bois de Lauzelle | –– | *Pinus sylvestris* | *Pinus sylvestris*<br>*Betula pendula* | *Pinus sylvestris*<br>*Betula pendula*<br>*Quercus robur*<br>*Castanea sativa*<br>*Corylus avellana* |

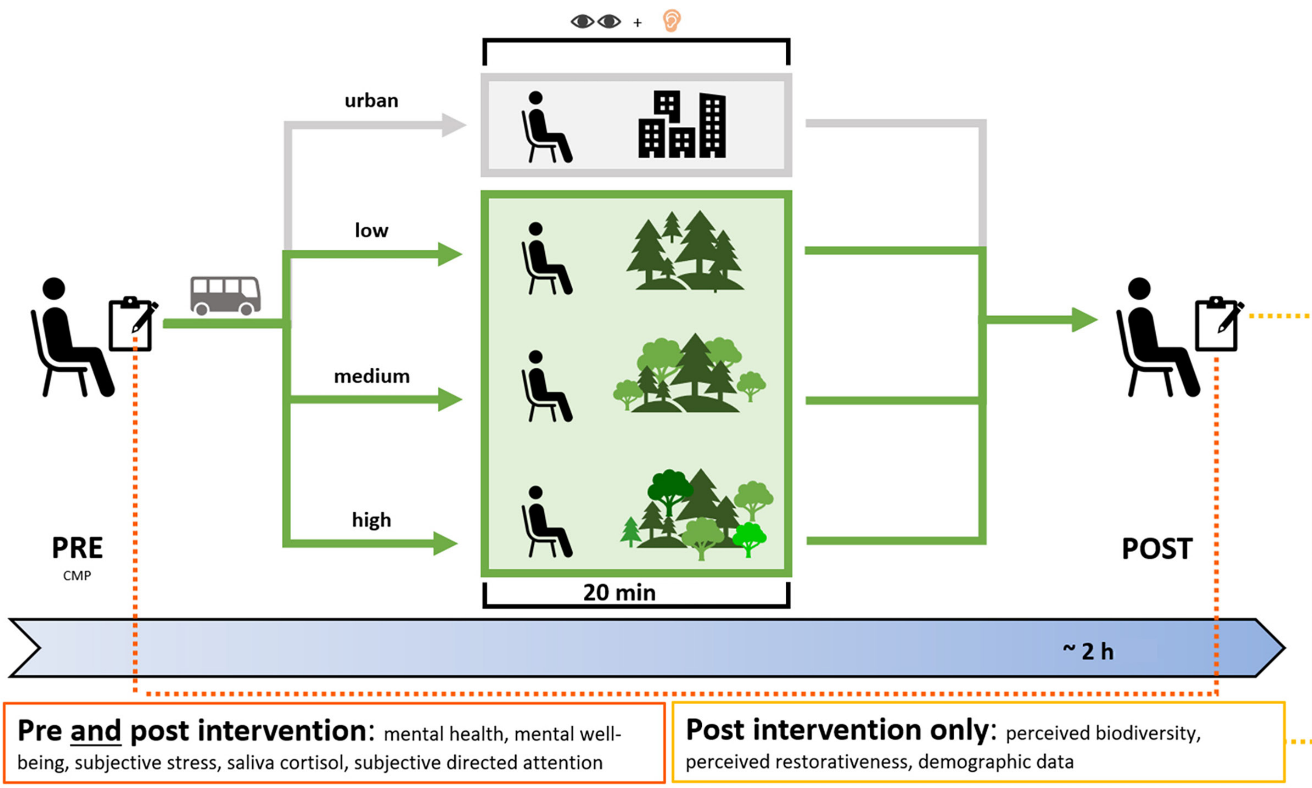


**FIGURE 2** Overview of the study design. CMP, central meeting point; forest diversity: low = monoculture, medium = 2 tree species mix, high = 4–5 tree species mix; short-term mental health: anxiety; short-term mental well-being: positive and negative affect.

perceived overall biodiversity was assessed by asking participants how biodiverse they thought the environment they sat in was (iii). Measures (i) and (ii) ask for the perception of particular biodiversity indicators while with measure (iii) we followed recommendations from Marselle et al. (2015) and enabled participants to rate biodiversity based on their subjective understanding of what biodiversity is.

### 2.4.2 | Outcome measures

*Short-term mental health and well-being*

We measured both mental health, that is the absence of symptoms associated with psychological conditions, as well as mental well-being, that is the participant's emotional state. Following other studies, we assessed anxiety to represent short-term mental

TABLE 2 Description of variables and indicators with potential values and the time of measurement.

| | Variable | Indicator(s) | Description | Potential values/categories | Time (pre/ postintervention) | References |
|---|---|---|---|---|---|---|
| Predictors | Actual forest diversity | Tree species richness | Number of tree species present in the participants' field of vision | Low (1 species), medium (2 species), high (>4 species) | Pre | See, e.g. Wolf et al. (2017) |
| | Perceived forest biodiversity | Perceived overall biodiversity | Participants' estimations of the environment's overall biodiversity; questionnaire/single item on a visual analogue scale (VAS) | 0 = 'no biodiversity'–100 = 'extremely biodiverse' | Post | — |
| | | Biodiversity Experience Index (BEI) | Participants' experience of biodiversity; questionnaire/compound value derived from 4 5-point Likert scale items on (i) perceived plant and (ii) animal species richness and how (iii) wild and iv) varied participants thought the environment was; response options: 1 = 'little' to 4 = 'much'; Formula: $\frac{\sum_{i=1}^{n}(\mathrm{FL}_i \cdot R_i)}{\sum_{i=1}^{n}\mathrm{FL}_i}$ with $n = 4$ (number of items), $\mathrm{FL}_i$ = factor loading of each item, $R_i$ = item score; factor loadings per item: perceived plant species richness: 0.81, perceived animal species richness: 0.66, wild = 0.76, varied = 0.55 | 1 = little experienced biodiversity–5 = much experienced biodiversity | Post | Gyllin and Grahn (2005) |
| | | Perceived tree species richness | Participants' estimations of tree species richness in the environment; questionnaire/single item on a 5-point Likert scale | 1 = 1 tree species–5 = 5 tree species | Post | Fuller et al. (2007) |
| | | Perceived plant species richness | Participants' estimations of plant species richness in the environment; questionnaire/single item on a 5-point Likert scale | 1 = 1 plant species–5 = >15 plant species | Post | Fuller et al. (2007) |
| | | Perceived bird species richness | Participants' estimations of bird species richness in the environment; questionnaire/single item on a 5-point Likert scale | 1 = 1 bird species–5 = >15 bird species | Post | Fuller et al. (2007) |
| Outcomes | Short-term mental health (absence of symptoms of psychological conditions) | State anxiety (STAI) | Symptoms associated with generalised anxiety disorder; momentary 'feelings of tension and apprehension' (Spielberger et al., 1971, p. 2); questionnaire with 20 4-point Likert scale items; response options: 1 = 'not at all' to 4 = 'very much so' | 20 = low state anxiety–80 = high state anxiety | Pre & post | Spielberger et al. (1971) |
| | | Δ state anxiety | Difference between postintervention and preintervention anxiety (post–pre) | — | — | — |
| | Short-term mental well-being (emotional state) | Positive affect (PANAS) | Emotional well-being; momentary tendencies of positive emotions; questionnaire with 10 5-point Likert scale items; response options: 1 = 'very slightly or not at all' to 5 = 'extremely' | 10 = low positive affect–50 = high positive affect | Pre & post | Watson et al. (1988) |
| | | Δ positive affect | Difference between postintervention and preintervention positive affect (post–pre) | — | — | — |
| | | Negative affect (PANAS) | Emotional well-being; momentary tendencies of negative emotions; questionnaire with 10 5-point Likert scale items; response options: 1 = 'very slightly or not at all' to 5 = 'extremely' | 10 = low negative affect–50 = high negative affect | Pre & post | Watson et al. (1988) |
| | | Δ negative affect | Difference between postintervention and preintervention negative affect (post–pre) | — | — | — |

| | Variable | Indicator(s) | Description | Potential values/categories | Time (pre/ postintervention) | References |
|---|---|---|---|---|---|---|
| Mediators | Stress | Subjective stress | Subjective perception of being stressed; questionnaire/single item on a visual analogue scale (VAS) | 0 = 'not stressed at all'–100 = 'extremely stressed' | Pre & post | See, e.g. Schebella et al. (2019) |
| | | Δ subjective stress | Difference between postintervention and preintervention subjective stress (post–pre) | — | — | — |
| | | Saliva cortisol | Biomarker of stress; reflects activity of the hypothalamic–pituitary–adrenal axis | Inter- and intraindividual differences; diurnal course | Pre & post | See, e.g. Lee et al. (2018) |
| | | Δ saliva cortisol | Difference between postintervention and preintervention saliva cortisol levels (post–pre) | — | — | — |
| | Attention | Perceived restorativeness of the environment (PRS) | Subjective perception of the environment's restorative potential according to ART; questionnaire with 16 7-point items; response options: 0 = 'not at all' to 6 = 'completely' | 0 = low perceived restorativeness of the environment–6 high perceived restorativeness of the environment | Post | Hartig et al. (1997) |
| | | Perceived restorativeness of the soundscape (PRSS-SF) | Subjective perception of the soundscapes' restorative potential according to ART; questionnaire with 5 7-point items; response options: 0 = 'not at all' to 6 = 'completely' | 0 = low perceived restorativeness of the soundscape–6 high perceived restorativeness of the soundscape | Post | Uebel et al. (2021) |
| | | Subjective directed attention | Subjective perception of the ability to direct the attentional focus; questionnaire with 7 4-point Likert scale items; response options 1 = 'disagree' to 4 = 'agree' | 7 = low subjective directed attention–28 = high subjective directed attention | Pre & post | Adapted from Derryberry and Reed (2002) |
| | | Δ subjective directed attention | Difference between postintervention and preintervention subjective directed attention (post–pre) | — | — | — |

Abbreviations: ART, Attention Restoration Theory; PANAS, positive and negative affect schedule; PRS, Perceived Restorativeness Scale; PRSS-SF, perceived restorativeness soundscape scale—short form; STAI, state–trait anxiety inventory.

health (Fisher et al., 2021; Wolf et al., 2017), along with positive and negative affect to represent short-term mental well-being (Fisher et al., 2021; Marselle et al., 2016; Nghiem et al., 2021; Wolf et al., 2017).

*Short-term mental health*

Momentary levels of anxiety were measured via the state version of the state–trait anxiety inventory (STAI; Spielberger et al., 1971). The STAI comprises 20 items targeting momentary tendencies for 'feelings of tension and apprehension' (Spielberger et al., 1971, p. 2; e.g. 'I feel anxious'). Before and after the intervention, participants were asked to indicate how much each item applied to their current state. For each participant and time point (pre/post), a sum score of all 20 items was calculated. Cronbach's $\alpha$ values (see, e.g. Tavakol & Dennick, 2011) of 0.85 for the pre- and 0.91 for the postintervention measurement imply good-to-excellent internal consistency of the scale.

*Short-term mental well-being*

We quantified positive and negative affect through the positive and negative affect schedule (PANAS; Watson et al., 1988). The PANAS consists of 20 items, with 10 items emphasising positive and 10 items emphasising negative affect (e.g. 'interested' for positive affect or 'guilty' for negative affect). Before and after the intervention, participants rated their current emotional state on all 20 items. Internal consistency for positive affect was good with Cronbach's $\alpha$ values of 0.84 (pretest) and 0.87 (post-test), yet reliability of negative affect was good for post-test scores only ($\alpha = 0.82$) while pretest scores showed 'questionable' internal consistency ($\alpha = 0.63$; Hair et al., 2010). Due to broad acceptance and use of the PANAS and good internal consistency of the scale in published literature (see, e.g. Marselle et al., 2016 with Cronbach's $\alpha$ ranging from 0.82–0.87 for negative affect), the relatively low reliability scores in our data might reflect true variation in items measuring negative affect at the preintervention level rather than the scale failing to adequately measure the construct.

### 2.4.3 | Mediators

*Stress*

We quantified a subjective and a physiological measure of stress.

*Subjective stress ratings.* In order to detect pre–post changes in subjective stress, we used a single item asking the participants to rate how stressed they felt at a given moment.

*Saliva cortisol.* On a physiological level, time-delayed (30 mins), endocrine-driven hypothalamic–pituitary–adrenal (HPA axis) stress effects were measured. Activity of the HPA axis was assessed by salivary cortisol concentration before and after the intervention. Higher cortisol levels reflect a stronger physiological stress response (Kirschbaum & Hellhammer, 1989). Samples were frozen and stored at −20°C until analysis. After thawing, samples were centrifuged at 3000 rpm for 5 min, which resulted in a clear supernatant of low viscosity. Salivary concentrations were measured using commercially available ELISA with high sensitivity (Tecan—IBL International, Hamburg, Germany; catalogue number R52611). The intra- and interassay coefficients of variance were below 11%.

*Attention*

We measured both perceived restorativeness (e.g. Marselle et al., 2016; Nghiem et al., 2021), as well as subjective directed attention as restorative outcome (Schebella et al., 2019).

*Perceived restorativeness.* As we emphasised on the effect of both vision and hearing, perceived restorativeness was assessed using the 16-item Perceived Restorativeness Scale (PRS; Hartig et al., 1997) that serves a vision-centred evaluation of an environment, as well as the 5-item short form of the perceived restorativeness soundscape scale (PRSS_SF; Uebel et al., 2021, adapted from Payne & Guastavino, 2018). In both scales, respondents are asked to evaluate: fascination (e.g. PRS: 'This place has fascinating qualities'), being away (e.g. PRSS-SF: 'The sounds here give me a good break from my day-to-day routine'), extent (e.g. PRS: 'it is chaotic here') and compatibility (e.g. PRSS-SF: 'These sounds here relate to activities I like to do'). All items on both scales were answered once, after the intervention. Internal consistency of both scales was excellent ($\alpha_{PRS} = 0.93$; $\alpha_{PRSS\text{-}SF} = 0.94$).

*Directed attention.* Preceding studies of biodiversity's effect on self-report-directed attention have used single items (Schebella et al., 2019) or the Restorative Outcome Scale (Korpela et al., 2008; used in, e.g. Simkin et al., 2020). However, neither of these measures are state-dependent, that is targeting temporal changes on a short term which makes these measures unsuitable for pre–post intervention comparisons. Since—to our knowledge—there is no state-sensitive attention questionnaire, we adapted the Attentional Control Scale (ACS; Derryberry & Reed, 2002) to measure short-term temporal fluctuations in directed attention. Specifically, we adapted the attentional *focussing* subscale of the ACS, as there is substantial overlap in definitions of focussed attention and directed attention (Diamond, 2013; Stevenson et al., 2018), and studies show that nature exposure can enhance attentional focussing (Berman et al., 2008; Gamble et al., 2014). Seven out of the original 10 attentional focussing items were adapted to create a state-sensitive measure of attentional focussing (e.g. original item 'when trying to focus my attention on something, I have difficulty blocking out distracting thoughts' was adapted to 'at this point in time, I have difficulty blocking out distracting thoughts'). The remaining three items were removed as they could not be adapted appropriately since these statements are too specific or tied to co-occurring events (e.g. 'It's very hard for me to concentrate on a difficult task when there are noises around'; see Supporting Information S1 for original and adapted items). The scale showed acceptable to good internal consistency with Cronbach's $\alpha$ equalling 0.76 for the pre- and 0.82 for the postintervention questionnaire.

Hereafter, we refer to this scale as the 'directed attention scale' (see Supporting Information S1).

### 2.4.4 | Covariates

Site (i.e. Leipzig, Vienna, Louvain-la-Neuve), species, sex, age, nature relatedness and ecological knowledge were included as covariates. Nature relatedness was measured with the 21-item Nature Relatedness Scale (NRS; Nisbet et al., 2009), while a single item was used to assess the participants' perceptions of their ecological knowledge ('how much do you know about biology or ecology?').

## 2.5 | Statistical analyses

Analyses were conducted using R (version 4.2.1; R Core Team, 2022). Of the psycho- and psychophysiological data, 0.49% was missing, through, for example, unintentional skipping of an item in the paper questionnaires. We imputed missing values using k nearest neighbour imputation provided by the R package 'VIM' (Kowarik & Templ, 2016).

To address Hypotheses 1 and 2 (i.e. forest > built, and high actual forest diversity > lower actual forest diversity), we tested for temporal changes in anxiety, positive affect, negative affect, subjective and physiological stress, and subjective directed attention depending on experimental condition. Mixed ANOVAs were computed using the R packages 'lmerTest' (Kuznetsova et al., 2017) and 'WRS2' (for robust mixed ANOVAs; Mair & Wilcox, 2020) with experimental condition (i.e. actual forest diversity) serving as fixed-effect/between-subjects factor and participant (i.e. the pre–post comparison) as the random-effect/within-subjects factor. Furthermore, the group, in which each participant experienced the intervention, was added as a random effect while covariates (see Section 2.4.4) were included in the model as fixed effects. A robust Welch ANOVA and an ANCOVA were conducted to test for differences in perceived restorativeness of the environment and perceived restorativeness of the soundscape as a function of experimental condition under consideration of the covariates (see Supporting Information S2 for the full models).

To test Hypotheses 3 and 4, we investigated the effects of *perceived* biodiversity. We first checked whether actual and perceived biodiversity aligned (Hypothesis 3). Due to the ordered-categorical nature of actual forest diversity (i.e. the experimental conditions; low, medium and high tree species richness), bivariate polychoric correlations (e.g. Olsson, 1979) were calculated to check for associations with the three ordered-categorical perceived biodiversity measures: perceived tree, plant and bird species richness. Correlation coefficients and p-values were calculated using the R package 'lavaan' (Rosseel, 2012). For continuous perceived biodiversity variables (perceived overall biodiversity and the BEI), ANOVAs were conducted to investigate whether those variables varied as a function of actual tree species richness (i.e. the experimental conditions).

We then calculated Spearman's correlation coefficients to check for meaningful associations between perceived biodiversity and state anxiety, momentary positive and negative affect, as well as the potential mediators (Hypothesis 4). For all variables that were measured before and after the intervention (anxiety, positive and negative affect, subjective and physiological stress and subjective directed attention) we calculated difference values (postintervention score—preintervention score) reflecting the magnitude of change in those variables over time.

To test Hypothesis 5, findings from the preceding analyses were collated to test mediation effects as suggested in the conceptual framework linking biodiversity to health proposed by Marselle et al. (2021). Data were analysed using structural equation modelling (SEM) with latent variable analysis in the R package 'lavaan' (Rosseel, 2012). Again, the created difference values (post- minus preintervention) were taken where needed. Continuous variables were standardised to allow direct comparison between different variables. Multicollinearity of variables was accounted for through checking bivariate correlations and assuring that all $r$ values fell below 0.80 (e.g. Shrestha, 2020). We performed maximum likelihood estimation with robust standard errors and Satorra-Bentler test statistics. Since indirect effects are particularly sensitive to violations of multivariate normality, robust Monte Carlo confidence intervals for mediation estimates were calculated. Model selection and path specification were based on theory (i.e. the conceptual framework, Marselle et al., 2021) and data/model fit. As model fit indices for SEM differ in their sensitivity to different model misspecifications (e.g. misspecification of factor loadings vs. factor covariances; Hu & Bentler, 1999), a holistic consideration of several indices is necessary. Accordingly, we strove for a nonsignificant $\chi^2$ test, a comparative fit index (CFI) ≥0.90 (ideally ≥0.95), a root mean square error of approximation (RMSEA) ≤0.07, a standardised root mean square residual (SRMR) that should fall below 0.08 and a relative $\chi^2$ ($\chi^2$/df) between 2 and 5 (Hooper et al., 2008). Data from the built control condition were excluded from the analyses of Hypotheses 3, 4 and 5 for two reasons: First, there was negligible actual biodiversity at the built control conditions which was also perceived as such (i.e. low perceived biodiversity ratings in the built condition). Second, including participants from the built control would not have allowed us to disentangle potential effects of mere forest exposure (i.e. forest > built) from the effects of perceived biodiversity per se (high perceived biodiversity > low perceived biodiversity).

# 3 | RESULTS

## 3.1 | Effects of forests and actual forest diversity

Our results show restorative effects for forest visits in comparison with the built control for most outcome measures. In detail, significant interaction effects reveal diverging trends of state anxiety, momentary positive and negative affect, subjective stress and subjective directed attention from pre- to postintervention levels depending on whether participants were in the forest or the built condition (all $p < 0.001$; see Figure 3; Supporting Information S3 and S4 for main effects, effects of covariates and effect sizes). Whereas state anxiety, negative affect and subjective stress increased or stayed at a constant level in the

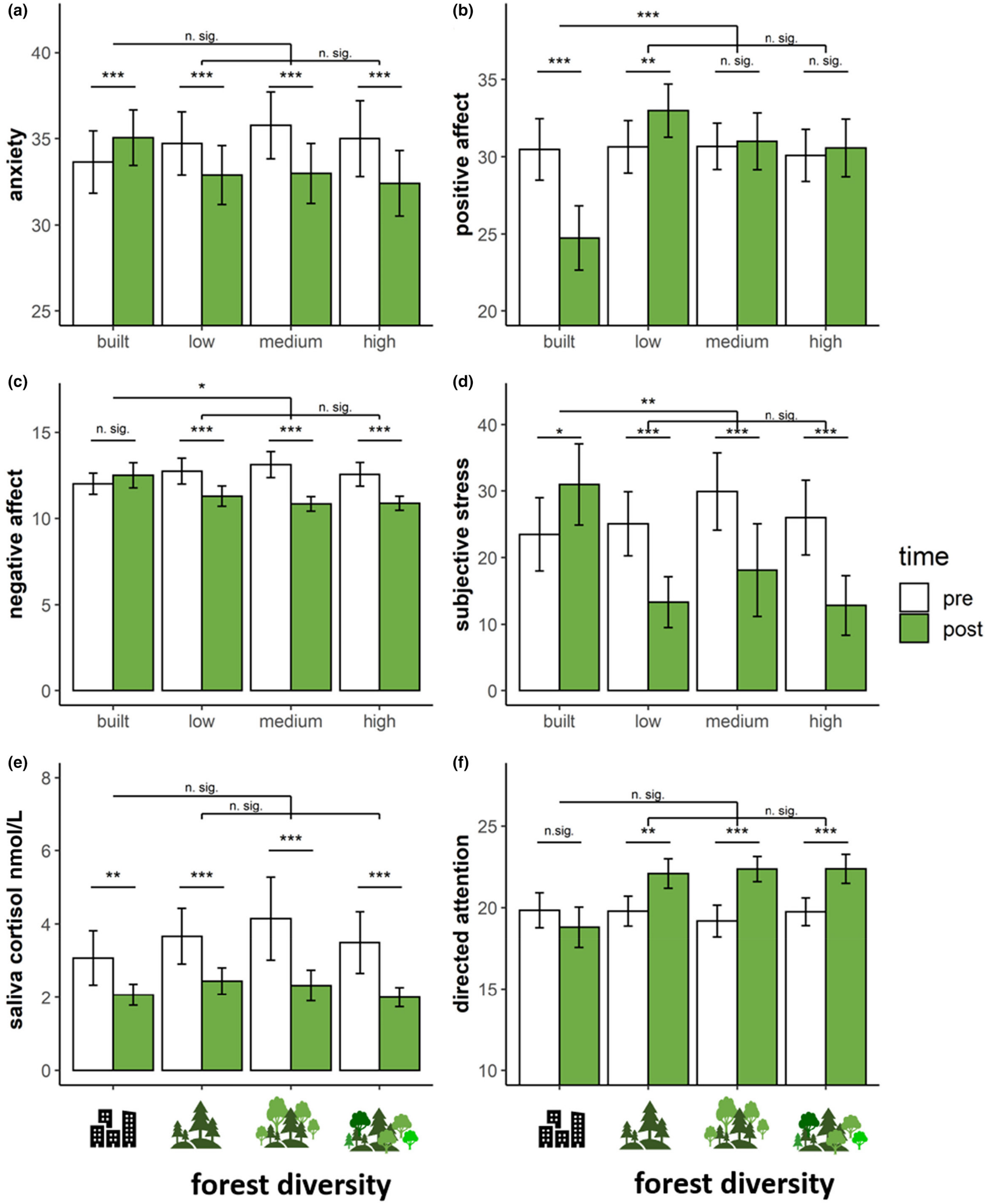


FIGURE 3 Forest diversity effects on well-being as compared to a built environment, analysed by mixed ANOVAs. N.sig., not significant; pre = preintervention; post = postintervention. *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$. Error bars are 95% confidence intervals. Asterisk or 'n.sig.' above comparison of built versus forest (upper horizontal line) refers to the least significant comparison, for example *all comparisons are significant at the 5% level at least. Forest diversity: low = monoculture, medium = 2 tree species mix, high = 4–5 tree species mix. Dependent variables: (a) anxiety, (b) positive affect, (c) negative affect, (d) subjective stress, (e) saliva cortisol, (f) directed attention.

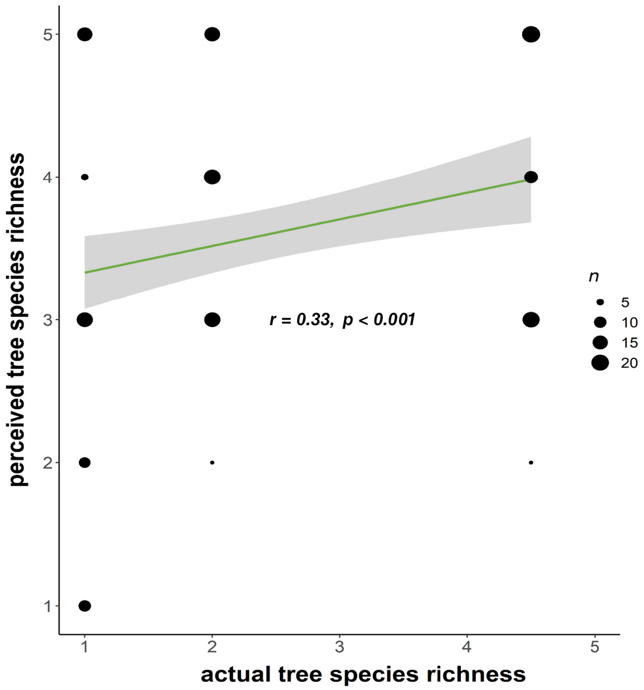


FIGURE 4 Relationship between actual and perceived tree species richness. Dots with larger diameters indicate a higher frequency of respective perceived tree species richness ratings given per forest condition (=actual tree species richness).

built control, they decreased after visits to any of the forest conditions (Figure 3a,c,d). Positive affect and subjective directed attention either decreased or stayed at a constant level in the built control, while showing no change or increases for the forest groups (Figure 3b,f).

There was no significant time × environment interaction for saliva cortisol ($p = 0.41$). Only a main effect of time was found with salivary cortisol declined in the forest and the built control condition (Figure 3e).

A robust Welch ANOVA and an ANCOVA further showed that perceived restorativeness and perceived restorativeness of the soundscape were significantly higher in the forest conditions opposed to the built control (Supporting Information S3, S5, S6).

Actual forest diversity, by means of tree species richness, however, was not a significant moderator of any of the aforementioned associations. No significant differences were found between the three forest conditions for any of the postintervention outcome variables (Figure 3a–e). Also perceived restorativeness of the environment and perceived restorativeness of the soundscape did not vary as a function of forest diversity (Supporting Information S3, S5, S6).

## 3.2 | Effects of perceived forest biodiversity

### 3.2.1 | Relationship between actual and perceived biodiversity and between the five perceived biodiversity measures

We found a statistically significant correlation between actual and perceived tree species richness ($r_{polychoric} = 0.33$, $p < 0.001$; see Figure 4). None of the other perceived biodiversity measures varied as a function of actual tree species richness (Supporting Information S7).

We also found significant associations among perceived biodiversity measures. Items targeting perceived species richness (i.e. perceived tree, plant and bird species richness) were moderately correlated (Supporting Information S8). While the BEI was weakly correlated with perceived tree and plant species richness (Supporting Information S8), it was strongly related to perceived overall biodiversity ($r_s = 0.57$; Supporting Information S8).

### 3.2.2 | Relationship between perceived biodiversity and well-being measures and mediators

We found several significant associations between measures of perceived biodiversity and well-being. Seven out of the nine significant correlations were found for the BEI or perceived overall biodiversity (Figure 5a–g).

## 3.3 | Testing the conceptual framework linking biodiversity to mental health and well-being

To test whether forest biodiversity has an indirect effect on short-term mental health and well-being through stress recovery and attention restoration, we assessed pathways through a SEM. For this, we specified a set of (latent) variables and pathways linking these variables (see Figure 6 for the final model). Actual forest diversity was excluded from the SEM for two reasons: First, no effects of actual diversity on either the discussed outcome variables or potential mediators were found (see Section 3.1). Second, actual tree species richness was unrelated to four out of five measures of perceived biodiversity. Saliva cortisol and perceived tree, plant and bird species richness were excluded from the final model since their inclusion decreased model fit. The final model resulted in the three latent variables (i) perceived biodiversity (comprised of perceived overall biodiversity, BEI), (ii) perceived restorativeness (comprised of PRS, PRSS), (iii) short-term mental ill-health and ill-being (comprised of STAI, negative affect), and the three observed variables stress, directed attention and positive affect that were covered by one source of information only. We did not include a latent variable containing state anxiety and both positive and negative affect, since positive affect only weakly loaded onto that factor in a preliminary model. Fit indices of the final model indicate rather low ($\chi^2 = 36.65$; $df = 18$, $p = 0.006$ and RMSEA = 0.079 [90% CI 0.041–0.115]), medium (CFI = 0.939) to good model fit (SRMR = 0.050; relative $\chi^2 = 2.04$; Hooper et al., 2008; Hu & Bentler, 1999).

Path coefficients (from left to right and top to bottom according to Figure 6) indicate a significant negative relationship between perceived biodiversity and subjective stress ($\beta = -0.16$, SE = 0.07, $p = 0.03$). This means that as perception of biodiversity increased, participants reported less stress. Perceived biodiversity

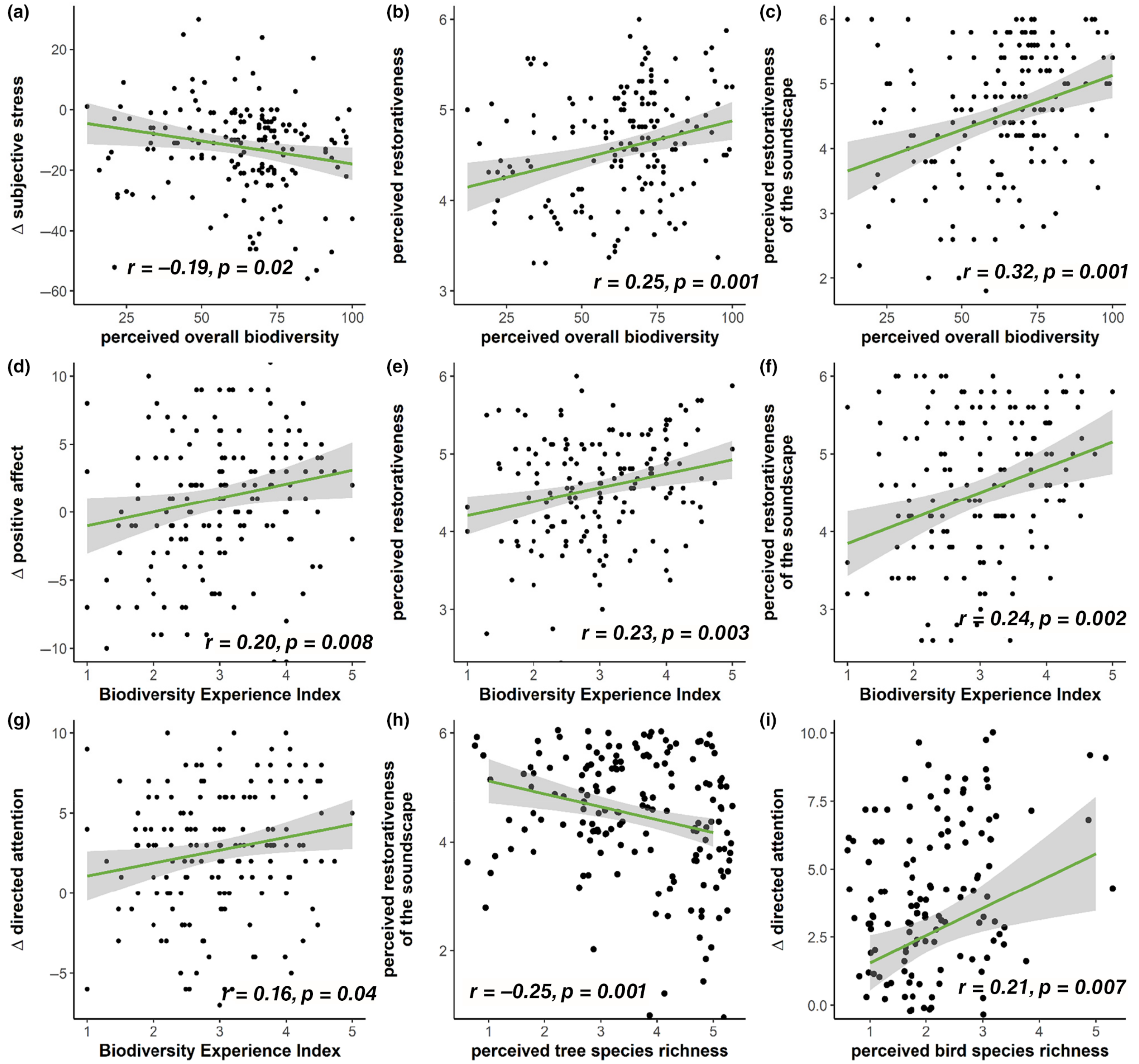


**FIGURE 5** Relationships between different measures of perceived biodiversity and well-being (scatterplots for significant Spearman's correlation coefficients). Depicted correlations: (a) perceived overall biodiversity (pob) - subjective stress, (b) pob - perceived restorativeness (PRS), (c) pob - perceived restorativeness of the soundscape (PRSS), (d) Biodiversity Experience Index (BEI) - positive affect, (e) BEI - PRS, (f) BEI - PRSS, (g) BEI - directed attention (da), (h) perceived tree species richness - PRSS, (i) perceived bird species richness - da.

was positively associated with perceived restorativeness ($\beta = 0.40$, SE = 0.12, $p = 0.001$), indicating that if people perceived the forest patch to be more biodiverse, they also perceived the forest to be more restorative. No effect of perceived biodiversity on subjective directed attention was found ($\beta = 0.05$, SE = 0.10, $p = 0.58$). While no relationship was found between subjective stress and positive affect ($\beta = -0.06$, SE = 0.07, $p = 0.38$), more subjective stress was related to higher levels of momentary mental ill-health and ill-being ($\beta = 0.74$, SE = 0.28, $p = 0.008$). Higher perceived restorativeness was not associated with increased subjective directed attention ($\beta = 0.14$, SE = 0.08, $p = 0.09$). There were, however, significant positive associations for both perceived restorativeness and subjective directed attention with positive affect (PRS: $\beta = 0.17$, SE = 0.06, $p = 0.004$; subjective directed attention: $\beta = 0.17$, SE = 0.06, $p = 0.003$), while negative relationships were found between the two constructs and short-term mental ill-health and ill-being (PRS: $\beta = -0.41$, SE = 0.16, $p = 0.009$; subjective directed attention: $\beta = -0.53$, SE = 0.15, $p < 0.001$).

Eight indirect effects were investigated based on the conceptual framework by Marselle et al. (2021); see Table 3). First, we tested whether perceived biodiversity indirectly increased (i) positive affect and (ii) decreased short-term mental ill-health and

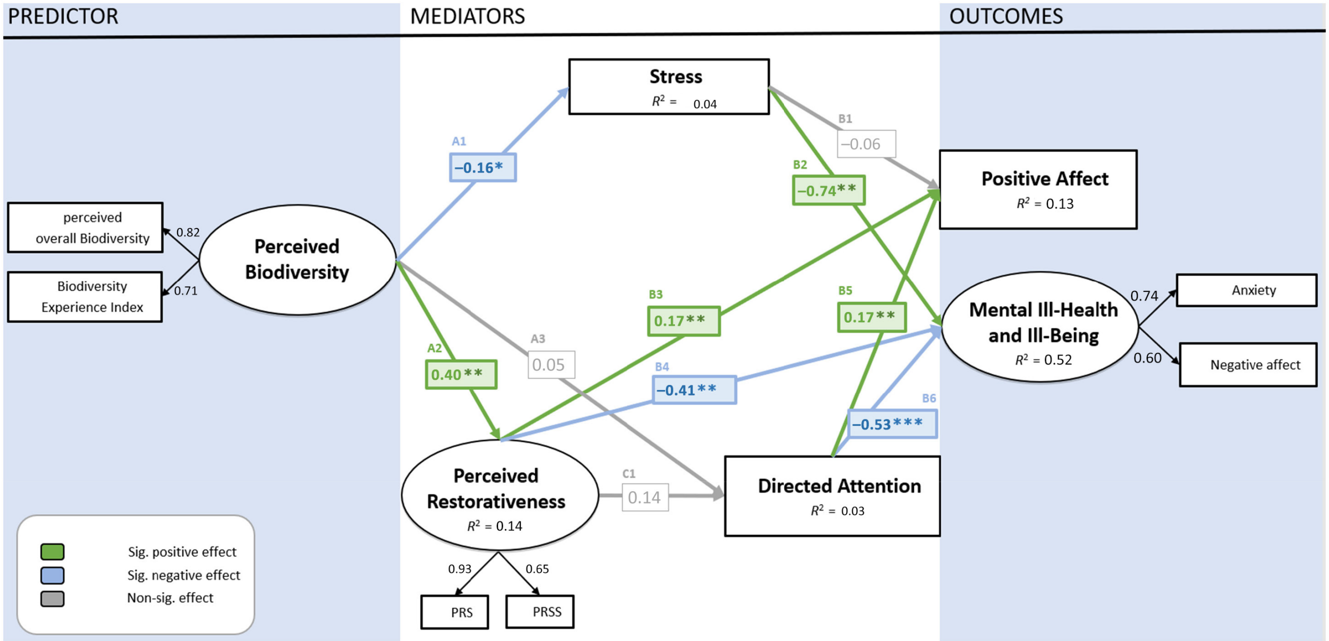


**FIGURE 6** Pathways of biodiversity–health linkages for the fitted structural equation model. Arrows indicate pathways between perceived biodiversity, perceived restorativeness, subjective directed attention, subjective stress, positive affect and mental ill-health and ill-being. Numbers in boxes represent standardised path coefficients. (A) paths = relationship between perceived biodiversity and mediators, (B) paths = relationship between mediators and outcome variables, (C) path = relationship between mediators. Latent and measured variables are indicated by ovals and rectangles, respectively—for example, the latent variable perceived biodiversity comprises the two measured variables perceived overall biodiversity and the Biodiversity Experience Index. Numbers along the arrows pointing from the latent variables to the indicators represent factor loadings (lambda). See Table 3 for indirect effects which are the product of combinations of A, B and C paths. PRS, perceived Restorativeness Scale; PRSS, perceived restorativeness soundscape scale—short form. *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

ill-being by reducing subjective stress. The SEM did not support these mediations (positive affect: $\beta = 0.01$; mental ill-health and ill-being: $\beta = -0.12$). We then tested the effect of perceived biodiversity on (iii) short-term positive affect and (iv) mental ill-health and ill-being via perceived restorativeness. The SEM supported both indirect effects (positive affect: $\beta = 0.07$, $p = 0.03$; mental ill-health and ill-being: $\beta = -0.16$, $p = 0.02$)—participants who perceived their environment as more biodiverse reported more positive affect and less short-term mental ill-health and ill-being when they also perceived the environment as more restorative. Third, we tested the indirect effects of perceived biodiversity on (v) positive affect and (vi) short-term mental ill-health and ill-being via subjective directed attention; no significant mediations were found (positive affect: $\beta = 0.01$; mental ill-health and ill-being: $\beta = -0.03$). Finally, we tested two multiple mediation effects where perceived biodiversity indirectly (vii) increases positive affect and (viii) decreases short-term mental ill-health and ill-being via both perceived restorativeness and subjective directed attention. SEM rejected both indirect effects (positive affect: $\beta = 0.01$; mental ill-health and ill-being: $\beta = -0.03$). In sum, the only evidence of an indirect effect of perceived biodiversity on short-term positive affect and mental ill-health and ill-being was via perceived restorativeness.

## 4 | DISCUSSION

### 4.1 | General discussion

The present study highlights the association between forest diversity and short-term mental health and well-being with a particular emphasis on stress recovery and attention restoration as mediating pathways. We showed that 20-min visits to a forest compared with a built environment improved short-term anxiety, positive affect, negative affect, subjective stress and subjective attention restoration. Saliva cortisol levels, however, declined both in the forest and the built control, indicating that—at a physiological level—participants relaxed to a comparable extent in both environments. We could not ascertain an association of actual tree species richness with a change in state anxiety, positive affect, negative affect, subjective stress, saliva cortisol and subjective attention restoration. In contrast, higher perceived biodiversity was positively correlated with positive affect, perceived restorativeness and subjective directed attention, and negatively correlated with subjective stress. SEM further revealed that perceived biodiversity indirectly supports short-term mental health and well-being by increasing perceived restorativeness. Subjective stress and subjective directed attention were not found to be mediators in the SEM.

TABLE 3 Indirect effects of perceived biodiversity on positive affect and mental ill-health and ill-being via stress, perceived restorativeness and directed attention.

| Predictor | Mediators | Outcomes | Path label Figure 6 | Estimate | 95% CI | SE | p |
|---|---|---|---|---|---|---|---|
| Single mediation analyses | | | | | | | |
| | Stress → | Positive affect | A1 B1 | 0.01 | −0.01 to 0.04 | 0.01 | 0.40 |
| | | Mental ill-health and ill-being | A1 B2 | −0.12 | −0.27 to −0.01 | 0.06 | 0.06 |
| **Perceived Biodiversity →** | **Perceived restorativeness →** | **Positive affect** | **A2 B3** | **0.07** | **0.02–0.14** | **0.03** | **0.03** |
| | | **Mental ill-health and ill-being** | **A2 B4** | **−0.16** | **−0.32 to −0.03** | **0.07** | **0.02** |
| | Directed attention → | Positive affect | A3 B5 | 0.01 | −0.02 to 0.05 | 0.02 | 0.60 |
| | | Mental ill-health and ill-being | A3 B6 | −0.03 | −0.14 to 0.08 | 0.05 | 0.58 |
| Multiple mediation analyses | | | | | | | |
| Perceived biodiversity → | Perceived restorativeness → Directed attention → | Positive affect | A2 C1 B5 | 0.01 | −0.001 to 0.03 | 0.01 | 0.18 |
| | | Mental ill-health and ill-being | A2 C1 B6 | −0.03 | −0.09 to 0.004 | 0.02 | 0.19 |

*Note*: Estimates are standardised regression weights. Confidence intervals (CI) represent robust Monte Carlo confidence intervals for mediation analyses. Statistically significant indirect effects are highlighted in bold and light green.

Abbreviations: *p*, *p*-value; SE, standard error.

Our results align with previous studies showing that forests are better than built environments in promoting short-term mental health and well-being, subjective stress recovery and attention restoration (e.g. Grilli & Sacchelli, 2020; Kotera et al., 2020; Wolf et al., 2020). Contrary to our expectations, physiological stress as measured by saliva cortisol concentration was equally reduced in all participants, regardless of whether they were in the forest or the built control. Although there are many studies indicating that visits to forests are beneficial for reducing saliva cortisol levels (Antonelli et al., 2019), Tyrväinen et al. (2014) also found a significant decline of saliva cortisol in both the forest and the built control condition as seen in our sample, while other studies found no effect at all (Lee et al., 2011; Park et al., 2007). We took baseline samples between 9:45 AM and 2 PM. According to reference values of saliva cortisol concentration in early morning or late afternoon hours (Kirschbaum & Hellhammer, 1989), the average preintervention cortisol levels in our study tended towards the lower boundary of normal values. It is thus possible that our participants already were in a relaxed state prior to undertaking the forest (or built) intervention. It is, however, also possible that we took the second saliva sample too early. Saliva cortisol concentration at the time of taking the sample reflects a physiological response to events that took place 20–30 min earlier (Kirschbaum & Hellhammer, 1989). Postintervention saliva samples in the present study were taken 15 min after the intervention ended, potentially capturing participants' physiological state 5–15 min after the intervention began. Stress mitigation in the forest might thus not yet have unfold its full potential (that might have been detected 5–10 min later). Future studies may consider collecting salivary cortisol 20–30 min following environmental exposure.

No positive well-being effects of tree species richness—both actual and perceived—were found. To our best knowledge, Wolf et al. (2017) is the only previous experimental study to also investigate tree species richness effects: The authors compared videos showing one or four tree species regarding effects on anxiety, positive affect and vitality. Lower anxiety and more positive affect were registered in the 4-species condition, compared with the single-species condition. However, there are two major differences between Wolf et al. (2017) and the present study: First, Wolf et al. (2017) did not collect pretest measures to assess existing interindividual differences between subjects at the start of the study. Second, the study lacks ecological validity as it was not conducted in situ. As our results further suggest that the perceived biodiversity measures that consider species richness to a lesser extent were the best predictors of positive well-being outcomes, we speculate that species richness may not be the decisive biodiversity indicator that drives short-term mental health and well-being increments in forest settings. This might be a consequence of being entirely surrounded by vegetation, which may impede the assessment of species richness in forest environments compared with, for example urban green spaces, open grasslands and the like.

Using perceived biodiversity measures, which allow for more degrees of freedom when assessing an environment's biodiversity, might be more eligible when addressing biodiversity–health linkages than items with setting-specific response options (Marselle et al., 2015). Such options, as those designed by Fuller et al. (2007), seek to align ecological survey data with people's perception by asking for numerical estimations of the species richness present in an environment. We therefore created the item of perceived overall biodiversity; that is, participants just had to state how biodiverse they thought the environment was. In addition, we assessed the BEI that combines perceived plant and animal species richness with estimates of how wild and varied participants experience an environment. Response options range from 'a little' to 'much', thus avoiding numerical classification. In fact, neither perceived overall biodiversity nor the BEI significantly aligned with actual tree species richness. In addition, no significant associations between perceived overall biodiversity and any of the perceived species richness variables were found, while the BEI only weakly aligned with perceived tree and plant species richness. Simultaneously, we found a strong link between perceived overall biodiversity and the BEI. This suggests that BEI items addressing perceived structural diversity ('wild' and 'varied') may have been more important than those targeting perceived species richness. As a consequence, one may argue that it is a combination of structural aspects of biodiversity such as vegetation layers together with resulting perceptual properties such as variations in colour, different light patterns as well as scents or sounds that is crucial when investigating effects of biodiversity on short-term mental health and well-being. Indeed, several other studies directly or indirectly support this assumption (Carrus et al., 2015; Johansson et al., 2014; Lee et al., 2018; Meyer-Grandbastien et al., 2020; Schebella et al., 2019; Simkin et al., 2020). Schebella et al. (2019), for example, reported significant positive associations between actual structural heterogeneity and habitat diversity with mental well-being, subjective stress and subjective attention/concentration. Additionally, Meyer-Grandbastien et al. (2020) found a positive relationship between both actual landscape heterogeneity (i.e. complex spatial arrangements) and perceived landscape diversity and mental well-being. Interestingly, the majority of studies that found an effect of actual forest biodiversity on mental health or well-being also considered structural diversity (through, e.g. vegetation layers and types, stand age class distribution or successional stages) when selecting their study sites (Johansson et al., 2014; Lee et al., 2018; Simkin et al., 2020), which could be seen as corroborating evidence highlighting the importance of forest structural diversity for human well-being.

With our findings from SEM, we partially align with assumptions made in the conceptual framework by Marselle et al. (2021). As suggested by the framework, we found a significant indirect effect of perceived biodiversity on short-term mental health and well-being via perceived restorativeness. That is, higher perceived biodiversity indirectly improved short-term positive affect and reduced short-term mental ill-health and ill-being in participants who perceived their environment and soundscape as more restorative. Our findings are in line with previous work that tested the indirect link between biodiversity and mental well-being (Carrus et al., 2015; Fisher et al., 2021; Marselle et al., 2016; Nghiem et al., 2021) or mental health in particular (Fisher et al., 2021). This is of relevance, not only because one in 10 persons worldwide suffers from a psychological condition (World Health Organization, 2019) but also due to the immense economic burden through direct and indirect costs arising from treatment and revenue loss (Trautmann et al., 2016). Our findings diverge from assumptions made by the conceptual framework (Marselle et al., 2021) and theories of SRT (Ulrich, 1983; Ulrich et al., 1991) and ART (Kaplan, 1995) because perceived biodiversity did not indirectly promote short-term mental health and well-being through (i) fostering a more pronounced recovery from subjective stress, (ii) increasing subjective directed attention or (iii) increasing both perceived restorativeness and subjective directed attention.

Theories of restorative environments such as SRT or ART assume that for an environment to be restorative, people would have to be in need for restoration (i.e. stressed or depleted in attentional capacities) beforehand (Hartig, 2011). However, as we did not induce mental fatigue or stress, it could be stated that our participants were not in need of restoration. In addition, perceived restorativeness needs to be better understood with regard to its intermediate character in linking biodiversity to directed attention. Even though previous research confirmed links between perceived restorativeness and directed attention (Barbiero et al., 2021; Berto, 2005), no such association was found in our SEM. As such, perceived restorativeness might not just be a necessary precondition for attention restoration, but may also function as a standalone feature of nature exposure that serves as a predictor for mental health and well-being in itself. Results from Carrus et al. (2015), Marselle et al. (2016), Fisher et al. (2021), Nghiem et al. (2021), all found that perceived restorativeness mediated the relationship between biodiversity and mental health and well-being, providing empirical evidence enforcing perceived restorativeness as an independent mediator. More research specifically addressing the mechanistic link between perceived restorativeness and directed attention is needed. Ideally, directed attention would then be operationalised in a multifaceted manner through, for example a combined assessment of subjective directed attention, behavioural measures such as cognitive tests that ideally separate several attentional subdomains (e.g. the Attention Network Test; Fan et al., 2002) and (neuro-) physiological correlates of these domains (e.g. event-related potentials).

### 4.2 | Outlook and future studies

We could show that the mere presence of a forest and perceived forest diversity exert positive effects on well-being indicators, but that tree species diversity did not. With a total of 223 participants, the present study constitutes one of the biggest experimental forest intervention studies to date (cf. Kotera et al., 2020). We chose a between-subjects design allowing us to control for many obstacles that are inherent to environmental psychological field experiments (e.g. parallel testing of participants in each plot to account for the effects of alternating weather conditions). To further increase statistical power, future studies could strive for applying a within-subjects design (i.e. all participants being exposed to all experimental conditions; see, e.g. Johansson et al., 2014; Simkin et al., 2020). This could be achieved by further (possibly global) multicentre studies using an agreed-upon, highly controlled study design.

To enhance testing for possible associations of biodiversity and mental health and well-being, future studies could also induce mental fatigue activities prior to testing SRT and ART by exposing participants to a potentially stressful and cognitively demanding task prior to the experiment. As stated by Stevenson et al. (2018), a validity check of successful mental fatigue induction is recommended as the mere assumption of successful induction through, for example testing students during their examination phase neglects interindividual differences in coping with natural stressors and by doing so potentially contributes to the heterogeneity of results when investigating restorative effects of nature or biodiversity. More research is needed, specifically targeting the reconciliation of theory (i.e. ART) and practice (i.e. eligible attentional subdomains sensitive to restorative environments and the selection of respective attentional tests to induce mental fatigue and measure directed attention, Stevenson et al., 2018).

A second outlook points to the focus on species richness as a proxy for forest biodiversity. Tree species richness is the total number of tree species in a defined area, but variations in stand age, forest architecture or structure, as indicated by the variables 'wild' and 'varied' of the BEI, may be important in addition to species richness. Another potential issue relates to species identity effects, i.e. people's psychological responses to certain species and its specific set of traits (An et al., 2019; Elsadek et al., 2019; Guan et al., 2017; Sivarajah et al., 2018). To account for differences, we selected a different monoculture species in each of the three forests that may compensate for potential identity effects. Future studies should take this into account and vary species where possible.

In addition, the field could benefit from more equivalence and follow-up trials. Equivalence trials test the effectiveness of an intervention compared with already well-established treatment procedures or protocols. McEwan et al. (2021), for example, compared forest bathing to compassionate mind training and a combination of forest bathing and compassionate mind training and found that mental well-being improved in participants from all three conditions, thus showing that forest bathing is as effective in promoting well-being as an established well-being intervention. Follow-up trials would have the great benefit of mirroring dynamics in mental health and well-being in the long-term, as both constructs are considered conceptually and temporarily stable. More longitudinal studies using long-term mental health and well-being measures such as the Mental Health Inventory (MHI-5; Berwick et al., 1991) or the Warwick-Edinburgh Mental Wellbeing Scale (WEMWBS; Tennant et al., 2007) are hence of utmost importance.

Recently, positive forest diversity effects have been shown for several other health-related outcomes, such as thermal comfort (Gillerot et al., 2022; Gillerot et al., 2024), the productivity of mushrooms that provide health-relevant nutrients (Stojek et al., 2022), the prevalence of tick-borne pathogens (Bourdin et al., 2022) or particulate matter retention (Steinparzer et al., 2022). Future studies may thus emphasise synergetic effects between different aspects of health. For instance, Gillerot et al. (2024) found an interaction between mental and thermal well-being in forests; that is, the better forest visitors felt mentally, the greater the thermal comfort they stated and vice versa.

## 5 | CONCLUSION

Our findings highlight that 20-min stays in a forest can promote short-term mental health and well-being. These relatively short forest visits fostered subjective stress recovery and increased subjective directed attention as well as perceived restorativeness. This effect was irrespective of tree species richness. Importantly, perceived forest biodiversity indirectly promoted short-term mental health and well-being by increasing perceived restorativeness. As we could—in our study—not find an association between actual tree species richness and short-term mental health and well-being, restorative effects also seem to be offered by currently less diverse forests; that is, forests can be managed for different purposes and still provide restorative environments, when accessible, while perceived biodiversity also played a role. Here, a deeper investigation of the drivers of perceived biodiversity, such as structure or perceived 'wildness' and 'variation' in biodiversity experiences, will be beneficial to further understand and promote biodiversity-mental health linkages.

In the face of the multiple crises of climate change, biodiversity loss and health deterioration, promoting the conservation and restoration of forests may not only contribute to climate change mitigation and adaptation but also provide beneficial effects for human mental health and well-being as a nature-based solution. Overall, our findings contribute to the growing body of evidence of biodiversity–health linkages. We recommend public health programmes to encourage visits to forests as proactive health measures and also to conserve old-growth pristine forests while restoring and planting new forests to secure and enhance healthy, liveable environments as contribution to our planetary health in an increasingly urbanised world.

### AUTHOR CONTRIBUTIONS

Kevin Rozario, Rachel Rui Ying Oh, Melissa Marselle, Erich Schröger, Loïc Gillerot and Aletta Bonn contributed to conceptualisation and design; Kevin Rozario, Rachel Rui Ying Oh, Loïc Gillerot, Quentin Ponette, Douglas Godbold, Daniela Haluza, Katriina Kilpi and Aletta Bonn contributed to data collation; Kevin Rozario, Rachel Rui Ying Oh, Melissa Marselle and Aletta Bonn contributed to formal analysis; Kevin Rozario contributed to writing—first draft and writing—review and editing. All authors contributed critically to the drafts and gave final approval for publication.

## ACKNOWLEDGEMENTS

We are grateful to all participants making this study possible. We further like to extend our gratitude for assistance in finding appropriate forest patches, access permission and experimental set-up to: Martin Opitz, Andreas Sickert and Jana Kriebel from 'Stadtforst Leipzig'; Susann Willnecker from 'Sachsenforst'; Paula Mercier from the office for environmental protection Leipzig; Tobias Pross and Ronny Richter from iDiv; Alexandra Wieshaider from 'Österreichischer Bundesforst'; Harald Brenner from the 'Biosphärenpark Wienerwald'; Arnauld Morize and Thibaut Thyrion from UCLouvain. We warmly thank Max Bierwirth, Tanja Lazic, Pauline Kersten, Ines Dorn, Felipe Benra, Ariane Chamoin, Maria Felipe-Lucia, Volker Grescho, Reinhard Klenke, Hannah Moersberger, Birte Peters, Wolfram Reglich, Thora Herrmann, Merle Schreiner, Julia von Gönner, Jana Kachler, Christian Nappert, Paula Sanchez Alandete, Jana Haseloh, Laura Stratakis, Matthias Steinparzer, Emiel Hernalsteen, Dominick Crespin, Fanny Langhendries, Audrey Binet, Louis Cordonnier, Jasmine De Wulf, François Joussemet, Joël Lapierre, Xavière Lucas and Frédéric Viatour for their help with conducting this study and Mara Breitenbücher and David Rieker for digitising the data. Thanks also to Gabriele Brandes, Carola Gaunersdorfer and Anne Bolle for leading and organising the forest bathing workshops. Last but not least, we express our gratitude to the iDiv Data & Code Unit and particularly Ludmilla Figueiredo for assistance with curation and archiving of the dataset. This research is part of the project 'Dr. FOREST' investigating the link between forest biodiversity and human health and was funded under the BiodivERsA3 ERA-Net COFUND programme with the national funding organisations DFG (Germany, DFG—428795724), ANR (France), FWO (Belgium), FWF (Austria) and NCN (Poland). We were further supported through the Flexpool Support Fund of the German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, funded by the German Research Foundation (DFG-FZT 118, 202548816). Open Access funding enabled and organized by Projekt DEAL.

## CONFLICT OF INTEREST STATEMENT

Aletta Bonn, Rachel Oh and Melissa Marselle are associate editors of People and Nature, but were not involved in the peer review and decision-making processes for this paper.

## DATA AVAILABILITY STATEMENT

All data considered for the analysis of this study are stored and available at: https://doi.org/10.25829/idiv.3538-su6fj5.

## ORCID

*Kevin Rozario* https://orcid.org/0009-0004-6731-0342
*Rachel Rui Ying Oh* https://orcid.org/0000-0003-2716-7727
*Melissa Marselle* https://orcid.org/0000-0002-3245-7473
*Erich Schröger* https://orcid.org/0000-0002-8321-6629
*Loïc Gillerot* https://orcid.org/0000-0002-0699-4478
*Quentin Ponette* https://orcid.org/0000-0002-2726-7392
*Douglas Godbold* https://orcid.org/0000-0001-5607-5800
*Daniela Haluza* https://orcid.org/0000-0001-5619-2863
*Katriina Kilpi* https://orcid.org/0000-0002-6450-9127
*Dagmar Müller* https://orcid.org/0000-0001-9289-1215
*Urte Roeber* https://orcid.org/0000-0002-6631-5828
*Kris Verheyen* https://orcid.org/0000-0002-2067-9108
*Bart Muys* https://orcid.org/0000-0001-9421-527X
*Sandra Müller* https://orcid.org/0000-0003-4289-755X
*Taylor Shaw* https://orcid.org/0000-0003-4117-4552
*Aletta Bonn* https://orcid.org/0000-0002-8345-4600

## REFERENCES

An, B. Y., Wang, D., Liu, X. J., Guan, H. M., Wei, H. X., & Ren, Z. B. (2019). The effect of environmental factors in urban forests on blood pressure and heart rate in university students. *Journal of Forest Research*, *24*(1), 27–34. https://doi.org/10.1080/13416979.2018.1540144

Antonelli, M., Barbieri, G., & Donelli, D. (2019). Effects of forest bathing (shinrin-yoku) on levels of cortisol as a stress biomarker: A systematic review and meta-analysis. *International Journal of Biometeorology*, *63*(8), 1117–1134. https://doi.org/10.1007/s00484-019-01717-x

Austen, G. E., Dallimer, M., Irvine, K. N., Maund, P. R., Fish, R. D., & Davies, Z. G. (2021). Exploring shared public perspectives on biodiversity attributes. *People and Nature*, *3*(4), 901–913. https://doi.org/10.1002/pan3.10237

Barbiero, G., Berto, R., Venturella, A., & Maculan, N. (2021). Bracing Biophilia: When biophilic design promotes pupil's attentional performance, perceived restorativeness and affiliation with nature. *Environment, Development and Sustainability*, *0123456789*, 1–15. https://doi.org/10.1007/s10668-021-01903-1

Berdejo-Espinola, V., Suárez-Castro, A. F., Amano, T., Fielding, K. S., Oh, R. R. Y., & Fuller, R. A. (2021). Urban green space use during a time of stress: A case study during the COVID-19 pandemic in Brisbane, Australia. *People and Nature*, *3*(3), 597–609. https://doi.org/10.1002/pan3.10218

Berman, M. G., Jonides, J., & Kaplan, S. (2008). The cognitive benefits of interacting with nature. *Psychological Science*, *19*(12), 1207–1212. https://doi.org/10.1111/j.1467-9280.2008.02225.x

Berto, R. (2005). Exposure to restorative environments helps restore attentional capacity. *Journal of Environmental Psychology*, *25*(3), 249–259. https://doi.org/10.1016/j.jenvp.2005.07.001

Berwick, D. M., Murphy, J. M., Goldman, P. A., Ware, J. E., Jr., Barsky, A. J., & Weinstein, M. C. (1991). Performance of a five-item mental health screening test. *Medical Care*, *29*, 169–176.

Beute, F., Andreucci, M. B., Lammel, A., Davies, Z., Glanville, J., Keune, H., Marselle, M., O'Brien, L., Olszewska-Guizzo, A., Remmen, R., Russo, A., & de Vries, S. (2020). *Types and characteristics of urban and peri-urban green spaces having an impact on human mental health and wellbeing: A systematic review*. Technical report, EKLIPSE. http://kar.kent.ac.uk/contact.html

Bielinis, E., Jaroszewska, A., Łukowski, A., & Takayama, N. (2020). The effects of a forest therapy programme on mental hospital patients with affective and psychotic disorders. *International Journal of Environmental Research and Public Health*, *17*(1), 1–10. https://doi.org/10.3390/ijerph17010118

Bourdin, A., Bord, S., Durand, J., Galon, C., Moutailler, S., Scherer-Lorenzen, M., & Jactel, H. (2022). Forest diversity reduces the prevalence of pathogens transmitted by the tick *Ixodes ricinus*. *Frontiers in Ecology and Evolution*, *10*, 891908.

Bowler, D. E., Buyung-Ali, L. M., Knight, T. M., & Pullin, A. S. (2010). A systematic review of evidence for the added benefits to health of exposure to natural environments. *BMC Public Health*, *10*(1), 1–10. https://doi.org/10.1186/1471-2458-10-456

Cameron, R. W. F., Brindley, P., Mears, M., McEwan, K., Ferguson, F., Sheffield, D., Jorgensen, A., Riley, J., Goodrick, J., Ballard, L., &

Richardson, M. (2020). Where the wild things are! Do urban green spaces with greater avian biodiversity promote more positive emotions in humans? *Urban Ecosystems*, *23*(2), 301–317. https://doi.org/10.1007/s11252-020-00929-z

Carrus, G., Scopelliti, M., Lafortezza, R., Colangelo, G., Ferrini, F., Salbitano, F., Agrimi, M., Portoghesi, L., Semenzato, P., & Sanesi, G. (2015). Go greener, feel better? The positive effects of biodiversity on the well-being of individuals visiting urban and peri-urban green areas. *Landscape and Urban Planning*, *134*, 221–228. https://doi.org/10.1016/j.landurbplan.2014.10.022

Cervinka, R., Schwab, M., & Haluza, D. (2020). Investigating the qualities of a recreational forest: Findings from the cross-sectional hallerwald case study. *International Journal of Environmental Research and Public Health*, *17*(5), 1676. https://doi.org/10.3390/ijerph17051676

Chiang, Y. C., Li, D., & Jane, H. A. (2017). Wild or tended nature? The effects of landscape location and vegetation density on physiological and psychological responses. *Landscape and Urban Planning*, *167*(June), 72–83. https://doi.org/10.1016/j.landurbplan.2017.06.001

Cox, D. T. C., Shanahan, D. F., Hudson, H. L., Plummer, K. E., Siriwardena, G. M., Fuller, R. A., Anderson, K., Hancock, S., & Gaston, K. J. (2017). Doses of neighborhood nature: The benefits for mental health of living with nature. *Bioscience*, *67*(2), 147–155. https://doi.org/10.1093/biosci/biw173

Dallimer, M., Irvine, K. N., Skinner, A. M. J., Davies, Z. G., Rouquette, J. R., Maltby, L. L., Warren, P. H., Armsworth, P. R., & Gaston, K. J. (2012). Biodiversity and the feel-good factor: Understanding associations between self-reported human well-being and species richness. *Bioscience*, *62*(1), 47–55. https://doi.org/10.1525/bio.2012.62.1.9

Derks, J., Giessen, L., & Winkel, G. (2020). COVID-19-induced visitor boom reveals the importance of forests as critical infrastructure. *Forest Policy and Economics*, *118*(July), 1–5. https://doi.org/10.1016/j.forpol.2020.102253

Derryberry, D., & Reed, M. A. (2002). Anxiety-related attentional biases and their regulation by attentional control. *Journal of Abnormal Psychology*, *111*(2), 225–236. https://doi.org/10.1037/0021-843X.111.2.225

Diamond, A. (2013). Executive functions. *Annual Review of Psychology*, *64*, 135–168. https://doi.org/10.1146/annurev-psych-113011-143750

Elsadek, M., Liu, B., Lian, Z., & Xie, J. (2019). The influence of urban roadside trees and their physical environment on stress relief measures: A field experiment in Shanghai. *Urban Forestry and Urban Greening*, *42*(May), 51–60. https://doi.org/10.1016/j.ufug.2019.05.007

Fan, J., McCandliss, B. D., Sommer, T., Raz, A., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of Cognitive Neuroscience*, *14*(3), 340–347. https://doi.org/10.1162/089892902317361886

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *2*(39), 175–191.

Fiksdal, A., Hanlin, L., Kuras, Y., Gianferante, D., Chen, X., Thoma, M. V., & Rohleder, N. (2019). Associations between symptoms of depression and anxiety and cortisol responses to and recovery from acute stress. *Psychoneuroendocrinology*, *102*, 44–52. https://doi.org/10.1016/j.psyneuen.2018.11.035

Fisher, J. C., Irvine, K. N., Bicknell, J. E., Hayes, W. M., Fernandes, D., Mistry, J., & Davies, Z. G. (2021). Perceived biodiversity, sound, naturalness and safety enhance the restorative quality and wellbeing benefits of green and blue space in a neotropical city. *Science of the Total Environment*, *755*, 143095. https://doi.org/10.1016/j.scitotenv.2020.143095

Foo, C. H. (2016). Linking forest naturalness and human wellbeing-a study on public's experiential connection to remnant forests within a highly urbanized region in Malaysia. *Urban Forestry and Urban Greening*, *16*, 13–24. https://doi.org/10.1016/j.ufug.2016.01.005

Fuller, R. A., Irvine, K. N., Devine-Wright, P., Warren, P. H., & Gaston, K. J. (2007). Psychological benefits of greenspace increase with biodiversity. *Biology Letters*, *3*(4), 390–394. https://doi.org/10.1098/rsbl.2007.0149

Gamble, K. R., Howard, J. H., & Howard, D. V. (2014). Not just scenery: Viewing nature pictures improves executive attention in older adults. *Experimental Aging Research*, *40*(5), 513–530. https://doi.org/10.1080/0361073X.2014.956618

Gao, T., Zhu, L., Zhang, T., Song, R., Zhang, Y., & Qiu, L. (2019). Is an environment with high biodiversity the most attractive for human recreation? A case study in Baoji, China. *Sustainability*, *11*(15), 4086. https://doi.org/10.3390/su11154086

Gillerot, L., Landuyt, D., Oh, R., Chow, W., Haluza, D., Ponette, Q., Jactel, H., Bruelheide, H., Jaroszewicz, B., Scherer-Lorenzen, M., De Frenne, P., Muys, B., & Verheyen, K. (2022). Forest structure and composition alleviate human thermal stress. *Global Change Biology*, *28*(24), 7340–7352.

Gillerot, L., Rozario, K., De Frenne, P., Oh, R. R. Y., Ponette, Q., Bonn, A., Chow, W., Godbold, D. L., Steinparzer, M., Haluza, D., Landuyt, D., Muys, B., & Verheyen, K. (2024). Forests are chill: The interplay between thermal comfort and mental wellbeing. *Landscape and Urban Planning*, *242*, 104933.

Gonçalves, P., Grilo, F., Mendes, R. C., Vierikko, K., Elands, B., Marques, T. A., & Santos-Reis, M. (2021). What's biodiversity got to do with it? Perceptions of biodiversity and restorativeness in urban parks. *Ecology and Society*, *26*(3), 25. https://doi.org/10.5751/ES-12598-260325

Grilli, G., & Sacchelli, S. (2020). Health benefits derived from forest: A review. *International Journal of Environmental Research and Public Health*, *17*(17), 1–11. https://doi.org/10.3390/ijerph17176125

Guan, H. M., Wei, H. X., He, X. Y., Ren, Z. B., & An, B. Y. (2017). The tree-species-specific effect of forest bathing on perceived anxiety alleviation of young-adults in urban forests. *Annals of Forest Research*, *60*(2), 327–341. https://doi.org/10.15287/afr.2017.897

Gyllin, M., & Grahn, P. (2005). A semantic model for assessing the experience of urban biodiversity. *Urban Forestry and Urban Greening*, *3*(3–4), 149–161. https://doi.org/10.1016/j.ufug.2005.04.004

Hair, J. F., Anderson, R. E., Babin, B. J., & Black, W. C. (2010). *Multivariate data analysis: A global perspective* (Vol. 7). Pearson Education.

Hartig, T. (2011). Issues in restorative environments research: Matters of measurement. In B. Fernández-Ramírez, C. Hidalgo Villodres, C. M. Salvador Ferrer, & M. J. Martos Méndez (Eds.), *Psicología ambiental* (pp. 41–66). University of Almería & the Spanish Association of Environmental Psychology.

Hartig, T., Kaiser, F. G., & Bowler, P. A. (1997). *Further development of a measure of perceived environmental restorativeness*. Institutet För Bostadsforskning, Uppsala Universitet. http://www.ibf.uu.se/PUBL/Wp/Wp5.pdf

Hedin, M., Hahs, A. K., Mata, L., & Lee, K. (2022). Connecting biodiversity with mental health and wellbeing—A review of methods and disciplinary perspectives. *Frontiers in Ecology and Evolution*, *10*(May), 1–13. https://doi.org/10.3389/fevo.2022.865727

Hooper, D., Coughlan, J., & Mullen, M. R. (2008). Structural equation modelling: Guidelines for determining model fit. *Electronic Journal of Business Research Methods*, *6*(1), 53–60.

Hu, L. T., & Bentler, P. M. (1999). Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Structural Equation Modeling: A Multidisciplinary Journal*, *6*(1), 1–55.

James, W. (1890). *Principles of psychology*. Holt.

Johansson, M., Gyllin, M., Witzell, J., & Küller, M. (2014). Does biological quality matter? Direct and reflected appraisal of biodiversity in temperate deciduous broad-leaf forest. *Urban Forestry and Urban Greening*, *13*(1), 28–37. https://doi.org/10.1016/j.ufug.2013.10.009

Kaplan, S. (1995). The restorative benefits of nature: Toward an integrative framework. *Journal of Environmental Psychology*, *15*(3), 169–182. https://doi.org/10.1016/0272-4944(95)90001-2

Keniger, L. E., Gaston, K. J., Irvine, K. N., & Fuller, R. A. (2013). What are the benefits of interacting with nature? *International Journal of Environmental Research and Public Health*, *10*(3), 913–935. https://doi.org/10.3390/ijerph10030913

Kirschbaum, C., & Hellhammer, D. H. (1989). Salivary cortisol in psychobiological research: An overview. *Neuropsychobiology*, *22*(3), 150–169. https://doi.org/10.1159/000118611

Korpela, K. M., Ylén, M., Tyrväinen, L., & Silvennoinen, H. (2008). Determinants of restorative experiences in everyday favorite places. *Health and Place*, *14*(4), 636–652. https://doi.org/10.1016/j.healthplace.2007.10.008

Kotera, Y., Richardson, M., & Sheffield, D. (2020). Effects of shinrin-yoku (forest bathing) and nature therapy on mental health: A systematic review and meta-analysis. *International Journal of Mental Health and Addiction*, *20*, 337–361. https://doi.org/10.1007/s11469-020-00363-4

Kowarik, A., & Templ, M. (2016). Imputation with the R package VIM. *Journal of Statistical Software*, *74*(7), 1–16. https://doi.org/10.18637/jss.v074.i07

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest package: Tests in linear mixed effects models. *Journal of Statistical Software*, *82*(13), 1–26. https://doi.org/10.18637/JSS.V082.I13

Larsson, M. R., Bäckström, M., & Johanson, A. (2008). The interaction between baseline trait anxiety and trauma exposure as predictor of post-trauma symptoms of anxiety and insomnia. *Scandinavian Journal of Psychology*, *49*(5), 447–450. https://doi.org/10.1111/j.1467-9450.2008.00649.x

Lee, J., Park, B. J., Tsunetsugu, Y., Ohira, T., Kagawa, T., & Miyazaki, Y. (2011). Effect of forest bathing on physiological and psychological responses in young Japanese male subjects. *Public Health*, *125*(2), 93–100. https://doi.org/10.1016/j.puhe.2010.09.005

Lee, K. J., Hur, J., Yang, K. S., Lee, M. K., & Lee, S. J. (2018). Acute biophysical responses and psychological effects of different types of forests in patients with metabolic syndrome. *Environment and Behavior*, *50*(3), 298–323. https://doi.org/10.1177/0013916517700957

Lindemann-Matthies, P., Junge, X., & Matthies, D. (2010). The influence of plant diversity on people's perception and aesthetic appreciation of grassland vegetation. *Biological Conservation*, *143*(1), 195–202. https://doi.org/10.1016/j.biocon.2009.10.003

Lindemann-Matthies, P., & Matthies, D. (2018). The influence of plant species richness on stress recovery of humans. *Web Ecology*, *18*(2), 121–128. https://doi.org/10.5194/we-18-121-2018

Lovell, R., Wheeler, B. W., Higgins, S. L., Irvine, K. N., & Depledge, M. H. (2014). A systematic review of the health and well-being benefits of biodiverse environments. *Journal of Toxicology and Environmental Health—Part B: Critical Reviews*, *17*(1), 1–20. https://doi.org/10.1080/10937404.2013.856361

Mair, P., & Wilcox, R. (2020). Robust statistical methods in R using the WRS2 package. *Behavior Research Methods*, *52*(2), 464–488. https://doi.org/10.3758/s13428-019-01246-w

Marselle, M. R., Hartig, T., Cox, D. T. C., de Bell, S., Knapp, S., Lindley, S., Triguero-Mas, M., Böhning-Gaese, K., Braubach, M., Cook, P. A., de Vries, S., Heintz-Buschart, A., Hofmann, M., Irvine, K. N., Kabisch, N., Kolek, F., Kraemer, R., Markevych, I., Martens, D., … Bonn, A. (2021). Pathways linking biodiversity to human health: A conceptual framework. *Environment International*, *150*, 106420. https://doi.org/10.1016/j.envint.2021.106420

Marselle, M. R., Irvine, K. N., Lorenzo-Arribas, A., & Warber, S. L. (2015). Moving beyond green: Exploring the relationship of environment type and indicators of perceived environmental quality on emotional well-being following group walks. *International Journal of Environmental Research and Public Health*, *12*(1), 106–130. https://doi.org/10.3390/ijerph120100106

Marselle, M. R., Irvine, K. N., Lorenzo-Arribas, A., & Warber, S. L. (2016). Does perceived restorativeness mediate the effects of perceived biodiversity and perceived naturalness on emotional well-being following group walks in nature? *Journal of Environmental Psychology*, *46*, 217–232. https://doi.org/10.1016/j.jenvp.2016.04.008

Marselle, M. R., Martens, D., Dallimer, M., & Irvine, K. N. (2019). Review of the mental health and well-being benefits of biodiversity. In M. Marselle, J. Stadler, H. Korn, K. N. Irvine, & A. Bonn (Eds.), *Biodiversity and health in the face of climate change* (pp. 175–211). Springer.

Marselle, M. R., Warber, S. L., & Irvine, K. N. (2019). Growing resilience through interaction with nature: Can group walks in nature buffer the effects of stressful life events on mental health? *International Journal of Environmental Research and Public Health*, *16*(6), 986. https://doi.org/10.3390/ijerph16060986

Mavoa, S., Davern, M., Breed, M., & Hahs, A. (2019). Higher levels of greenness and biodiversity associate with greater subjective wellbeing in adults living in Melbourne, Australia. *Health and Place*, *57*(May), 321–329. https://doi.org/10.1016/j.healthplace.2019.05.006

McEwan, K., Giles, D., Clarke, F. J., Kotera, Y., Evans, G., Terebenina, O., Minou, L., Teeling, C., Basran, J., Wood, W., & & Weil, D. (2021). A pragmatic controlled trial of forest bathing compared with compassionate mind training in the UK: Impacts on self-reported wellbeing and heart rate variability. *Sustainability*, *13*(3), 1380.

McNally, R. J. (2019). Attentional bias for threat: Crisis or opportunity? *Clinical Psychology Review*, *69*, 4–13. https://doi.org/10.1016/j.cpr.2018.05.005

Methorst, J., Rehdanz, K., Mueller, T., Hansjürgens, B., Bonn, A., & Böhning-Gaese, K. (2021). The importance of species diversity for human well-being in Europe. *Ecological Economics*, *181*, 106917.

Meyer-Grandbastien, A., Burel, F., Hellier, E., & Bergerot, B. (2020). A step towards understanding the relationship between species diversity and psychological restoration of visitors in urban green spaces using landscape heterogeneity. *Landscape and Urban Planning*, *195*, 103728. https://doi.org/10.1016/j.landurbplan.2019.103728

Mogg, K., & Bradley, B. P. (2018). Anxiety and threat-related attention: Cognitive-motivational framework and treatment. *Trends in Cognitive Sciences*, *22*(3), 225–240. https://doi.org/10.1016/j.tics.2018.01.001

Nghiem, T. P. L., Wong, K. L., Jeevanandam, L., Chang, C. C., Tan, L. Y. C., Goh, Y., & Carrasco, L. R. (2021). Biodiverse urban forests, happy people: Experimental evidence linking perceived biodiversity, restoration, and emotional wellbeing. *Urban Forestry and Urban Greening*, *59*, 127030. https://doi.org/10.1016/j.ufug.2021.127030

Nguyen, P. Y., Astell-Burt, T., Rahimi-Ardabili, H., & Feng, X. (2021). Green space quality and health: A systematic review. *International Journal of Environmental Research and Public Health*, *18*(21), 11028. https://doi.org/10.3390/ijerph182111028

Nisbet, E. K., Zelenski, J. M., & Murphy, S. A. (2009). The Nature Relatedness Scale: Linking individuals' connection with nature to environmental concern and behavior. *Environment and Behavior*, *41*(5), 715–740.

Olsson, U. (1979). Maximum likelihood estimation of the polychoric correlation coefficient. *Psychometrika*, *44*(4), 117–132. https://doi.org/10.1007/bfb0067701

Park, B. J., Tsunetsugu, Y., Kasetani, T., Hirano, H., Kagawa, T., Sato, M., & Miyazaki, Y. (2007). Physiological effects of shinrin-yoku (taking in the atmosphere of the forest)—Using salivary cortisol and cerebral activity as indicators. *Journal of Physiological Anthropology*, *26*(2), 123–128. https://doi.org/10.2114/jpa2.26.123

Payne, S. R., & Guastavino, C. (2018). Exploring the validity of the Perceived Restorativeness Soundscape Scale: A psycholinguistic approach. *Frontiers in Psychology*, *9*(November), 1–17. https://doi.org/10.3389/fpsyg.2018.02224

Pettersson, A., Supervisor, L. W., & Bergman, K.-O. (2021). *The role of biodiversity in stress alleviation: An experiment using VR*. http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-180651

Poortinga, W., Bird, N., Hallingberg, B., Phillips, R., & Williams, D. (2021). The role of perceived public and private green space in subjective health and wellbeing during and after the first peak of the COVID-19 outbreak. *Landscape and Urban Planning*, *211*(March), 104092. https://doi.org/10.1016/j.landurbplan.2021.104092

Qi, M., Gao, H., Guan, L., Liu, G., & Yang, J. (2016). Subjective stress, salivary cortisol, and electrophysiological responses to psychological stress. *Frontiers in Psychology*, *7*(February), 1–9. https://doi.org/10.3389/fpsyg.2016.00229

R Core Team. (2022). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Rosseel, Y. (2012). Lavaan: An R package for structural equation modeling. *Journal of Statistical Software*, *48*(2), 1–36.

Schebella, M. F., Weber, D., Schultz, L., & Weinstein, P. (2019). The well-being benefits associated with perceived and measured biodiversity in Australian urban green spaces. *Sustainability*, *11*(3), 802. https://doi.org/10.3390/su11030802

Scopelliti, M., Carrus, G., Cini, F., Mastandrea, S., Ferrini, F., Lafortezza, R., Agrimi, M., Salbitano, F., Sanesi, G., & Semenzato, P. (2012). Biodiversity, perceived restorativeness, and benefits of nature: A study on the psychological processes and outcomes of on-site experiences in urban and peri-urban green areas in Italy. In S. K. Kabisch, A. K. Kunath, P. Schweizer-Ries, & A. S. Steinfuhrer (Eds.), *Vulnerability, risks, and complexity: Impacts of global change on human habitats*, *1977* (pp. 255–269). Hogrefe & Huber Publishers. http://ovidsp.ovid.com/ovidweb.cgi?T=JS&CSC=Y&NEWS=N&PAGE=fulltext&D=psyc9&AN=2012-22680-020%5Cnhttp://openurl.ac.uk/athens:lee/?sid=OVID:psycdb&id=pmid:&id=doi:&issn=&isbn=978-0-88937-435-5&volume=&issue=&spage=255&pages=255-269&date=2012&title=Vulnerabi

Shrestha, N. (2020). Detecting multicollinearity in regression analysis. *American Journal of Applied Mathematics and Statistics*, *8*(2), 39–42. https://doi.org/10.12691/ajams-8-2-1

Simkin, J., Ojala, A., & Tyrväinen, L. (2020). Restorative effects of mature and young commercial forests, pristine old-growth forest and urban recreation forest—A field experiment. *Urban Forestry and Urban Greening*, *48*, 126567. https://doi.org/10.1016/j.ufug.2019.126567

Simkin, J., Ojala, A., & Tyrväinen, L. (2021). The perceived restorativeness of differently managed forests and its association with Forest qualities and individual variables: A field experiment. *International Journal of Environmental Research and Public Health*, *18*(2), 422. https://doi.org/10.3390/ijerph18020422

Sivarajah, S., Smith, S. M., & Thomas, S. C. (2018). Tree cover and species composition effects on academic performance of primary school students. *PLoS One*, *13*(2), 1–11. https://doi.org/10.1371/journal.pone.0193254

Southon, G. E., Jorgensen, A., Dunnett, N., Hoyle, H., & Evans, K. L. (2018). Perceived species-richness in urban green spaces: Cues, accuracy and well-being impacts. *Landscape and Urban Planning*, *172*, 1–10. https://doi.org/10.1016/j.landurbplan.2017.12.002

Spielberger, C. D., Gonzalez-Reigosa, F., Martinez-Urrutia, A., Natalicio, L. F., & Natalicio, D. S. (1971). The state-trait anxiety inventory. *Revista Interamericana de Psicologia/Interamerican Journal of Psychology*, *5*(3 & 4), 145–158.

Steinparzer, M., Haluza, D., & Godbold, D. L. (2022). Integrating tree species identity and diversity in particulate matter adsorption. *Forests*, *13*(3), 481.

Stevenson, M. P., Schilhab, T., & Bentsen, P. (2018). Attention Restoration Theory II: A systematic review to clarify attention processes affected by exposure to natural environments. *Journal of Toxicology and Environmental Health—Part B: Critical Reviews*, *21*(4), 227–268. https://doi.org/10.1080/10937404.2018.1505571

Stojek, K., Gillerot, L., & Jaroszewicz, B. (2022). Predictors of mushroom production in the European temperate mixed deciduous forest. *Forest Ecology and Management*, *522*, 120451.

Tavakol, M., & Dennick, R. (2011). Making sense of Cronbach's alpha. *International Journal of Medical Education*, *2*, 53–55. https://doi.org/10.5116/ijme.4dfb.8dfd

Tennant, R., Hiller, L., Fishwick, R., Platt, S., Joseph, S., Weich, S., Parkinson, J., Secker, J., & Stewart-Brown, S. (2007). The Warwick-Edinburgh mental well-being scale (WEMWBS): Development and UK validation. *Health and Quality of Life Outcomes*, *5*(1), 1–13.

Trautmann, S., Rehm, J., & Wittchen, H. (2016). The economic costs of mental disorders. *EMBO Reports*, *17*(9), 1245–1249. https://doi.org/10.15252/embr.201642951

Tyrväinen, L., Ojala, A., Korpela, K., Lanki, T., Tsunetsugu, Y., & Kagawa, T. (2014). The influence of urban green environments on stress relief measures: A field experiment. *Journal of Environmental Psychology*, *38*, 1–9. https://doi.org/10.1016/j.jenvp.2013.12.005

Uebel, K., Marselle, M., Dean, A. J., Rhodes, J. R., & Bonn, A. (2021). Urban green space soundscapes and their perceived restorativeness. *People and Nature*, *3*(3), 756–769. https://doi.org/10.1002/pan3.10215

Ulrich, R. S. (1983). Aesthetic and Affective Response to Natural Environment. *Behavior and the Natural Environment* (pp. 85–125). Springer US. https://doi.org/10.1007/978-1-4613-3539-9

Ulrich, R. S., Simons, R. F., Losito, B. D., Fiorito, E., Miles, M. A., & Zelson, M. (1991). Stress recovery during exposure to natural and urban environments. *Journal of Environmental Psychology*, *11*(3), 201–230. https://doi.org/10.1016/S0272-4944(05)80184-7

United Nations. (1992). *Convention on biological diversity* [WWW document]. https://www.cbd.int/doc/legal/cbd-en.pdf

von Lindern, E., Lymeus, F., & Hartig, T. (2017). The restorative environment: A complementary concept for salutogenesis studies. In M. B. Mittelmark, S. Sagy, M. Eriksson, G. F. Bauer, J. M. Pelikan, B. Lindström, & G. A. Espnes (Eds.), *The handbook of salutogenesis* (pp. 181–195). Springer.

Watson, D., Clark, L. A., & Tellegen, A. (1988). Development and validation of brief measures of positive and negative affect: The PANAS scales. *Journal of Personality and Social Psychology*, *54*(6), 1063–1070.

Wei, H., Zhang, J., Xu, Z., Hui, T., Guo, P., & Sun, Y. (2022). The association between plant diversity and perceived emotions for visitors in urban forests: A pilot study across 49 parks in China. *Urban Forestry and Urban Greening*, *73*(May), 127613. https://doi.org/10.1016/j.ufug.2022.127613

Wen, Y., Yan, Q., Pan, Y., Gu, X., & Liu, Y. (2019). Medical empirical research on forest bathing (shinrin-yoku): A systematic review. *Environmental Health and Preventive Medicine*, *24*(1), 1–21. https://doi.org/10.1186/s12199-019-0822-8

Wolf, K. L., Lam, S. T., McKeen, J. K., Richardson, G. R. A., van den Bosch, M., & Bardekjian, A. C. (2020). Urban trees and human health: A scoping review. *International Journal of Environmental Research and Public Health*, *17*(12), 1–30. https://doi.org/10.3390/ijerph17124371

Wolf, L. J., Zu Ermgassen, S., Balmford, A., White, M., & Weinstein, N. (2017). Is variety the spice of life? An experimental investigation into the effects of species richness on self-reported mental well-being. *PLoS One*, *12*(1), 1–17. https://doi.org/10.1371/journal.pone.0170225

World Health Organization. (2019). *About mental disorders (No. WHO-EM/MNH/212/E)*. World Health Organization, Regional Office for the Eastern Mediterranean.

World Health Organization. (2022). *ICD-11: International classification of diseases (11th revision)*. https://icd.who.int/

Zabini, F., Albanese, L., Becheri, F. R., Gavazzi, G., Giganti, F., Giovanelli, F., Gronchi, G., Guazzini, A., Laurino, M., Li, Q., Marzi, T., Mastorci, F., Meneguzzo, F., Righi, S., & Viggiano, M. P. (2020). Comparative study of the restorative effects of forest and urban videos during covid-19 lockdown: Intrinsic and benchmark values. *International Journal of Environmental Research and Public Health*, *17*(21), 1–13. https://doi.org/10.3390/ijerph17218011

## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

**Appendix S1.** Directed attention scale.

**Appendix S2.** Formula of mixed ANOVA, robust mixed ANOVA, robust Welch-ANOVA and ANCOVA.

**Appendix S3.** Interaction effects, main effects and post-hoc tests with p values and effect sizes.

**Appendix S4.** Effects of covariates.

**Appendix S5.** Results from the robust Welch-ANOVA assessing changes in perceived restorativeness.

**Appendix S6.** Results from the ANCOVA assessing changes in perceived restorativeness of the soundscape.

**Appendix S7.** Correlations between actual tree species richness and perceived biodiversity measures.

**Appendix S8.** Correlation among perceived biodiversity measures, of perceived biodiversity and well-being measures andamong well-being measures.

**Appendix S9.** Survey.

**How to cite this article:** Rozario, K., Oh, R. R. Y., Marselle, M., Schröger, E., Gillerot, L., Ponette, Q., Godbold, D., Haluza, D., Kilpi, K., Müller, D., Roeber, U., Verheyen, K., Muys, B., Müller, S., Shaw, T., & Bonn, A. (2024). The more the merrier? Perceived forest biodiversity promotes short-term mental health and well-being—A multicentre study. *People and Nature*, *6*, 180–201. https://doi.org/10.1002/pan3.10564