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Azim Premji University, India
Viliam Pichler,
Technical University in Zvolen, Slovakia

*CORRESPONDENCE

Wuji Lin
✉ linwuji5555@sicnu.edu.cn

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Effects of restorative environments on mental health and its cognitive neural mechanisms

Peng Wang, Jingyuan Lin and Wuji Lin*

Institute of Brain and Psychological Sciences, Sichuan Normal University, Chengdu, China

The well-established improvement effect of restorative environments on mental health has been demonstrated by numerous studies. However, there are relatively few related environmental neuroscience studies. Therefore, regarding the cognitive neural mechanism of the restorative environment in improving mental health, there are still many unknowns. In this article, we conducted a scoping review of the research in this field to map the current evidence base. Firstly, we summarized the main viewpoints of the existing theories and analyzed the limitations of each theory. After integrating the empirical studies on the regulation of mental health by the restorative environment, it was found that exposure to the restorative environment is associated with significant changes in mental health, as well as the cerebral cortex activity, brain structure, and functional connectivity. Based on the current literature, we proposed further suggestions from the aspects of theoretical development, study design, and analysis method.

KEYWORDS

restorative environment, mental health, neural mechanisms, brain network, natural environment

1 Introduction

The widespread deterioration of mental health among urban residents has become a significant public health issue. Numerous studies have found that the mental health of urban residents is generally poor, exhibiting higher levels of psychological distress (Dunleavy et al., 2020; Gong et al., 2016; Williams et al., 2017), depression (Lecic-Tosevski, 2019; Xu et al., 2023), and anxiety (van der Wal et al., 2021; Ventimiglia and Seedat, 2019). Environmental psychology explains this as the continuous consumption of individual psychological resources by the urban environment and the lack of a recovery mechanism. Since the 1970s, scholars have increasingly recognized the key role of the physical environment in supporting the restoration of psychological resources and introduced the concept of “restorative environments” (Hartig, 2004).

Restorative environments are defined as physical environments that allow and promote the renewal, recovery, or reconstruction of depleted physical, psychological, and social resources during the continuous adaptation to demands (Hartig, 2004). A core premise of restorative environment research is that psychological resources are depleted in the process of meeting life demands and need to be replenished through a “recovery” process. Two basic requirements for an environment to have restorative functions are: “allowing”

and “promoting.” First, the environment needs to allow restoration, meaning it should enable individuals to temporarily disengage from or pause activities that require significant resource consumption, and avoid introducing new demands that further deplete already exhausted resources (von Lindern et al., 2016). Second, the environment should be able to promote resource recovery. Although psychological activities are not necessarily directly related to specific environments, people may feel fatigued and troubled in any environment (e.g., those with rumination) (Collado et al., 2017), environments with restorative characteristics can attract and focus people’s attention, prompting them to engage with the external world, thereby extending the recovery process. In essence, restorative environments not only have low demands on depleted resources but also possess positive characteristics that can more quickly and thoroughly renew depleted psychological resources.

Restorative environments are a conceptual expression of such environments, with natural environments being their archetypal manifestation. On one hand, natural environments are considered to have lower arousal characteristics than urban environments, such as complexity, intensity, and mobility (Wohlwill, 1974), which reduces the continuous depletion of psychological resources. Moreover, natural environments lack many of many of the cognitive, social, and physical demands found in urban environments, and this reduction of “stressors” facilitates relaxation and promotes recovery (Kaplan and Kaplan, 1982; Staats et al., 2010). Therefore, natural environments, or those rich in natural elements, are widely recognized as prototypical examples of restorative environments, including forests, grasslands, wetlands, and rivers. However, the scope of restorative contexts extends beyond these natural archetypes to include urban green spaces (e.g., parks, community gardens, greenways) and select non-natural venues with restorative affordances, such as museums (Annechini et al., 2020), cafés (Staats et al., 2016), temples and churches (Ouellette et al., 2005), and public squares (Abdulkarim and Nasar, 2014). These settings can foster restoration through cultural immersion, aesthetic engagement, or social support, provided that they minimize environmental demands and avoid introducing new stressors. It is also important to recognize that restorative potential is not guaranteed; contextual barriers—such as overcrowding, noise, safety concerns, or social tensions—can diminish or even negate restorative benefits, even in otherwise supportive environments (Hartig et al., 2007). Conversely, by shaping certain conditions in the environment and increasing elements that promote resource recovery (mainly natural elements), residential areas (Dzhambov, 2018), workspaces (Bringslimark et al., 2011), schools (Han, 2009), and hospitals (Gao and Zhang, 2020) can also have restorative effects. The core of restorative environments lies in reducing psychological resource consumption (low arousal characteristics) and eliminating stressors (cognitive, social, and physical demands). Given the diversity of restorative contexts, it is essential to consider not only environmental attributes but also individual psychological needs, cultural backgrounds, and situational constraints that may facilitate or hinder restoration.

A substantial body of research has demonstrated the significant role of restorative environments in maintaining mental health, improving mood, promoting cognitive resource recovery, and enhancing wellbeing. For example, a meta-analysis of 263 studies found that 70% (184 out of 263 studies) of the studies support a positive relationship between restorative environments and mental

health (Wendelboe-Nelson et al., 2019). Restorative environments not only contribute positively to individual psychological wellbeing but also yield substantial economic benefits at the societal level. A study found that the economic value of global nature reserves in enhancing mental health amounts to \$6 trillion, which exceeds the value generated by tourism in protected areas by an order of magnitude and surpasses management costs by two to three orders of magnitude (Buckley et al., 2019).

Despite this clear evidence of their benefits, a comprehensive synthesis of the field’s current state is still needed. Therefore, the primary objective of this study is to systematically synthesize and critically evaluate current research on restorative environments. Furthermore, a key goal is to identify existing gaps in the literature and, based on this analysis, propose clear and actionable directions for future research.

2 Theories of restorative environments

There is currently a wealth of theoretical perspectives on how restorative environments promote mental health and overall recovery capacity, driving the research paradigm shift from phenomenological description to mechanistic analysis.

2.1 Attention Restoration Theory

Attention Restoration Theory (ART) was proposed by Kaplan and Kaplan (1989) and proposes that the perceptual features of natural environments can attract an individual’s involuntary attention, while also allowing for the restoration of limited, voluntary attention resources (Kaplan and Berman, 2010; Schertz and Berman, 2019). This perceptual feature in natural environments is referred to as “soft fascination.” Voluntary attention, which requires sustained effort to suppress distractions, is a limited cognitive resource (James, 1892), and under long-term cognitive load, it can lead to fatigue from directed attention. ART suggests that attention processing in natural environments is bottom-up and effortless. The perceptual features in these environments can automatically capture involuntary attention, and Kaplan and Kaplan (1989) refer to this state as “fascination.” During this process, voluntary attention enters an inactive state, allowing for cognitive resource recovery and alleviating fatigue. This theoretical framework presents four key restorative features: (1) Soft fascination; (2) Sense of being away; (3) Feeling of extent; (4) Compatibility with goals. However, the definitions in this theoretical framework are somewhat vague and lack operational clarity, making it difficult to clearly measure and manipulate the specific impacts of these features in empirical research.

Attention Restoration Theory is a functionalist psychological theory that has driven much research on restorative environments promoting cognitive resource recovery. Experimental paradigms typically induce attention fatigue through pre-test tasks and then compare cognitive performance differences after exposure to natural and urban environments. A meta-analysis found that exposure to restorative environments led to better performance on cognitive tasks such as working memory, cognitive flexibility, and

attention control, which require attention involvement (Stevenson et al., 2018). However, there is no direct evidence to suggest that the process of cognitive resource recovery in natural environments is a process of restoring voluntary attention (Joye and Dewitte, 2018).

2.2 Stress Recovery Theory

Based on evolutionary psychology, Ulrich et al. (1991) proposed the Stress Recovery Theory (SRT), with the core hypothesis being: the environmental adaptation mechanisms formed during human evolution not only shaped the stress response system to threatening stimuli (Ulrich, 1983), but also built the neurobiological foundation for quickly recovering stress homeostasis in safe environments. Ulrich et al. (1991) proposed two aspects of recovery: (1) activation of the parasympathetic nervous system; (2) positive emotional state changes, both of which work together to maintain the dynamic balance of the stress system. They believed that physiological arousal and emotional changes serve adaptive purposes, helping individuals prepare for fight or flight when responding to threatening stimuli, with the resulting stress being an adaptive response beneficial for survival (Ulrich, 1983). SRT emphasizes that humans' preference for natural environments has deep evolutionary logic. For example, savanna like landscapes—open terrain with abundant water sources—resemble early human evolutionary environments, suggesting the possibility of survival and thus fostering a sense of safety and adaptability. Such natural scenes replace negative emotions with positive emotions, thus promoting stress recovery and emotional.

Studies of comparing the recovery effects different environmental types and characteristics on emotions and stress-related physiological measures provide experimental support for the Stress Recovery Theory (Chiang et al., 2017; Huang et al., 2020; Tang et al., 2017). However, as an evolutionary psychological theory, its assumptions are difficult to test, and there is no empirical evidence confirming the recovery mechanisms outlined by SRT. Instead, it often aligns with research findings to some extent. In urban environments, SRT's explanatory power is limited, particularly when explaining restorative effects in non-natural settings.

2.3 Biophilia hypothesis

The biophilia hypothesis suggests that humans have an inherent biophilia, defined as an innate tendency to affiliate with life and life-like processes (Wilson, 1984). Wilson argued from an evolutionary perspective that, in the long course of evolution, humans developed an intrinsic need to stay connected with the natural environment in order to adapt and optimize survival. This long-term interaction with nature shaped the human brain, enabling it to efficiently extract, process, and assess information from the natural world. Therefore, biophilia often becomes embedded in human cognition, emotions, and even artistic expression in an instinctive or subconscious way. Wilson further emphasized that continuous contact with the natural environment is a necessary condition for the development of human mental health. Deprivation of direct interaction with other species or life forms for extended periods can

lead to psychological deprivation and functional decline, potentially causing issues like loneliness and depression.

Empirical evidence supporting the biophilia hypothesis mainly comes from the positive emotional and behavioral tendencies exhibited by humans when they come into contact with life and life-like forms. Examples include: studies showing that grassland landscapes can effectively induce positive emotional experiences (Heerwagen and Orians, 1993; Kahn, 1997). Animal-Assisted Therapy (AAT) has been proven to significantly improve mental health levels (Frumkin, 2001; Lin and Li, 2024), and vegetated environments often trigger positive aesthetic responses (Ulrich, 1993). A major criticism is that it is difficult to exclude the possibility that human biophilia is not an inherent instinct, but rather a product of cultural learning and social construction (Lewis, 2005).

2.4 Nature-Based Biopsychosocial Resilience Theory

The Nature-Based Biopsychosocial Resilience Theory (NBRT), proposed by White et al. (2023), integrates biological, psychological, and social resilience perspectives into a comprehensive framework that explains how nature contact influences mental health. The framework first addresses the relationship between stressors and adaptive resources. When an individual's adaptive resources are sufficient to meet situational demands, the system maintains homeostasis. In contrast, stress involves the disruption of homeostasis (McEwen and Stellar, 1993), leading to imbalance. Following a stressful event, one may recover to the original state of equilibrium, improve beyond the initial state, or deteriorate. Under persistent stress, the lack of effective recovery may result in the accumulation of adaptive resource depletion, leading to allostatic load, which in turn reduces the capacity to cope with new stressors.

(White et al., 2023). This explanation clarifies why urban residents face greater mental health challenges and underscores the importance of restoring adaptive resources. NBRT conceptualizes adaptive resources as biopsychosocial resilience resources, emphasizing that resilience is shaped by biological, psychological, and social factors. Biological resilience resources may include a healthy immune system, endocrine and neural functions, autonomic nervous system regulation, and higher levels of cardiovascular health (Dedoncker et al., 2021). Psychological resilience resources encompass personality traits such as openness, mindfulness, and optimism (Fletcher and Sarkar, 2013). Social resilience resources include personality characteristics such as extraversion, agreeableness, empathy, and general trust (Davydov et al., 2010). Moreover, White et al. (2023) posits that biopsychosocial resilience plays a functional role in responding to stressors, encompassing three key processes:

prevention (reducing the risk of potential stressors), coping (mitigating the immediate impact of stressors), and recovery (restoring homeostasis). The natural environment plays a crucial role in constructing, restoring, and maintaining biopsychosocial resilience resources across physiological, psychological, and social dimensions. For example, microbial diversity in natural environments supports immune regulation (Andersen et al.,

2021) and reduces sympathetic nervous system activity (Jimenez et al., 2020), while exposure to nature effectively alleviates negative emotions, enhances positive emotions, and restores attentional resources through soft fascination (Kaplan and Kaplan, 1989). Additionally, nature-based experiences (e.g., community gardening) (McKlveen et al., 2013) strengthen social support networks.

Nature-Based Biopsychosocial Resilience Theory specifies the adaptive resources into biological, psychological, and social resources, which have high operability in empirical research. Based on existing research, this theory explains how biopsychosocial resilience resources are constructed, restored, and maintained in the process of contact with the natural environment. Although there is a lack of quantitative tools to assess biopsychosocial resilience resources, future research can further address this issue by developing new measurement tools and techniques.

2.5 Other theories

Prospect-Refuge Theory (Appleton, 1975), Perceptual Fluency Account Hypothesis (Joye and van den Berg, 2011), and Relational Restoration Theory (Hartig, 2021) offer complementary perspectives on the mechanisms underlying environmental preferences and restorative experiences. The Prospect-Refuge Theory emphasizes aesthetic preferences in landscapes, suggesting that individuals are drawn to environments offering both “prospects” (open views) and “refuges” (places of concealment) (Appleton, 1975). Empirical research supports this view, indicating that natural trails with greater “prospect” characteristics yield more substantial cognitive restoration compared to those with limited visibility (Dosen and Ostwald, 2016). The Perceptual Fluency Account Hypothesis, in contrast, approaches restoration from a cognitive processing perspective, proposing that natural environments exhibit higher perceptual fluency than urban settings, thereby reducing cognitive load and facilitating positive emotional responses. Urban environments, with their complex structures and high information density, impose greater cognitive demands, whereas the simplicity and coherence of natural scenes make them easier to process, leading to attention restoration and stress reduction as byproducts of enhanced perceptual fluency (Joye and van den Berg, 2011). Expanding beyond individual cognitive and affective processes, the Relational Restoration Theory introduces a relational dimension, arguing that restorative experiences are shaped not only by the physical environment but also by the quality of social interactions and shared experiences in nature (Hartig, 2021). Evidence suggests that positive social support buffers the neural impacts of urban life and enhances both wellbeing and social cohesion (Pasanen et al., 2023). Studies have shown that viewing images of close partners increases activity in rewards-related areas such as the vmPFC (Eisenberger et al., 2011) and caudate (Younger et al., 2010), whereas physically holding a partner's hand reduces activity in threat-sensitive regions, including the anterior cingulate cortex and the insula (Coan et al., 2006). Collectively, these findings underscore that restoration is a multifaceted process shaped by environmental, cognitive, and social resources. Collectively, these theories underscore that restoration is a multifaceted process shaped by environmental, cognitive, and social resources.

Table 1 shows a table of theories vs. operational tests.

3 Research on restorative environment and mental health

The positive effects of exposure to restorative environments on mental health have been repeatedly validated in numerous studies. The common research method is the Randomized Controlled Trial (RCT), psychological variables such as depression, stress, anxiety, positive emotions, and negative emotions. Additionally, some studies incorporate physiological indicators such as salivary cortisol and heart rate variability (HRV) to provide additional evidence for the benefits.

3.1 Depression

Depression, as a complex emotional disorder, is characterized by persistent low mood, anhedonia, and cognitive dysfunction, often accompanied by physiological and psychological symptoms such as sleep rhythm disturbances, changes in appetite, fatigue, and difficulties in concentration (Fried, 2017; Rotenstein et al., 2016; Tian et al., 2023; Lin et al., 2024). Its pathogenesis involves multiple factors, including genetics, social relationships, and the environment (Wray et al., 2018). Emerging environmental stressors in modern urban settings, such as air pollution, noise interference, and exposure to artificial electromagnetic fields, have been shown to potentially increase the risk of depression (van den Bosch and Meyer-Lindenberg, 2019). Therefore, whether restorative environments can reduce or prevent depression has become one of the important topics in this field of research.

Several studies have demonstrated that restorative environments, such as natural environments, can effectively improve depression levels or cognitive deficits caused by depression (Meuwese et al., 2021; Owens and Bunce, 2022; Watkins-Martin et al., 2022). For instance, Berman et al. (2012) compared emotional and cognitive changes in patients with depression after walking for 50 min in urban and natural environments, finding that the natural environment significantly improved the patients' working memory and cognitive flexibility. In addition to direct exposure to natural environments, viewing images, videos, and virtual reality of natural environments can also effectively reduce depression levels (Li et al., 2021; Shu et al., 2022; Wang et al., 2022).

Roberts et al. (2019) conducted a meta-analysis of 33 studies on the effects of short-term exposure to natural environments on depression, revealing that natural environments have a significant but small effect on depression, potentially related to differences across studies. Although certain restorative benefits can be observed in single or short-term studies, depression, as an enduring emotional condition, is clinically diagnosed when it persists for at least 2 weeks. Therefore, it is necessary to assess the long-term benefits of restorative environments over time. Research on the timing of single exposures shows that exposure lasting over 60 min is needed to produce significant effects (Yeon et al., 2021). Frequent exposure (at least once a week, for 30 min each time) can significantly reduce the prevalence of depression in urban residents, with a reduction rate of 7% (Shanahan et al., 2016).

TABLE 1 Theories vs. operational tests.

Theory	Key claims	Candidate measures	Representative tasks	Limitations
Attention Restoration Theory	Nature restores depleted directed attention through “soft fascination,” a type of involuntary attention.	Objective cognitive tests assessing attention capacity; digit span; digit span forward; digit span backward; combined digit span backward/forward; proofreading task; necker cube pattern control; search and memory task; sustained attention to response test; symbol digit modalities test; symbol substitution test; trail making test	Induce fatigue (e.g., proofreading or sustained attention task), then expose to nature vs. urban views/walks, followed by cognitive tests to measure restoration	Directed attention is not uniformly defined; Ambiguity in the relationship between restoration of attentional resources and mental health
Stress Recovery Theory	Humans have an evolved, neurobiological mechanism to rapidly recover from stress by being in safe, natural environments.	Self-reported mood and affect (PANAS, POMS), physiological markers (HRV, skin conductance, blood pressure), salivary cortisol.	Participants are exposed to stressful scenarios and then view pictures or are immersed in natural versus urban environments. Physical and psychological measures are taken before and after the intervention to assess recovery	Evolutionary claims are hard to test; mainly short-term effects observed; ignores cognitive mechanisms; conflates emotion and cognition; fails to specify mediating neural processes.
Biophilia hypothesis	An innate tendency to connect with nature is essential for cognition, adaptation, and mental health.	Biophilic attitude inventory; environment preference ratings; self-reported wellbeing/mood;	Cross-cultural surveys evaluate “natural preferences”; Biophilic design principles in architectural contexts.	Difficult to operationalize innate “affinity”; vagueness and conceptual breadth; broad overlap with other frameworks; cultural and contextual variation is high; lack of direct causal testing; evolutionary claims controversial.
Nature-Based Biopsychosocial Resilience Theory	Contact with natural environments enhances biopsychosocial resilience, including biological, psychological, and social adaptive capacities.	Biological: cortisol/oxytocin levels, heart rate variability; psychological: resilience scales (e.g., CD-RISC), mood (PANAS), attention tasks; social: social cohesion/loneliness surveys	Longitudinal survey; physiological and neuroimaging; multimodal analysis	Unclear interaction with socio-ecological systems; supporting evidence is selective and not always robust; limited explanation of how different resilience resources influence each other
Prospect-Refuge Theory	Human prefer landscapes offering both open views and sheltered spaces	Preference/liking ratings	Rate different virtual room images for preference/comfort; Navigate virtual spaces to select hiding/observation spots, then rate prospect-refuge	Evolutionary claims controversial; Lacks clear and testable definitions, and its validity as a predictor of preferences remains contested.
Perceptual Fluency Account Hypothesis	Natural environments’ ease of processing reduces cognitive load, restoring attention and improving emotions.	Eye-tracking metrics	Eye-movement analysis of viewing high- vs. low-fractal images	No direct fluency measures specified; Limited empirical research
Relational Restoration Theory	Restorative experiences are influenced by both the physical environment and the quality of social interactions in nature.	Questionnaire measures of relationship quality, community cohesion, and wellbeing	Comparison of exposure to nature alone vs. with others	Limited empirical research; Spanning individual, social, and normative levels, it is difficult to operationalize and measure

Thus, conducting studies to comprehensively evaluate the effects of restorative environments on depression over time is crucial.

3.2 Stress

Stress refers to an individual’s physiological or psychological response to external or internal stressors, involving changes in multiple physiological systems that influence sensations and behaviors (VandenBos, 2015). Perceived stress (such as threats) is key to how humans cope with environmental challenges (McEwen, 2013). If stress is not alleviated or recovered from over a long

period, it can turn into chronic stress, leading to persistent negative emotions and ultimately causing serious illness.

Existing studies have found that exposure to restorative environments can improve self-reported stress levels (Beyer et al., 2014; Lega et al., 2021; Van den Berg et al., 2014). From a physiological perspective, stress-related neurophysiological signals, including salivary cortisol (Daniels et al., 2022), hair cortisol (Jezova et al., 2025), norepinephrine (Mygind et al., 2021), and vagally mediated heart rate variability (Yin et al., 2020), indicate that restorative environments can significantly alleviate stress, with some effects, such as heart rate variability, varying with air temperature (Lamatunga et al., 2024). Daniels et al. (2022)

conducted a study where two groups of participants engaged in activities (such as walking, cycling, etc.) twice a week for 2 h each over a period of 3 weeks. The results showed that the group exposed to natural environments had lower heart rates and salivary cortisol levels, indicating that nature exposure significantly reduces stress levels. A cross-sectional survey showed that people who rarely had contact with nature had a 97.95% probability of experiencing moderate stress, while those who frequently interacted with nature had a probability of only 20.98% (Bressane et al., 2022). Moreover, many studies have explored the restorative effects of virtual natural environments (such as virtual reality, images, and videos) as an alternative, finding positive effects on emotional recovery (Gu et al., 2021), psychological stress reduction (Yu et al., 2018), and occupational stress (Naylor et al., 2020). Short-term (20–30 min) exposure to nature has also been shown to effectively reduce stress (Aziz et al., 2021; Takayama et al., 2014). Despite some evidence supporting the effects of short-term exposure to nature, there is still a lack of research on long-term stress management and coping abilities, which is particularly important for urban residents who are more susceptible to chronic stress (Berto, 2014).

3.3 Anxiety

Anxiety is an emotion characterized by worry and tension, often occurring when an individual anticipates an impending threat or misfortune, representing a long-term reaction to future events (VandenBos, 2015). A large number of studies have shown that exposure to restorative environments helps alleviate anxiety (Bray et al., 2022; Browning et al., 2023; Song et al., 2020; Grassini, 2022). For example, Song et al. (2020) assessed the changes in anxiety levels of 650 college students after watching a forest landscape for 15 min. They found that, compared to watching an urban landscape, watching the forest landscape significantly reduced anxiety levels. Moreover, this effect was particularly significant among participants with higher anxiety levels. This suggests that individuals with more depleted psychological resources have a greater potential to recover in restorative environments. It should be further clarified that anxiety includes various types such as generalized anxiety, state anxiety, trait anxiety, and social anxiety, and restorative environments show different effects in alleviating each type of anxiety. Kotera et al. (2021) conducted a systematic review of 12 studies on the effects of natural walking on mental health and found that natural walking significantly reduced state anxiety but had a smaller effect on generalized anxiety. This may be because generalized anxiety is a persistent state of anxiety not limited to specific situations or triggers and is less influenced by situational factors (Spitzer et al., 2006). State anxiety, on the other hand, is a temporary response to specific situations or events, and its intensity and variation are more susceptible to situational factors (Spielberger, 1983). These differences lead to better intervention effects of restorative environments on state anxiety, as safe, lowdistraction restorative environments can help individuals temporarily detach from anxietyinducing situations or events, thus restoring psychological resources and enhancing adaptive levels.

3.4 Wellbeing

Wellbeing refers to a state of happiness and life satisfaction, encompassing both physical and mental health (VandenBos, 2015). Exposure to restorative environments has been shown to enhance wellbeing (de Vries et al., 2021; Feng and Astell-Burt, 2017; White et al., 2019). For instance, White et al. (2019) found that spending over 120 min in nature per week predicted higher wellbeing and better health. Beyond self-reports, biomarkers have also been used to assess these effects (Jezova et al., 2025). Moreover, the quality of forest experiences, such as sensory features like smell, further shapes wellbeing gains (Výboštok et al., 2024; Hedblom et al., 2019). Moreover, this effect was consistent across different groups. One explanation is that the wellbeing benefits of restorative environments may be closely linked to nature relatedness (NR), which describes the physical and psychological connection between humans and nature, including cognitive and emotional aspects (Nisbet et al., 2011). Samus et al. (2022) further demonstrated that the wellbeing effects of restorative environments are moderated by nature relatedness. The stronger an individual's connection to nature, the greater the wellbeing benefits they experience from nature exposure. Research also suggests that species diversity in natural environments enhances nature relatedness, further amplifying the wellbeing benefits of restorative environments (Southon et al., 2018). Therefore, studies should also consider the moderating role of nature relatedness.

4 Cognitive neuroscience research on restorative environments

With advances in cognitive neuroscience technologies in recent years, environmental neuroscience has emerged. Environmental neuroscience is an interdisciplinary field that examines the bidirectional interactions between physical environments, brain activity, and behavior (Berman et al., 2019). This field investigates how environmental factors influence brain structure and function, ultimately shaping individual behavior and mental health. Numerous studies have sought to uncover the effects of restorative environments on mood enhancement and their underlying neural mechanisms. However, much remains unknown about the specific neural pathways involved.

4.1 Frontal cortex

The prefrontal cortex plays a central role in cognitive functions such as attention, working memory, and emotional regulation. Its activity is closely associated with the onset and persistence of emotional disorders like depression. Recent research suggests that exposure to restorative environments can modulate prefrontal cortex activity, thereby contributing to the alleviation of depressive symptoms (Bratman et al., 2015; Olszewska-Guizzo et al., 2020). For example, Bratman et al. (2015) used fMRI to examine brain activity in 31 participants after a forest walk and found reduced activation in the subgenual prefrontal cortex (sgPFC), alongside decreased self-reported rumination. Given the sgPFC's involvement in self-focused emotional evaluation, this reduction

may reflect a neural mechanism through which nature exposure disrupts repetitive negative thinking and facilitates more balanced emotional processing.

Beyond depressive symptoms, prefrontal cortex activity is also linked to stress responses and the experience of positive emotions. When stress levels decline, prefrontal activation tends to decrease, while positive affect increases (McKlveen et al., 2013). Tost et al. (2019) employed ecological momentary assessment over 7 days and found a significant positive correlation between exposure to urban green spaces and emotional wellbeing. MRI data further revealed that individuals with greater exposure to green spaces exhibited lower prefrontal cortex activity. This finding suggests that contact with natural environments may reduce the cognitive effort required to manage negative emotions, thereby allowing for more efficient emotional regulation and improved mood.

In terms of brain structure, exposure to green environments appears to support healthy development of the prefrontal cortex, particularly in children. Dadvand et al. (2018) studied 253 children aged 6–7 and found that increased time spent in green spaces was associated with greater gray matter volume in the bilateral prefrontal cortices and left premotor cortex, as well as increased white matter volume in the right prefrontal area, left premotor area, and cerebellar hemisphere. These structural changes may reflect enhanced neurodevelopmental processes such as synaptic growth and myelination, which are supported by reduced exposure to environmental stressors. In contrast, studies have consistently shown that individuals raised in urban environments tend to exhibit lower gray matter volume and reduced cortical thickness in the dorsolateral prefrontal cortex (Besteher et al., 2017; Haddad et al., 2014; Lammeyer et al., 2019).

In summary, restorative environments influence both the function and structure of the prefrontal cortex through mechanisms such as reducing cognitive strain associated with emotional regulation and supporting neurodevelopmental integrity. These effects collectively contribute to improved emotional resilience and mental health.

4.2 Amygdala

The amygdala, a central structure within the limbic system, plays a pivotal role in processing emotional stimuli, particularly those related to fear and anxiety (Davis, 1992). A growing body of research has demonstrated a significant link between exposure to restorative environments and modulation of amygdala activity (Kühn et al., 2017; Sudimac and Kühn, 2022; Sudimac et al., 2022). For instance, Sudimac et al. (2022) found that participants who walked in natural environments exhibited significantly reduced amygdala activation, whereas those who walked in urban settings showed no notable change. This reduction in activity may reflect a neurobiological mechanism through which nature exposure dampens emotional reactivity and facilitates psychological recovery from stress. However, this effect is not uniformly observed across populations. Sudimac and Kühn (2022) reported that the reduction in amygdala activity was significant only among female participants, suggesting potential gender differences in neural sensitivity to environmental stressors. The authors proposed that such variation may be rooted in differential amygdala responsivity

to emotionally salient stimuli, as supported by prior findings (Goldfarb et al., 2019; Stevens and Hamann, 2012).

Beyond physical immersion in nature, visual exposure to environmental stimuli also appears to influence amygdala responses. Kim et al. (2010) found that viewing urban scenes elicited heightened amygdala activation, whereas rural landscapes did not produce such effects. These findings suggest that even passive exposure to restorative environments may help regulate emotional arousal by reducing the salience of potentially threatening or overstimulating cues.

Importantly, the influence of natural environments on the amygdala extends beyond transient changes in neural activity. Kühn et al. (2017) identified a positive correlation between forest coverage in residential areas and amygdala integrity, indicating that long-term exposure to green spaces may support structural resilience in emotion-related brain regions. Given the amygdala's role in stress regulation, enhanced integrity may contribute to more effective coping strategies and improved emotional stability over time.

4.3 Other brain regions

Beyond the prefrontal cortex and amygdala, restorative environments have also been shown to influence a broader network of brain regions involved in spatial cognition, attentional control, and sensory integration. For instance, Chang et al. (2021) found that viewing urban landscapes with varying levels of green density activated multiple regions, including the bilateral posterior cingulate cortex (dPCC and vPCC), superior temporal gyrus (STG), and superior parietal lobule (SPL)—areas implicated in environmental awareness and attentional modulation. Given the posterior cingulate cortex's established role in stress regulation and emotional disorders (Leech and Sharp, 2013), its activation pattern may reflect a mechanism through which restorative environments support psychological resilience by enhancing attentional disengagement from stress-inducing stimuli.

Complementary evidence from Dimitrov-Discher et al. (2022) showed that individuals residing in areas with greater green space within a 5-km radius exhibited reduced neural activity in the right insular cortex, superior parietal cortex, and lateral occipital cortex under stress conditions. These regions are involved in interoceptive awareness, sensory processing, and visuospatial attention, and their reduced activation may indicate a dampening of stress-related sensory vigilance in response to natural surroundings.

While these findings collectively suggest that restorative environments modulate neural systems beyond emotion-specific circuits, variability across studies—stemming from differences in experimental design, stimulus type, and measurement techniques—highlights the complexity of brain–environment interactions. As Berman et al. (2019) note, understanding how specific environmental features shape neural responses remains a central challenge in environmental neuroscience.

4.4 Brain functional network

Several studies have investigated how restorative environments influence brain functional connectivity. For example, Gould van

Praag et al. (2017) compared the overall activation levels of the default mode network (DMN) under natural and artificial environmental sounds. Results indicated that while natural environmental sounds did not significantly enhance overall DMN activation, they shifted functional connectivity from the anterior to the posterior midline. This suggests that the focus of functional connectivity shifted from the front part of the DMN (such as the anterior cingulate cortex and medial prefrontal cortex) to the posterior part (such as the posterior cingulate cortex and precuneus), indicating that natural environmental sounds have a specific regulatory effect on the functional connectivity patterns of the DMN. Stobbe et al. (2024) studied the differences in resting-state fMRI (rs-fMRI) functional connectivity under natural and urban soundscapes and found that, under natural soundscape conditions, functional connectivity significantly increased between auditory networks, cingulate-insular networks, and somatomotor hand and mouth networks.

In terms of vision, Kühn et al. (2021) found that viewing images of natural environments enhanced connectivity between the dorsolateral attention network (DAN) and the visual attention network (VAN), as well as between DAN and the default mode network (DMN), and DMN and somatomotor networks. Among these, the DAN-DMN connection was the strongest, and numerous studies have linked it to cognitive processing (Dixon et al., 2017). Chang et al. (2021) found that when viewing urban green spaces, the effective connectivity between the ventral posterior cingulate cortex and prefrontal cortex and hippocampus may be one of the reasons for regulating stress. Since fMRI scanning environments cannot capture the real-time impact of natural settings on brain activity, some studies have employed portable EEG devices to investigate their effects on functional connectivity. Chen et al. (2020) compared the differences in EEG functional connectivity between exposure to natural and urban environments and found that functional connectivity was enhanced in the natural environment group, particularly in the right hemisphere. Moreover, the power correlations in delta, theta, alpha, and beta frequency bands were all significantly higher in the natural environment group compared to the urban environment group, indicating that the natural environment modulates functional connectivity across multiple EEG frequency bands. Imperatori et al. (2023) further observed that watching videos of natural environments increased theta wave power spectral density in the parietal region and significantly enhanced functional connectivity between brain regions. The topological patterns of these connections highly overlapped with the DMN.

Although relevant studies have explored the neural activity changes brought about by restorative environments from the perspective of brain connectivity, evidence for neural activity changes related to emotional improvement is still lacking. Limited by current equipment, most of the research focuses on observing resting-state neural activity before and after exposure to natural environments, or studying the effects of viewing restorative environment images and videos on brain activity. When investigating the effects on psychological health, short-term immediate changes are insufficient to fully reflect the impact of restorative environments. Therefore, it is more important to examine the long-term effects of restorative environments on mental health. This not only aligns with the need for psychological

resource recovery in daily life but also provides empirical evidence for the use of restorative environments as an adjunct to treatment.

4.5 Converging neural patterns

Synthesizing existing research, the neural effects of restorative environments converge on two primary patterns: downregulated activity in key brain regions and reconfigured connectivity between large-scale networks. First, fMRI studies consistently reveal decreased activation in the amygdala and the subgenual prefrontal cortex (sgPFC), providing direct neural evidence for stress reduction and decreased rumination, respectively (Bratman et al., 2015; Sudimac et al., 2022). Second, at the network level, a core change involves enhanced functional connectivity between the Default Mode Network (DMN) and executive attention networks, a pattern thought to be the neural basis for shifting cognitive resources from internal thought to external perception (Kühn et al., 2021).

The granularity of these neural patterns is, however, method-dependent. fMRI, with its high spatial resolution, excels at pinpointing activity changes in specific structures and mapping interactions between distinct networks (e.g., Chang et al., 2021; Kühn et al., 2021). In contrast, EEG captures high-resolution temporal dynamics, typically revealing more global effects such as hemisphere-specific increases in connectivity or modulations of specific frequency bands like theta and alpha waves (Chen et al., 2020; Imperatori et al., 2023). In short, while fMRI clarifies where restorative effects occur, EEG elucidates the brain's responsive rhythmic state.

5 Discussion

Research on the effects of restorative environments on mental health has been expanding annually. Methodologically, advancements in virtual reality, ecological momentary assessment, fMRI, and satellite remote sensing have improved the reliability of experimental studies. Theoretically, Attention Restoration Theory and Stress Recovery Theory remain dominant frameworks; however, both theories contain operationally ambiguous definitions and verification challenges. Despite these limitations, empirical findings consistently indicate that restorative environments positively impact depression, anxiety, stress, and wellbeing. This study confirms that restorative environments promote psychological improvements primarily through neural mechanisms involving two key brain regions: the amygdala and the prefrontal cortex. Exposure to these environments consistently downregulates amygdala activity, reducing emotional reactivity and stress responses, while concurrently enhancing prefrontal cortex function, supporting cognitive control and emotional regulation. These neural effects have been observed across both natural and simulated settings, with variations in intensity and duration depending on the mode of exposure. This complex process is summarized visually in Figure 1.

Notably, there is still no comprehensive model that systematically explains the relationship between environmental features, cognitive and neural responses, and psychological

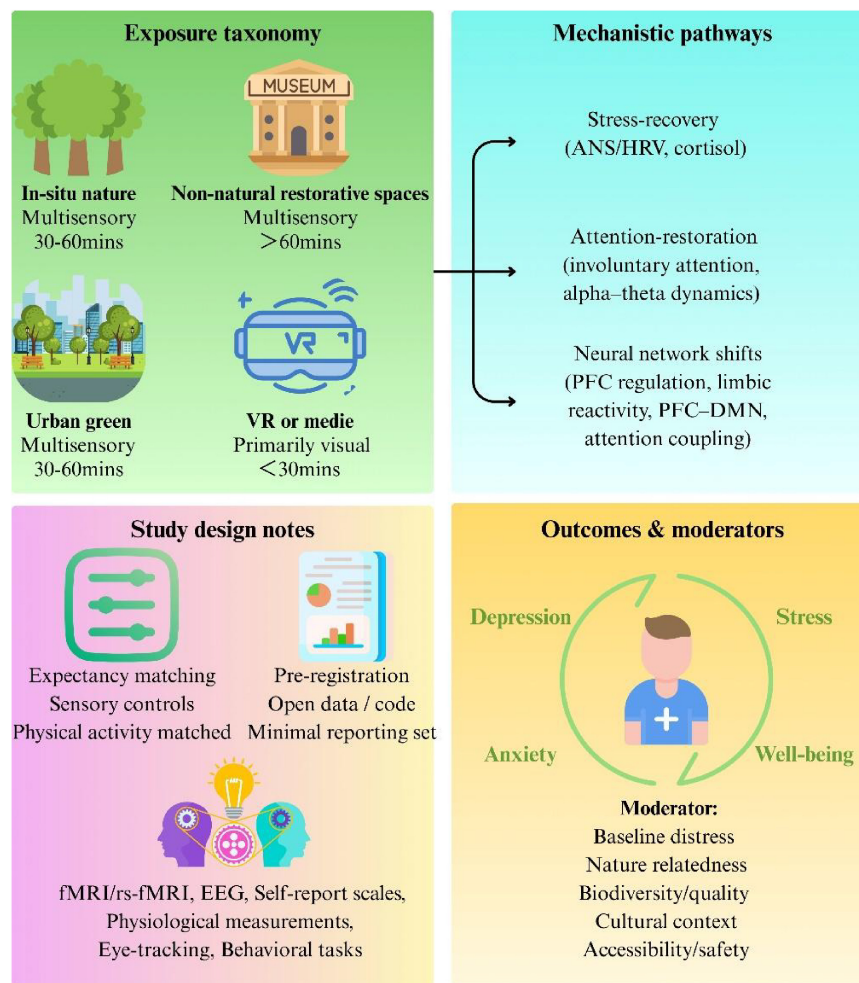


FIGURE 1
From setting to symptom: a multilevel map of restoration.

benefits. To address the limitations of current research, the following recommendations are proposed: Improvements in research methods: (1) Increase the collection and comprehensive analysis of multimodal data, integrating neuroimaging (e.g., fMRI/EEG), physiological biomarkers (e.g., cortisol, HRV), behavioral measurements (e.g., eye-tracking), and ecological sensor data (e.g., air quality, green space exposure) through machine learning algorithms. This could reveal the dynamic interactions between environmental stimuli, neural processing, and psychological outcomes. (2) Given evidence of reduced amygdala activation (Sudimac et al., 2022) and enhanced prefrontal connectivity (Chang et al., 2021), future studies are encouraged to develop nature-based interventions tailored to specific psychiatric conditions. Combining environmental exposure with neuroimaging may help identify neural markers of recovery and inform personalized treatment strategies. Additionally, early exposure to green environments during neurodevelopmental windows may support structural maturation of emotion- and cognition-related regions (Dadvand et al., 2018). It is recommended that future research examine how restorative environments contribute to long-term mental resilience in children through neural development pathways. (3) Incorporate

comparative studies on different modes of exposure. While virtual reality and mental imagery approaches provide controlled and cost-effective alternatives to field experiments, their ecological validity remains underexplored. Future research should systematically compare the psychological and neural effects of VR-based, imagery-based, and real-world forest exposures. (4) Increase long-term intervention studies: Currently, most research results are based on short-term exposures, and the long-term effects of repeated interventions remain unclear. Individuals living in areas with varied vegetation cover show significant differences in brain structure and neural activity levels (Besteher et al., 2017; Dadvand et al., 2018; Lammeyer et al., 2019), suggesting that long-term restorative environment interventions may lead to lasting changes in mental health. In addition, evidence from large-scale, longitudinal surveys (e.g., Pichlerová et al., 2021, 2023) suggests that cumulative, real-life visits offer more conclusive insights into holistic wellbeing and can reveal potential risks such as biophobia associated with rewilding environments. Mixed-method designs that combine experimental precision with long-term ecological assessment will provide a more comprehensive understanding of restorative effects. Future studies should explore the effects of long-term, repeated interventions on mental and neural health

and transform intervention strategies into practical tools for promoting mental health, ultimately improving public health. (5) Focus on individual differences and contextual moderators: Traits such as nature relatedness have been shown to amplify affective and cognitive benefits in natural settings (Southon et al., 2018), while baseline mental states like anxiety may modulate responsiveness to environmental cues (Song et al., 2020). Age-related variation is also salient: children and older adults exhibit distinct neural and behavioral restoration profiles (Wu and Gollo, 2025). Contextual factors—including urban density and the cultural symbolism of sites—can further influence perceived restorative value (Abdulkarim and Nasar, 2014; Ouellette et al., 2005). Future studies should incorporate these moderators into sampling, measurement, and analysis strategies to better capture population-specific dynamics and improve ecological validity. (6) Establish a minimal reporting set to enhance transparency and replicability. Future studies should clearly describe key methodological elements, including exposure characteristics (type, duration, intensity), comparator conditions, and blinding or expectancy control measures. Pre-registration of study protocols and hypotheses is strongly recommended. For neuroimaging studies, essential reporting should cover preprocessing pipelines, preregistered regions of interest or network-level analyses, and the availability of open data and code for independent verification. Adhering to such standardized reporting practices will facilitate cross-study comparisons and cumulative evidence synthesis.

New theoretical construction: Attention Restoration Theory and Stress Recovery Theory have evolutionary psychology implications, but they pose challenges in verification and cannot adequately explain the restorative effects of artificial environments. These theories do not provide sufficient guidance for applied research and practical environmental design. Future theoretical developments should evolve beyond a single perspective toward a multidimensional, interdisciplinary integration approach. Combining the cognitive appraisal model with a socio-ecological perspective—that is, considering human adaptation to nature as well as the role of cultural and social factors—should integrate individual differences, cognitive processing, and neural activity. This approach should also explore the complex interactions between these factors and the environment.

Brain network analysis methods: key cognitive functions do not rely on individual brain regions but rather on the communication between different brain regions. This view is increasingly accepted (Axe and Amunts, 2022; Lee et al., 2022; Thiebaut de Schotten and Forkel, 2022). But most studies on the cognitive-neural mechanisms of restorative environments focus on individual brain regions, with few studies exploring the effects from the perspective of brain connectivity (Chang et al., 2021; Kühn et al., 2021; Zhang et al., 2023). It is necessary to utilize global functional connectivity, non-linear brain dynamics, and brain network modularization to better reveal the interactions between the environment and the brain (Berman et al., 2019). Future research should focus on the changes in brain networks induced by restorative environments, as exploring the neural mechanisms of this impact is highly valuable. Yet the limited number of studies and their heterogeneous paradigms—for example, static images, virtual reality, or real-world exposure, as well as differing measures such as task-based activation, resting-state connectivity, and network-level dynamics—make it difficult to draw reliable

quantitative conclusions about which environmental dimensions most strongly influence neural activity. Future research with larger samples and more standardized designs will be crucial to resolve these differences.

Practical implications for policy and management: Beyond theoretical and methodological advancements, these findings hold implications for practice. For policy-makers, integrating green infrastructure into urban planning is essential for preventive mental health strategies. Forest managers and landscape designers should consider not only the amount of greenery but also its accessibility, perceived safety, and opportunities for social interaction. To enhance the applicability of restorative design in urban contexts, planners should tailor interventions to the needs of diverse populations. For children, proximity to biodiverse green spaces supports cognitive development and attentional restoration (Dadvand et al., 2018). Older adults may benefit from low-stimulation, accessible natural paths that promote calm and mobility (Qiu et al., 2021). Individuals with elevated stress or anxiety may respond best to quiet, enclosed settings such as meditation gardens or small-scale green refuges. Cultural preferences should also inform design—spaces imbued with local meaning, such as religious or historical sites, may foster deeper psychological engagement and social cohesion (Abdulkarim and Nasar, 2014; Ouellette et al., 2005). An inclusive, evidence-based framework that integrates these considerations can support more equitable and effective urban restoration strategies. Ultimately, interdisciplinary collaboration between environmental scientists, urban planners, and mental health professionals is critical for translating evidence into policies and interventions that promote population wellbeing.

Author contributions

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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