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EFFECTS OF URBAN, NATURAL, AND DIGITAL ENVIRONMENTS ON PHYSICAL ACTIVITY AND WELL-BEING

Addressing methodological challenges in restorative environments research

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Summary

Background. In recent years, the health benefits of exposure to natural environments have gained increasing attention across multiple fields, including psychology, public health, and urban planning. The growing body of research suggests that interaction with nature can support psychological and physiological well-being. While foundational theories such as the Stress Reduction Theory (SRT) and Attention Restoration Theory (ART) have laid the groundwork for understanding how nature influences psychological health, more recent perspectives, such as the instoration domain, highlight the role of physical activity in nature (green exercise) in enhancing overall well-being. This thesis explores these connections, explicitly focusing on the effects of green exercise on physical and mental health. By integrating psychological, physiological, and environmental factors, the research aims to comprehensively understand nature-based physical activity's restorative potential.

Methods. The research comprises three studies designed to investigate the multifaceted effects of nature exposure on health. The first study is a comprehensive review of green exercise research, evaluating the existing methodologies, findings, and potential gaps in the literature. This review also emphasizes methodological challenges such as inconsistent comparison conditions and limited measures of nature exposure, guiding future research directions.

The second study is an experimental investigation that assesses green exercise's psychological and physiological benefits. In this study, participants engaged in a one-hour walking session across three environments: urban, natural, and indoor. Physiological markers, including heart rate (HR), heart rate variability (HRV), and cortisol levels, were measured to assess the body’s recovery from stress. Psychological outcomes were evaluated using validated self-report measures of affective states (positive and negative emotions), perceived effort, psychological restoration, and enjoyment of the physical activity. The study examined how these outcomes varied depending on the environment, comparing the restorative and stress-reducing effects of physical activity in nature with those in urban and indoor settings.

The third study focuses on hypoxia as a physiological stressor and investigates how exposure to natural environments may support recovery from this stressor. This study explored the impact of hypoxia on both psychological and physiological outcomes, particularly anxiety. It examined whether the restorative qualities of nature (measured through perceived restorativeness) could buffer the psychological impact of oxygen deprivation.

Results. The review (Study 1) identified key gaps in the current literature, including inconsistencies in study designs and shortcomings in green space assessment. It highlighted the need for more precise and standardized measures of nature exposure and the integration of individual perceptions of restorative potential in future studies.

Results from Study 2 indicated that exposure to natural environments during physical activity significantly improved physiological and psychological health outcomes. Specifically, participants engaging in green exercise showed increased heart rate variability, reduced cortisol levels, and improved mood states compared to those in urban or indoor environments. These findings suggest that nature-based physical activity can enhance stress recovery, improve emotional well-being, and foster positive changes in health-related physiological markers.

Results from Study 3 demonstrated that hypoxia induces stress, as evidenced by increased anxiety and changes in physiological markers. However, individual perceptions of restorativeness, especially in natural environments, appeared to buffer the psychological impact of hypoxia. Participants who rated nature-related images as more restorative reported lower levels of anxiety, suggesting that the restorative qualities of nature can mitigate the adverse effects of stressors, even in challenging contexts like hypoxia.

Conclusion. Despite mixed findings in the previous literature, this thesis provides robust evidence for the restorative and enhancing effects of nature-based physical activity on psychological and physiological well-being. The findings support the integration of green exercise into public health strategies aimed at improving mental and physical health. Moreover, the results underscore the importance of further investigating the underlying mechanisms of these effects, mainly through the lens of the instoration

domain, which emphasizes not only recovery but also the promotion of adaptive behaviors and resilience. These findings contribute to developing interventions and policies that harness the health-promoting potential of natural environments, fostering both individual well-being and broader societal health.

Oversigt

Baggrund. I de senere år har sundhedsmæssige fordele ved eksponering for naturlige miljøer fået øget opmærksomhed på tværs af flere fagområder, herunder psykologi, folkesundhed og byplanlægning. Den voksende forskningsbase viser, at interaktion med naturen kan støtte både psykisk og fysiologisk velvære. Mens grundlæggende teorier som Stress Reduction Theory (SRT) og Attention Restoration Theory (ART) har lagt grundlaget for forståelsen af, hvordan natur påvirker psykisk sundhed, fremhæver nyere perspektiver, som instoration-domenet, rollen af fysisk aktivitet i naturen (green exercise) i at forbedre generelt velvære. Denne afhandling udforsker disse forbindelser med særlig fokus på effekterne af green exercise på fysisk og mental sundhed. Ved at integrere psykologiske, fysiologiske og miljømæssige faktorer sigter forskningen mod at opnå en omfattende forståelse af den restorative potentiale ved naturbaseret fysisk aktivitet.

Metoder. Forskningen består af tre studier, der er designet til at undersøge de mangeartede effekter af naturens eksponering på sundhed. Det første studie er en omfattende gennemgang af green exercise forskning, der vurderer eksisterende metoder, resultater og potentielle huller i litteraturen. Denne gennemgang fremhæver også metodologiske udfordringer som inkonsistente sammenligningsbetingelser og begrænsede målinger af naturens eksponering, og vejleder fremtidig forskning. Det andet studie er en eksperimentel undersøgelse, der vurderer green exercises psykologiske og fysiologiske fordele. I dette studie deltog deltagerne i en times gåtur i tre forskellige miljøer: urbane, naturlige og indendørs. Fysiologiske markører, herunder hjertefrekvens (HR), hjertefrekvensvariabilitet (HRV) og cortisolniveauer, blev målt for at vurdere kroppens restitution fra stress. Psykologiske resultater blev evalueret ved hjælp af validerede selvrapportmål for affektive tilstande (positive og negative følelser), opfattet indsats, psykologisk restitution og nydelse af den fysiske aktivitet. Studiet undersøgte, hvordan disse resultater varierede afhængigt af miljøet, ved at sammenligne de restorative og stressreducerende effekter af fysisk aktivitet i naturen med de i urbane og indendørs miljøer. Det tredje studie fokuserer på hypoxi som en fysiologisk stressfaktor og undersøger, hvordan eksponering for naturlige miljøer kan støtte restitution fra denne

stressfaktor. Dette studie undersøgte effekten af hypoxi på både psykologiske og fysiologiske resultater, især angst. Det blev undersøgt, om naturens restorative kvaliteter (målt gennem opfattet restorativeness) kunne reducere den psykologiske påvirkning af iltmangel.

Resultater. Gennemgangen (Studie 1) identificerede nøglehuller i den nuværende litteratur, herunder inkonsekvenser i studiedesign og mangler i vurdering af grønne områder. Den fremhævede behovet for mere præcise og standardiserede målinger af naturens eksponering og integration af individuelle opfattelser af restorative potentiale i fremtidige studier. Resultaterne fra Studie 2 viste, at eksponering for naturlige miljøer under fysisk aktivitet signifikant forbedrede fysiologiske og psykologiske sundhedsresultater. Deltagere, der deltog i green exercise, viste øget hjertefrekvensvariabilitet, reducerede cortisolniveauer og forbedrede humørtilstande sammenlignet med dem, der var i urbane eller indendørs miljøer. Disse fund tyder på, at naturbaseret fysisk aktivitet kan forbedre stressrestitution, forbedre følelsesmæssigt velvære og fremme positive ændringer i sundhedsrelaterede fysiologiske markører. Resultaterne fra Studie 3 viste, at hypoxi inducerede stress, som det fremgår af øget angst og ændringer i fysiologiske markører. Dog syntes individuelle opfattelser af restorativeness, især i naturlige miljøer, at reducere den psykologiske påvirkning af hypoxi. Deltagere, der vurderede naturrelaterede billeder som mere restorative, rapporterede lavere angstniveauer, hvilket tyder på, at naturens restorative kvaliteter kan afbøde de negative virkninger af stressorer, selv i udfordrende kontekster som hypoxi.

Konklusion. På trods af blandede fund i den tidligere litteratur, giver denne afhandling stærke beviser for de restorative og forbedrende effekter af naturbaseret fysisk aktivitet på psykologisk og fysiologisk velvære. Resultaterne understøtter integrationen af green exercise i folkesundhedsstrategier, der sigter mod at forbedre mental og fysisk sundhed. Desuden understreger resultaterne vigtigheden af at undersøge de underliggende mekanismer bag disse effekter, primært gennem instoration-domenet, som fremhæver ikke kun restitution, men også fremme af adaptive adfærdsmønstre og modstandsdygtighed. Disse fund bidrager til udviklingen af interventioner og politikker,

der udnytter naturens sundhedsfremmende potentiale, hvilket fremmer både individuelt velvære og samfundets sundhed.

Sommario

Background. Negli ultimi anni, i benefici per la salute derivanti dall'esposizione agli ambienti naturali hanno attirato un interesse crescente in vari ambiti, tra cui la psicologia, la sanità pubblica e la pianificazione degli spazi urbani. Un numero crescente di studi suggerisce che essere in contatto e interagire con la natura può supportare il benessere psicologico e fisiologico. Sebbene teorie come la Stress Reduction Theory (SRT) e la Attention Restoration Theory (ART) abbiano gettato le basi per comprendere come la natura influenzi la salute psicologica, approcci più recenti, che tengono conto delle capacità degli spazi verdi di incentivare comportamenti salutari, evidenziano il ruolo dell'attività fisica in natura (green exercise) ne sostenere il benessere complessivo. Questa tesi esplora queste la relazione tra esposizione alla natura e benessere, con particolare attenzione agli effetti del green exercise sulla salute fisica e mentale. Integrando lo studio di fattori psicologici, fisiologici e ambientali, la ricerca si propone di fornire una comprensione completa del potenziale rigenerativo dell'attività fisica svolta in differenti contesti ambientali.

Metodi. La tesi comprende tre studi progettati per indagare gli effetti dell'esposizione alla natura sulla salute. Il primo studio è una review della letteratura recente sul green exercise, finalizzata a valutare le metodologie esistenti nel campo, i principali effetto benefici – sia a breve che a lungo termine – e le potenziali lacune nella ricerca. La review evidenzia anche le sfide metodologiche in questo campo di studio, come la mancanza di coerenza nelle condizioni di confronto negli studi sperimentali e le limitazioni nella misurazione dell'esposizione alla natura, offrendo spunti per futuri sviluppi.

Il secondo studio è un esperimento che valuta *on field* i benefici psicologici e fisiologici del green exercise. In questo studio, i partecipanti hanno svolto una sessione di camminata della durata di un'ora in tre ambienti diversi: urbano, naturale e indoor. Sono stati misurati indicatori fisiologici come la frequenza cardiaca (HR), la variabilità della frequenza cardiaca (HRV) e livelli di cortisolo per valutare le risposte dell'organismo all'attività. Gli effetti psicologici sono stati valutati mediante misure self-report degli stati

affettivi (emozioni positive e negative), la percezione dello sforzo, la rigenerazione psicologica e piacere legato allo svolgimento dell'attività fisica. Lo studio ha esaminato come questi esiti varino a seconda dell'ambiente, confrontando gli effetti rigenerativi dell'attività fisica in natura rispetto agli ambienti urbani e indoor.

Il terzo studio si concentra sull'ipossia come fattore di stress fisiologico e indaga come l'esposizione agli ambienti naturali possa supportare il recupero da questo stato di stress. Questo studio ha esaminato l'impatto dell'ipossia su variabili piscologiche e fisiologiche, in particolare sull'ansia, e ha valutato se le percezioni delle potenzialità rigenerative della natura (misurate attraverso questionari standardizzati) potessero attenuare l'impatto psicologico e fisiologico della riduzione di ossigeno rappresentata dall'ipossia.

Risultati. La review della letteratura (Studio 1) ha evidenziato importanti lacune nella letteratura attuale, inclusi problemi di coerenza nei metodi e nelle procedure degli studi esaminati e limitazioni nelle modalità di valutazione degli spazi verdi, e ha indicato aree di sviluppo e spunti per future ricerche nel campo. I risultati dello Studio 2 hanno mostrato come l'esposizione agli ambienti naturali durante l'attività fisica impatti significativamente sia le variabili fisiologiche che psicologiche. In particolare, i partecipanti che hanno svolto green exercise hanno mostrato un aumento della variabilità cardiaca, una riduzione del cortisolo e un miglioramento dello stato emotivo rispetto allo svolgimento della stessa tipologia di attivtà fisica in ambienti urbano o indoor. Questi risultati suggeriscono che l'attività fisica in ambienti naturali può favorire il recupero dallo stress, migliorare il benessere emotivo e indurre cambiamenti positivi nei marker fisiologici legati alla salute. Inoltre, il green exercise può aiutare nel sostenere un maggior livello di attività fisica e quindi stili di vita più salutari.

I risultati dello Studio 3 hanno dimostrato che l'ipossia induce stress, come evidenziato dall'aumento dell'ansia e dalle modifiche nei marker fisiologici. Tuttavia, la percezione individuale della rigenerativià degli ambienti a cui sono stati esposti i partecipanti, sembra aver attenuato l'impatto psicologico dell'ipossia. I partecipanti che hanno attribuito un punteggio più alto alle immagini hanno riportato livelli più bassi di

ansia, suggerendo che le qualità rigenerative degli ambienti possano attenuare gli effetti negativi dei fattori di stress, anche in contesti difficili come l'ipossia.

Conclusioni. Nonostante i risultati contrastanti nella letteratura precedente, questa tesi fornisce prove solide sugli effetti rigenerativi e sui vantaggi dell'attività fisica svolta in natura sul benessere psicologico e fisiologico. I risultati supportano l'integrazione del green exercise nelle strategie di salute pubblica finalizzate al miglioramento della salute mentale e fisica. Inoltre, i risultati sottolineano l'importanza di approfondire ulteriormente i meccanismi alla base di questi effetti, in particolare attraverso il concetto di *instoration*, che enfatizza non solo il recupero, ma anche la promozione di comportamenti adattivi e di resilienza. Questi risultati contribuiscono allo sviluppo di interventi e politiche che sfruttano il potenziale salutare degli ambienti naturali, migliorando il benessere individuale e la salute pubblica.

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Abbreviations

AEAL	Achievement Emotions Adjective List
ANOVA	Analysis of Variance
ANS	Autonomic Nervous System
ART	Attention Restoration Theory
CR-10	Borg's category ratio scale of perceived exertion
ECG	Electrocardiogram
GE	Green Exercise
GPS	Global Positioning System
HR	Heart Rate
HRV	Heart Rate Variability
LMMs	Linear Mixed Models
NCDs	Noncommunicable Diseases
NDVI	Normalized Difference Vegetation Index
PA	Physical Activity
PACES	Physical Activity Enjoyment Scale
PFA	Perceptual Fluency Account
PNS	Parasympathetic Nervous System
PRS	Perceived Restorativeness Scale
RMSSD	Root Mean Square of Successive Difference
ROS	Restoration Outcome Scale
RPE	Rate of perceived exertion
SNS	Sympathetic Nervous System
SRT	Stress Recovery Theory
WHO	World Health Organization

Introduction

The importance of urban green spaces for promoting healthy living has gathered renewed attention in recent years. Historically, green spaces have been recognized as beneficial for public health, although the mechanisms behind these benefits were not always fully understood. Recent research advancements have clarified how green spaces contribute to preventing non-communicable diseases, such as mental illness, obesity, and cardiovascular conditions, which are often associated with chronic stress and physical inactivity.

Physical inactivity remains a significant public health concern in Europe and Italy, particularly regarding increasing urbanization and limited access to green spaces. According to the Special Eurobarometer 525 survey (European Commission, 2023), as of the latest data, 56% of Italians do not engage in any physical exercise or sports, compared to the EU average of 45%. Notably, 24% of boys and 30% of girls aged 15 to 24 report never or rarely participating in physical activity. When considering physical activities outside of organized sports—such as commuting, gardening, and dancing—46% of Italians do not engage in any form of physical activity, compared to 31% of Europeans. Furthermore, data indicate that 50% of Italians who participate in sports do so outdoors in parks and other natural settings, while only 16% exercise at home. In contrast, the European average shows that 37% of individuals practice sports indoors.

Green spaces promote health by providing environments encouraging physical activity, improving mental well-being, and reducing exposure to harmful environmental factors (WHO, 2016). This potential is reflected in international commitments, such as the WHO's 2010 Parma Declaration and the UN's Sustainable Development Goals, highlighting the need for universal access to safe and inclusive green spaces.

These considerations are increasingly urgent as urbanization continues to rise globally. Currently, over 55% of the world's population resides in urban areas, projected to reach 68% by 2050 (WHO, 2016). While urbanization brings economic growth and development, it also presents significant public health challenges. Urban areas suffer from environmental degradation, pollution, and inadequate infrastructure. For instance,

91% of urban residents breathe polluted air and nearly 40% lack access to safe sanitation services and clean drinking water. Inadequately designed urban transport systems contribute to traffic-related injuries and air and noise pollution, creating barriers to safe physical activity (WHO, 2021).

In addition to these challenges, urban environments are epicentres for noncommunicable diseases (NCDs), such as heart disease, asthma, cancer, and diabetes, which are exacerbated by unhealthy living conditions, limited access to green spaces, and high levels of pollution (WHO, 2021). Urbanization has also been linked to a rise in mental health disorders, including higher rates of depression and anxiety. As cities expand, the availability and quality of green spaces diminish, reducing opportunities for people to engage in outdoor physical activity and further limiting contact with restorative natural environments.

This reduction in access to green spaces curtails physical activity and deprives urban populations of the mental health benefits of nature exposure. Consequently, the need to preserve and expand urban green spaces becomes critical to mitigate the adverse effects of urbanization on public health, providing environments conducive to physical and psychological well-being.

1.1 Pathways linking green spaces to health and well-being

Several conceptual models have been proposed to explain the relationship between nature and health. Hartig et al. (Hartig et al., 2014) presented a model that identified four key pathways through which nature influences human health: air quality, physical activity, social contact, and stress reduction. The model also considers individual characteristics, such as age and gender, and broader contextual factors, including cultural practices, which may modulate the strength of these health benefits. Additionally, distance, accessibility, weather conditions, and perceived safety can influence how individuals engage with natural environments.

Hartig and colleagues (2014) further emphasized that these four pathways are inherently interconnected, as exposure to nature often engages multiple mechanisms simultaneously. For example, spending time in natural settings frequently entails physical

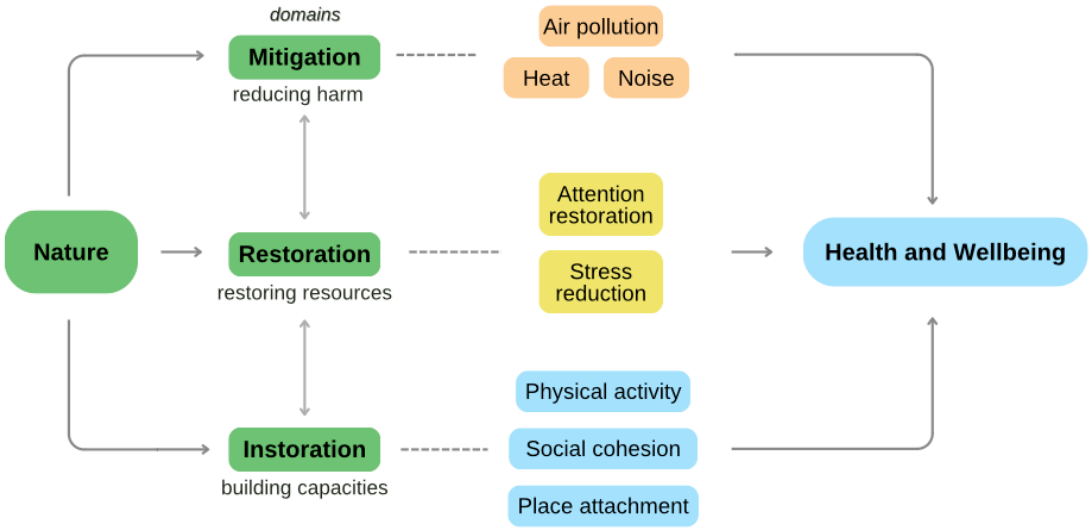
activity rather than mere passive exposure, leading to a combined effect of stress reduction and increased movement. This interplay highlights the need to consider the synergistic nature of these pathways when evaluating the benefits of natural environments on health and well-being.

Markevych et al. (Markevych et al., 2017) built on Hartig et al.'s work by organizing the pathways into three broad domains: reducing harm, restoring capacities, and building capacities. The mitigation domain focuses on greenspace's role in reducing exposure to environmental stressors, such as air pollution and noise. In contrast, the restoration domain replenishes depleted cognitive and emotional resources. The instoration domain highlights the capacity-building role of nature, which includes promoting physical activity and fostering social connections. This integrative framework better reflects the multidimensional ways green spaces promote health by mitigating exposure to stressors, replenishing depleted resources, and facilitating the development of new resources that support coping.

Bratman et al. (Bratman et al., 2019) added to this understanding by focusing specifically on the effects of nature on mental health. Their model is structured into four steps: natural features, exposure, experience, and mental health effects. Unlike previous models, Bratman et al. emphasize the importance of the quality and type of natural features and the amount and type of exposure.

Although none of these models systematically address biodiversity, each contributes valuable insights into understanding the health benefits of nature. Marselle and colleagues (2021) further expand on these frameworks by incorporating biodiversity as a key factor, organizing pathways linking biodiversity and health within the same three domains proposed by Markevych et al. (2017).

Figure 1. A pathways model of the benefits of natural environments on health and well-being adapted from Markevych et al. (2017) and Marselle et al. (2021).



It is important to note that the model proposed by Marselle et al. (2021) includes a fourth pathway through which nature can influence human well-being: its potential to pose health risks. This pathway, referred to by the authors as "causing harm," encompasses factors such as increased risk of allergies, infections, contact with wildlife, and other health hazards. However, this aspect falls beyond the scope of this thesis and, for simplicity, is not included in Figure 1.

1.1. Mitigation: reducing environmental stressors

Urban green spaces are critical in mitigating exposure to various environmental stressors detrimental to human health. One of the key mitigation effects of green spaces is their ability to improve air quality. Vegetation, such as trees and shrubs, can filter particulate matter, absorb gaseous pollutants, and release oxygen, thus reducing the concentration of harmful substances in the air (WHO, 2016). Research has shown that urban vegetation can decrease air pollutants and store carbon levels, contributing to better air quality in residential areas (Nowak et al., 2014; Vailshery et al., 2013); (Liu & Li, 2012). While some studies highlight the positive impact of green spaces on air quality,

others suggest that the effectiveness of vegetation in regulating pollutants may depend on factors such as species diversity, planting density, and structural complexity (Hewitt et al., 2020). Certain plants may also produce allergens or volatile organic compounds that could counteract some of the benefits of air quality (Xing & Brimblecombe, 2020).

Another essential function of green spaces is noise mitigation. Noise pollution, a well-known cause of adverse health outcomes such as cardiovascular diseases (Basner et al., 2014; Lelieveld et al., 2019), can be reduced through vegetation, which acts as a natural barrier to sound. Studies have shown that tree density and structural complexity effectively dampen noise from traffic and industrial sources, providing a quieter and healthier environment (Cohen et al., 2014; Haase et al., 2014). Despite these benefits, the tangible impact of vegetation on air quality and noise reduction remains a topic of ongoing debate due to the complex interactions between plants and the urban environment (Salmond et al., 2016).

Urban green spaces also reduce the urban heat island effect, a phenomenon where cities experience higher temperatures than surrounding rural areas due to the concentration of buildings and paved surfaces (Oke, 1982). Vegetation helps cool urban areas through evaporation, transpiration and shading, which reduce ambient temperatures and provide relief during heatwaves (Gill et al., 2007). Trees play a crucial role in moderating temperatures by intercepting solar radiation and enhancing water evaporation, which reduces heat stress in cities (Speak et al., 2020). However, the extent of cooling vegetation depends on several factors, including tree species, leaf area, canopy structure, and water availability (Gunawardena et al., 2017). Heatwaves, which disproportionately affect vulnerable populations such as older people, are becoming a significant public health concern due to climate change (European Environment Agency, 2017), and urban green spaces can play a key role in mitigating these impacts.

Overall, the mitigation domain of urban green spaces highlights their ability to reduce exposure to environmental stressors like air pollution, noise, and extreme heat. By doing so, these spaces improve physical health outcomes and contribute to a more comfortable and sustainable urban living environment.

1.2. Restoration: replenishing resources

Interest in the restorative effects of nature significantly expanded with the development of two key psychological theories in the late 1970s and 1980s: Attention Restoration Theory (ART; Kaplan and Kaplan, 1989, Kaplan, 1995) and Stress Recovery Theory (SRT; Ulrich, 1983; Ulrich et al., 1991). These theories provided new insights into how natural environments can promote mental and emotional recovery. ART focuses on cognitive restoration, proposing that natural settings help replenish depleted attention by offering environments that engage the mind effortlessly. In contrast, SRT emphasizes nature's emotional and physiological benefits, suggesting that exposure to natural environments can quickly alleviate stress and enhance positive emotions. Both theories have played a pivotal role in shaping the study of how nature contributes to psychological well-being.

Stress Recovery Theory (SRT)

Stress Recovery Theory (SRT) posits that natural environments benefit health by facilitating recovery from stress (Ulrich, 1983; Ulrich et al., 1991). According to SRT, environments promoting stress recovery elicit interest, pleasantness, and calmness. These positive affective responses are evidenced by reduced physiological arousal, negative emotions, and enhanced positive emotions (Ulrich et al., 1991). SRT primarily addresses how people perceive and react to environments, focusing on the affective response to specific visual stimuli (Von Lindern, Lymeus, & Hartig, 2017). The theory suggests that stress responses are triggered by visual stimuli perceived as threatening, leading to physiological activation for fight-or-flight responses. Environments containing threatening elements may provoke stress due to adverse affective reactions and behavioural responses aimed at ensuring personal safety (Ulrich, 1993). Conversely, pleasant emotions associated with natural scenes signal opportunities for relaxation and the recovery of depleted adaptive resources. This process is initiated by positive affective responses elicited by mild to moderately interesting landscapes and pleasant and calm scenes.

The visual characteristics that facilitate restoration include moderate depth, complexity, focal points, and specific environmental contents, such as savannah landscapes and the presence of water (Ulrich, 1983). These elements are believed to evoke restorative responses due to their resemblance to the primary environments of human evolution, signaling survival-relevant opportunities. Viewing such pleasant scenes replaces negative emotions with positive ones, leading to decreased physiological activation and faster recovery from acute stress. This innate response is thought to have evolutionary survival value by enabling quicker stress recovery and protecting against chronic stress, thus supporting long-term adaptation to changing circumstances.

Empirical support for SRT is found in laboratory and field experiments (Ulrich, 1979; Ulrich et al., 1991) and is consistent with similar theoretical notions tested by Fredrickson and Levenson (1998), who proposed an "undoing hypothesis" where positive affect evoked by environmental stimuli facilitates stress recovery by blocking negative affect. While studies affirm the beneficial effects of nature on reducing anger, anxiety, fatigue, and sadness, meta-analyses indicate a need for more reliable evidence on the physiological benefits of nature exposure (Bowler et al., 2010).

Attention Restoration Theory (ART)

Attention restoration theory (ART) focuses on the aspects of environmental experience that allow for restoring the ability to direct attention (R. Kaplan & Kaplan, 1989; S. Kaplan, 1995; S. Kaplan & Berman, 2010). According to ART, a person can restore a depleted ability to direct attention when they experience four restorative qualities of an environment (Kaplan and Kaplan, 1989, Kaplan, 1995):

- *fascination*, observation and exploration of an environment attract and hold a person’s attention without cognitive effort;
- *being away* from everyday tasks or demands that draw upon directed attention;
- *coherence*, the environment is perceived as coherently organized;
- *scope* refers to the potential of the environment being explored.

Changes in cognitive tests after exposure to an environment are commonly used as evidence of attention restoration in Attention Restoration Theory (ART) (Ohly et al., 2016; Stevenson et al., 2018). Ohly and colleagues (2016) conducted a systematic review of 31 studies and found moderate support for ART, showing that exposure to natural environments improved cognitive tasks, which assess working memory and cognitive flexibility. However, the findings were mixed, with some studies showing limited effects. Stevenson and colleagues (2018) updated this review and found that natural environments enhanced cognitive flexibility, working memory, and attentional control, with stronger effects from real-world exposure compared to virtual environments. Their findings also suggest that longer exposure durations may contribute to the effectiveness of cognitive restoration. Together, these studies support ART while pointing to the need for more consistent methodologies and clearer identification of the cognitive processes most responsive to nature exposure.

Perceptual Fluency Account (PFA)

Joye and Van den Berg (2011) offered a critical perspective on both the Attention Restoration Theory (ART) and the Stress Recovery Theory (SRT) by challenging the assumption that restorative responses to nature are primarily rooted in evolutionary adaptations. Instead, they propose the Perceptual Fluency Account (PFA) as an alternative framework for understanding the psychological benefits of natural environments.

According to the PFA, the restorative potential of nature can be better understood through the ease with which natural stimuli are processed. This concept aligns with the notion of fascination in ART, where certain environmental stimuli are effortlessly engaging and require minimal cognitive effort (Kaplan & Kaplan, 1989). PFA extends this idea by emphasizing that perceptual fluency—defined as the ease and speed with which visual and cognitive processes handle certain types of environmental stimuli—plays a crucial role in facilitating psychological restoration (Koivisto & Grassini, 2022).

Joye and Van den Berg argue that the evolutionary perspective underlying SRT, which posits that restorative responses are an adaptive trait evolved from our species'

long history in natural environments, lacks robust empirical support. Their critique suggests that the evidence for such evolutionary roots is not compelling and that its narrow focus may limit the theoretical framework. By contrast, PFA offers a more immediate explanation: natural environments may be perceived as restorative because they present stimuli that are easier for our cognitive systems to process, leading to a more effortless and positive experience.

Unlike ART, which emphasizes fascination, or SRT, which attributes restorative benefits to evolutionary adaptations, PFA centers on the subjective experience of processing fluency. Research indicates that stimuli that are processed more easily are typically evaluated more positively, as this ease suggests efficient cognitive functioning and adequate cognitive resources (Reber et al., 2004). The PFA posits that natural environments are more coherent and predictable due to their fractal characteristics, which contribute to their processing fluency. Fractal patterns, which involve self-similar structures at various scales, enhance perceptual predictability and reduce cognitive load, making natural scenes easier to process than urban environments' often complex and divergent structures (Joye, 2007; Purcell et al., 2001). Preliminary evidence supports this notion, with studies indicating that visual preference and quicker categorization of natural scenes can be attributed to their fractal properties (Hagerhall et al., 2004).

1.3. Instoration: enhancing healthy behaviours

In addition to factors such as improved air quality, social interaction, and stress reduction, physical activity (PA) is considered a key mechanism through which natural environments can enhance well-being (Hartig, 2014). Regular engagement in PA has been shown to offer a wide range of benefits for both mental and physical health. Physiologically, PA improves cardiovascular health, increases muscular strength, and regulates metabolism, reducing the risk of chronic conditions such as heart disease, diabetes, and obesity (Warburton et al., 2006). Psychologically, PA is known to reduce symptoms of depression and anxiety, enhance mood, and improve cognitive function (Reed & Ones, 2006). Acute bouts of aerobic exercise, for example, typically lead to significant increases in self-reported positive-activated affect (PAA), whereas control conditions generally produce decreases in PAA. These effects are influenced by factors

such as exercise intensity, duration, and individual differences, highlighting the complex ways in which PA can enhance mental well-being (Reed & Ones, 2006).

Research shows that green spaces promote an active lifestyle (James et al., 2015), with green exercise offering particularly restorative benefits by enabling individuals to interact with nature, which supports the replenishment of mental and physical resources (Collado et al., 2017). GE refers to the synergistic benefits of engaging in physical activities while being directly exposed to nature (Pretty, 2004; Pretty et al., 2003). Indeed, in addition to situations where individuals have indirect contact with nature, people are often engaged in activities while exposed to natural environments, rather than remaining in a static observational stance. However, these actions can be incidental, such as encountering green spaces while biking to work, or intentional, such as going to the park for jogging or hiking in the mountains (Pretty, 2004).

As highlighted by Hartig (2014), the pathways of restoration and instoration are intertwined, with the environment playing a critical role in influencing physical activity experiences. One key aspect in which the environment affects activity is through the modulation of perceived effort. For example, research has shown that the physical setting can alter how strenuous an individual perceives exercise to be, even when the intensity remains the same. A field study by LaCaille and colleagues (2004) revealed that runners reported the lowest ratings of perceived exertion (RPE) during outdoor runs compared to treadmill runs at the same intensity. Similarly, Dasilva and colleagues (2011) found that walking outdoors resulted in significantly lower perceived exertion despite a higher walking speed compared to walking on a treadmill. A meta-analysis by Lahart and colleagues (2019) of longitudinal studies further supported this, showing that individuals engaging in physical activity in natural environments reported slightly lower post-intervention RPE than those exercising in non-natural settings. These findings highlight the complex ways in which environmental contexts can shape the experience of physical activity, influencing not only physiological outcomes but also the perception of effort and exertion.

1.2 Methodological issues in assessing Green Exercise

Green exercise research encounters theoretical and practical challenges. Evidence supports GE's benefits, yet the relationship between exposure to natural environments and the resulting PA remains indistinct (Shanahan, Franco, et al., 2016). At least three different GE research approaches can be distinguished (Barton et al., 2016): 1) investigation of the effects of exercise in built environments compared to natural outdoor environments; 2) comparison of outcomes of GE with those of indoor exercise; 3) study of the effects of different visual environments (e.g. showing participants natural or urban videos or images) during indoor exercise. Therefore, the first significant methodological issue arises from the necessity of establishing a suitable comparator setting, which allows for a clear comparison of the effectiveness of a particular activity in nature versus other environments. However, the definition of the most appropriate comparator remains controversial, as differences between natural and alternative environments could potentially be attributed to factors associated with the alternative settings rather than the qualities of the natural environments themselves (Bowler et al., 2010). For example, urban environments can vary in the degree of stressors present, such as traffic and spaces for outdoor physical activity, and may therefore offer fewer positive effects on mental well-being and exercise adherence compared to an aesthetically pleasing and supportive indoor setting (Thompson Coon et al., 2011). So, each of the approaches has limitations and strengths, and comparing their results is challenging (Barton et al., 2016). Moreover, methodological constraints relate to both components of GE: the PA and the environment where it occurs.

Measuring physical activity and its typology

Quantifying physical activity (PA) necessary for a healthy lifestyle is complex due to behavioral variability (Loureiro & Veloso, 2017) In population-based studies, measuring PA levels largely relies on self-report questionnaires, despite their known lack of reliability compared to objective measures (Ding et al., 2017). The long form of the validated International Physical Activity Questionnaire (IPAQ-LF) is commonly used to measure PA levels (Craig et al., 2003). However, research indicates that self-reports can overestimate vigorous PA (Cerin et al., 2016). Discrepancies have also been observed

when comparing the IPAQ's short form with accelerometer data, suggesting an overestimation of moderate-intensity PA and an underestimation of sedentary behavior (Nelson et al., 2019; Steene-Johannessen et al., 2016).

However, in the field of green exercise, much of the research focuses on individual-level physical activity. Therefore, the type of activity performed, its quantity, and its intensity are critical methodological considerations. Typically, studies on green exercise focus on walking or running, while other types of physical activities are less common (Bowler et al., 2010; Thompson Coon et al., 2011; Wicks et al., 2022). However, various literature reviews have drawn conclusions based on studies with heterogeneous physical activity types, complicating the interpretation of green exercise effects. For instance, Bowler et al. (2010) included studies investigating gardening and mixed activities, while Lahart et al. (2019) reviewed studies examining both short-term effects of activities such as cycling and dancing and long-term effects of strength training and aerobic circuits. A more recent review by Noseworthy et al. (2023) on the long-term effects of green exercise confirmed this lack of homogeneity in terms of physical activity types. Among the trials included in their review, in addition to walking and running, other studies focused on combined aerobic exercises and other types of exercise, such as strength training, balance exercises, or agility training.

Additionally, it is important to note that recent reviews have not always compared the effects of activities in different environmental contexts (e.g., urban vs. nature) using the same type of activity. This methodological challenge in the comparison of physical activity types will be further discussed in Study 1.

Regarding the duration of the activity, it is often relatively short, typically between 15 and 30 minutes, or less than an hour (Bowler et al., 2010; Thompson Coon et al., 2011; Wicks et al., 2022). In rare cases, studies have investigated the effects of longer-duration activities, such as hiking for 3 hours (Niedermeier, Einwanger, et al., 2017). One of the main reasons for the relatively short duration of activity could lie in the results of a meta-analysis by Barton and Pretty (2010) which showed that just 5 minutes of green exercise are enough to stimulate an impact on affective responses.

In terms of intensity, the literature also shows considerable variability in the studies considered by the more recent reviews (Lahart et al., 2019). Given the significant differences in emotional responses associated with different levels of physical activity intensity, this variability represents a methodological limitation in the generalizability of the results and is a key aspect that researchers must control for. The use of tools such as activity trackers and GPS allows researchers to prescribe a fixed level of workload for participants (e.g., fixed pace) and monitor adherence (Berman et al., 2008). However, this methodology does not ensure that the workload is adequate or personalized according to each participant's fitness level (Ekkekakis & Brand, 2019). The issue of exercise intensity will be discussed in more detail in subsequent sections.

Measuring nature exposure

Understanding how nature exposure is measured is crucial for determining causal pathways and health implications (Hartig et al., 2014). Marselle and colleagues (2021) emphasized the importance of distinguishing between actual exposure to nature and proxy measures. Proxy measures, such as cumulative opportunity (the total biodiversity surrounding an individual's location), physical distance to green spaces (proximity), and availability, are essential for assessing exposure when direct measurement data is unavailable. These metrics are commonly used in studies where direct data on nature contact is difficult to obtain (Holland et al., 2021). For instance, metrics derived from remote sensing and satellite imagery can provide data on nature quantity in the surroundings, particularly in epidemiological studies. The Normalized Difference Vegetation Index (NDVI) is one of the most widely used tools for measuring vegetation density and distribution (Pettorelli et al., 2005). It is a standardized method that allows for the comparison of vegetation presence across different environments and scales (global, regional, local) (Holland et al., 2021). A positive NDVI index (e.g., values above 0.6) typically indicates the presence of high-density vegetation (Weier & Herring, 2000). However, this metric falls short in distinguishing between types of vegetation and does not provide insights into the quality of green spaces (Markevych et al., 2017)

In addition, studies use Google Street View to estimate the green view index from street-level imagery. While useful, this approach does not evaluate the quality of the

environment or the interaction of natural features within the activity setting (Lu, 2019; Remme et al., 2021). The underlying assumption of these methods is that the access to and quantity of green space nearby is positively correlated with the likelihood of spending time in nature (Ord et al., 2013) However, this assumption may be flawed, as researchers have suggested that other components of nature experience could influence the decision to spend time in natural environments (Holland et al., 2021). Measuring only the quantity of green spaces neglects factors like the duration and frequency of visits, which have been shown to be associated with higher levels of green exercise and greater well-being benefits (Shanahan, Bush, et al., 2016).

Moreover, various characteristics of green environments may be crucial for their restorative potential. Researchers have shown how the complexity of a scene influences both viewing time and the mental restoration associated with it (Van den Berg et al., 2016). Complexity, along with legibility, coherence, and mystery, forms what is known as the preference matrix (Kaplan & Kaplan, 1989) Complexity refers to the number and variety of visual components within a scene, indicating how rich and stimulating the environment is. Seminal studies by Berlyne (1960, 1974) demonstrated that people tend to prefer stimuli with moderate complexity, a relationship known as the inverted U-shape between preference and complexity. The mystery component refers to the potential for discovering new information from a changing perspective in the scene (e.g., pathways, trails, landmarks). Coherence refers to the order of elements in a scene, which facilitates quick understanding, while legibility makes the scene easier to comprehend and remember (Kaplan & Kaplan, 1989). Biodiversity is a measure of the complexity of a natural environment (Ulrich, 1983) and as such, it can play a significant role in its restorative potential.

Marselle and colleagues (2021) have provided a comprehensive framework for understanding the impact of interaction with nature on health benefits, distinguishing between exposure to nature and experience of nature. The experience of nature can be categorized into four types based on the type of interaction (intentional or incidental) and proximity (indirect or direct). Studies (Carrus et al., 2015) showed how different types of interactions with biodiversity in urban green spaces influence well-being and restorative

quality perceptions. People engaging in contemplative activities, walking, or exercising in these spaces reported better well-being and more restorative experiences than those reading, talking, or socializing with others (Carrus et al., 2015). While incidental exposure can still be significant, these results suggest that intentional interaction with nature may lead to greater benefits. Moreover, the framework by Marselle and colleagues (2021) emphasizes the experiential aspect of nature exposure, suggesting that how individuals interact with and perceive natural environments can significantly influence health benefits.

In broader terms, when comparing the same physical activity in natural outdoor environments versus non-natural settings, uncertainties remain regarding the quality and quantity of green space. As noted by Bowler et al. (2010), it is often unclear whether the environment provides sufficient greenery to effectively test the impact of nature. This ambiguity raises important questions about the potential differential effects of various types of natural environments, which may interact with participant characteristics in ways that are not yet fully understood.

Affective responses to physical activity

A further methodological challenge lies in distinguishing the emotional effects of physical activity (PA) from those of nature exposure. As previously discussed in the "instoration" section, it is important to highlight that physical activity itself has numerous beneficial psychological effects. The connection between physical activity and mood improvement (the "feel better" effect) has been a central idea in sports psychology for several decades. Specifically, regarding affective responses, mood enhancement, and the advancement of research in this area, one key researcher is Panteleimon Ekkekakis. In his seminal study on the emotional effects of physical activity (Ekkekakis et al., 2000) he demonstrated that even a brief 15-minute walk is associated with a shift toward a more activated, pleasant affect. This increase in energy and activation appears to be particularly true for moderate-intensity physical activities (below the ventilatory threshold), which do not compromise homeostasis and can be sustained over long periods of time (Ekkekakis et al., 2011). In contrast, higher-intensity physical activities tend to trigger a more stressful response with heterogeneous adaptations. Consequently, the affective responses

to such activities reflect greater individual differences (Ekkekakis et al., 2005a). As the intensity of exercise increases (for example, maximal efforts), emotional responses become more consistent and unambiguous: a general decline in positive emotions, prompting individuals to stop the activity as soon as possible to restore the body to a state of homeostasis or, at least, reduce exercise intensity (Ekkekakis et al., 2005b).

It's also important to note that when people engage in green exercise both the physical exercise and the natural environment together can influence emotional responses. Exercise itself often activates the sympathetic nervous system, increasing energy and alertness. While nature is generally thought to help calm us by lowering stress and heart rate variability (Ulrich et al., 1991), the study of Scott et al. (2021) showed that nature exposure can also make us feel more alert and energized. In their study, participants showed an increase in the sympathetic nervous system (the "fight or flight" response), in contrast with what is often suggested by Stress Recovery Theory (SRT), which proposes that nature typically has a calming effect by activating the parasympathetic nervous system (the "rest and digest" response), which helps us relax and recover. Researchers excluded that this activation was due to higher negative emotions as participants reported a significant decrease in negative affect after exposure to the natural environment compared to the indoor environment. In fact, participants reported feeling more relaxed and less stressed, which highlights that nature's emotional effects can vary depending on factors like the type of activity and the individual's experience. These conflicting findings between physiological and psychological data suggest that the emotional effects of nature exposure might not be as straightforward as is thought.

To better understand the full emotional experience during nature exposure, it is necessary to use a wide range of measures that capture both the activation (energizing) and deactivation (calming) effects. This would provide a clearer picture of how the sympathetic and parasympathetic systems interact when we are physically active in nature, helping explain the diverse emotional responses people may experience during green exercise (Scott et al., 2021).

1.3 Aims

These methodological challenges underscore the need for more refined research designs that can disentangle the complex interactions between physical activity, nature exposure, and psychological well-being. Therefore, the aim of this thesis is to explore the psychological and physiological benefits of different forms of exposure to natural environments, with a particular focus on green exercise. Through a series of studies, this research investigates how exposure to natural settings influences stress recovery, affective states, and overall well-being.

Given the abovementioned fragmented literature on GE effects, it is paramount to summarize and understand the state-of-the-art to clarify and suggest possible future research directions within the study of GE-environment transactions. The first part of this thesis addresses this aim, reviewing existing literature on green exercise, identifying key methodological gaps and providing a foundation for experimental studies. More specifically, it aims to describe both short and long-term green exercise effects while, at the same time, monitoring objective and subjective environmental measures adopted.

Built on the prescriptions that emerged from the literature review, the experimental section then evaluates the effects of green exercise in various environments, using both physiological markers and self-reported psychological outcomes. The second study is a field experiment in which the psychological and physiological restorative effects of a 1-hour light-to-moderate intensity exercise session are investigated. The third study will examine the role of indirect exposure to nature in supporting recovery from physiological stressors, such as hypoxia.

In both experimental studies, the approach recommended by Ekkekakis (2000) was followed by using an affective state assessment tool based on the circumplex model of affect, as it is particularly suitable for investigations aimed at describing the broad nature of emotional changes associated with physical activity. To address this, the Achievement Emotions Adjective List (AEAL; (Raccanello et al., 2022) was used, which captures various dimensions of emotional responses. Based on Russell's circumplex model of affect (Posner et al., 2005), this tool allows for the discrimination of emotions along two axes: arousal (activating vs. deactivating) and valence (positive vs. negative).

This approach enabled a more nuanced exploration of the emotional impacts of outdoor environments, aligning with the suggestion to diversify emotion-related assessments in nature research.

Through the AEAL questionnaire, it is possible to investigate the emotional effects of nature exposure and green exercise beyond the dimensions of pleasure-displeasure and activation-deactivation. Emotions such as pride and shame come into play when engaging in physical activity, as exercise is inherently a behavior embedded within a social and cultural context. Consequently, emotional effects are also influenced by factors like competence and self-perception of the body (Ekkekakis & Brand, 2019). This broader understanding of emotional responses to physical activity, particularly in natural environments, allows for a deeper investigation of how green exercise influences well-being across diverse emotional experiences.

Study 1. Reassessing Green Exercise research: unveiling methodological gaps and pathways for progress

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Abstract

The present review critically assesses the nexus between physical activity, nature exposure, and health benefits by analyzing environmental measures in green exercise research. A Cochrane-inspired review of systematic studies exposes methodological gaps, emphasising the scarcity of long-term research and the lack of rigorously designed studies. It calls for more robust, varied research designs and improved environmental metrics. The findings advocate for longitudinal research to better comprehend the mental and physical health benefits of exposure to nature. Embracing an ecological-dynamic perspective is recommended to advance our understanding of the intricate connections between activity, environment, and well-being.

1. Introduction

Currently, 55% of the global population resides in urban areas, which is projected to increase to 68% by 2050. The growing trend of urbanisation poses significant public health challenges, including environmental degradation, insufficient infrastructure, scarce green spaces, pervasive air pollution, and a dearth of areas designated for physical activity (PA) (WHO, 2016). Furthermore, the expansion and densification of cities are expected to reduce both the availability and quality of green spaces per capita, which could negatively impact the restorative potential of these areas (WHO, 2021).

However, the health benefits of green spaces in urban environments, such as reduced risk of noncommunicable diseases, have been well-documented (WHO, 2016), and the World Health Organization's "Global Action Plan for Physical Activity 2018-2030" highlights the crucial role of accessible green spaces in fostering environments that support PA (WHO, 2018). Green spaces also offer co-benefits in the context of climate change adaptation, contributing to heat stress reduction and improved water retention while simultaneously promoting mental well-being (WHO, 2021).

Engaging in PA exerts a plethora of physical and psychological benefits, such as reduced risk of chronic cardiovascular and musculoskeletal diseases, hypertension, diabetes, osteoporosis, fractures, and certain types of cancer (Warburton et al., 2006), as well as symptoms of anxiety and depression (WHO, 2020; Bull et al., 2020; Teychenne et al., 2020; Babyak et al., 2000). However, despite recognising sedentary lifestyles as a global public health issue, efforts to implement effective programs and policies promoting PA across populations have been inadequate (Pratt et al., 2020).

Within such a scenario, exposure to green spaces is linked to lower depression levels (Shanahan, Bush, et al., 2016), higher perceived mental health, lower mortality (Van den Berg et al., 2015), and improved affective states (McMahan & Estes, 2015), reduced stress and more rapid recovery from it (Maas et al., 2006; Kolokotsa et al., 2020).

1.1. Green Exercise

Researchers (Loureiro & Veloso, 2017) have advocated for the added physical and mental health benefits of green exercise (GE) — i.e., exercising while being immersed in nature (Pretty et al., 2005). GE condenses the psychological, physiological, and social gains obtained from PA while acknowledging the positive impact of exposure to nature (Rogerson et al., 2019). The main argument is that the benefits of PA and exposure to nature are amplified when combined, offering synergistic health effects (Pretty et al., 2005). Accordingly, the positive impact of nature on health and well-being can be categorised into three domains: mitigating damage (mitigation), fostering the recovery of resources (restoration), and enhancing capabilities (instoration) (Markevych et al., 2017).

Restoration domain

Beyond the mitigation effect of nature on physical and mental health (e.g., better air quality and heat and noise reduction; (Guerreiro et al., 2014) (Hartig et al., 2014) (Nowak et al., 2014) (Markevych et al., 2017), its restorative effect has been well documented. In fact, daily demands often deplete personal resources — physiological, psychological, or social — but can be replenished in restorative environments (Hartig, 2004; Von Lindern et al., 2016). Stress Reduction Theory (SRT) suggests that natural environments, unlike urban ones, elicit immediate stress relief due to an innate positive affective response, leading to quicker recovery (Ulrich et al., 1991; Nukarinen et al., 2022). Such responses are believed to be evolutionary and are triggered by specific environmental features (e.g., vegetation, water) that signal safety and foster well-being (Joye & Van den Berg, 2018; Hartig et al., 2014).

Attention Restoration Theory (ART) (Kaplan, 1995; Ulrich et al., 1991; Kellert & Wilson, 1993) proposes that natural environments aid cognitive function by replenishing attention. It differentiates between involuntary, effortless attention and voluntary, directed attention, with the former automatically activated by nature (Kaplan, 1995; Kaplan & Berman, 2010). Four features foster attention restoration, as stated by ART:

fascination, being away, extent, and compatibility (Hartig et al., 2003; Van den Berg et al., 2014; Joye & Dewitte, 2018).

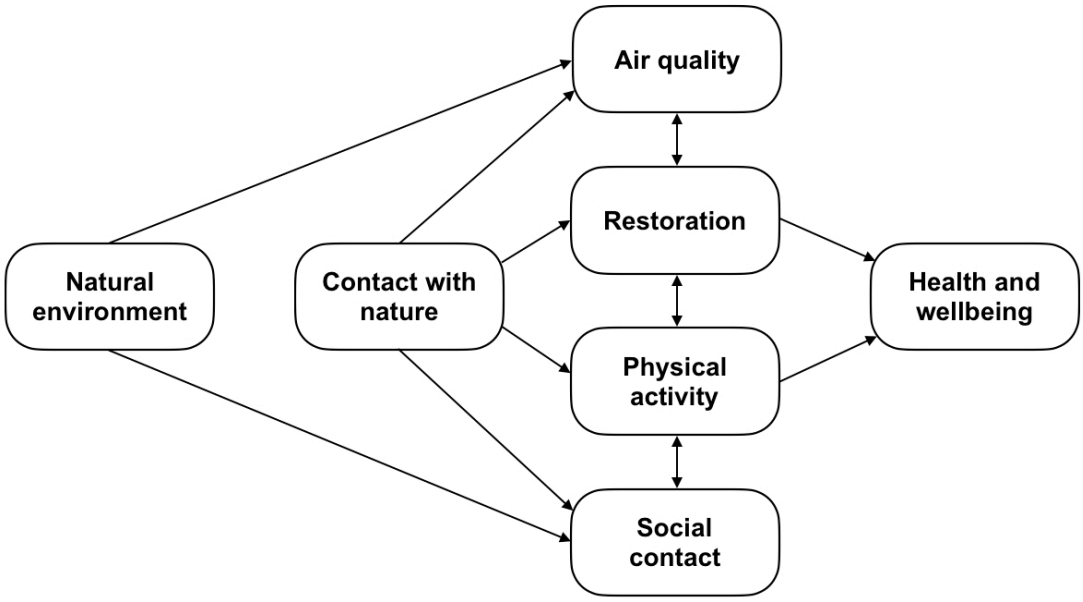
The Perceptual Fluency Account theory advises that an easier and more effortless visual perception of natural scenes leads to positive evaluations, aiding cognitive restoration and stress reduction (Joye & van den Berg, 2011; Joye et al., 2016; Reber et al., 2004).

Finally, the Relational Restoration Theory posits that replenishing depleted resources involves both individual and relational aspects, including the dynamic interaction between an individual and the environment (Korpela et al., 2008) and interactions within dyads or groups (Hartig, 2021).

Instoration domain

Along with other health-promoting factors like air quality, social interaction, and stress reduction, it is proposed that physical activity (PA) is a means through which natural environments can enhance well-being (Figure 1; Hartig, 2014). Green spaces have been shown to encourage an active lifestyle (James et al., 2015), and GE may be particularly restorative, as it allows people to engage with the environment to facilitate resource regeneration (Collado et al., 2017). However, while a meta-analysis found that green spaces are positively associated with higher physical activity levels in the elderly (Broekhuizen et al., 2013), the overall evidence is mixed and may vary across different population subgroups (Lachowycz & Jones, 2011; Shanahan, Franco, et al., 2016).

Figure 2. Pathways model of the benefits of natural environments on health and well-being adapted from Hartig et al. (2014).



Recently, the ecological dynamic perspective has been applied to GE to examine the interdependent relationship between individuals, their environments, and PA. This approach, grounded in Gibson's (1979) theory of perception, emphasises behaviour emergence, constraint interaction, and environmental affordances as crucial concepts in understanding health-related behaviours (Araújo et al., 2019; Bamberg et al., 2018; Yeh et al., 2016). Within this framework, Rogerson et al. (2019) proposed a two-pathway model, suggesting that exercise not only provides access to green spaces but that these settings can also have direct salutogenic effects, thereby influencing PA and health outcomes.

1.2. Methodological issues in green exercise research

GE research encounters theoretical and practical challenges. Evidence supports GE's benefits, yet the relationship between exposure to natural environments and the resulting PA remains indistinct (Shanahan et al., 2016). At least three different GE research approaches can be distinguished (Barton et al., 2016): 1) investigation of the effects of exercise in built environments compared to natural outdoor environments; 2)

comparison of outcomes of GE with those of indoor exercise; 3) study of the effects of different visual environments (e.g. showing participants natural or urban videos or images) during indoor exercise. Each approach has limitations and strengths, and comparing their results is challenging (Barton et al., 2016). Methodological constraints relate to both components of GE: the PA and the environment where it occurs.

Measuring PA

Quantifying the PA necessary for a healthy lifestyle is complex due to behavioural variability (Loureiro & Veloso, 2017). In the general population, measuring PA levels largely relies on self-report questionnaires despite their lack of reliability compared to objective measures (Ding et al., 2020). Researchers commonly use the long form of the validated International Physical Activity Questionnaire (IPAQ-LF) to measure PA levels (Craig et al., 2003). Nevertheless, research indicates that self-reports can overestimate vigorous PA (Cerin et al., 2016). Discrepancies have also been observed when comparing the IPAQ's short form with accelerometer data, suggesting an overestimation of moderate-intense PA and an underestimation of sedentariness (Nelson et al., 2019; Steene-Johannessen et al., 2016).

Measuring nature exposure

A significant methodological gap in studying nature's health effects lies in measuring nature exposure (Hartig, 2014). At the epidemiological level, exposure is typically assessed through exposure frequency and duration, the distance of green space from the residence or its amount in the surroundings (Holland et al., 2021). The Normal Difference Vegetation Index (NDVI) is one of the most widely used metrics for providing data on vegetation density and distribution (Pettorelli et al., 2005). However, it falls short of differentiating between vegetation types and does not convey the quality of green spaces (Markevych et al., 2017). Studies also utilise Google Street View to estimate the green view index from street-level imagery. This approach falls short in evaluating environmental quality and the interaction of natural features within the activity setting (Lu, 2019; Remme et al., 2021). Thus, given the abovementioned fragmented literature, it

is paramount to summarise and understand the state-of-the-art to clarify and suggest possible future research directions within the study of GE-environment transactions.

2. Review

2.1. Scope

Accordingly, this review aims to clarify methodological issues concerning the study of the role of the physical environment in GE research. This analysis uses a framework based on the Cochrane methodology to overview systematic reviews (Pollock et al., 2020). This approach is well-suited for reviewing multiple systematic reviews on a shared topic while addressing questions not initially included in the reviews. Specifically, this overview will: a) compare study conditions and research approaches, following Barton et al.'s (2016) methodological classification; b) highlight key findings by considering comparison conditions and research designs (e.g., short-term and long-term effects); c) synthesise the features of green spaces where activities occur, detailing the type of greenspace, objective, and subjective measures of nature exposure.

2.2. Method

An electronic literature search was conducted to identify reviews and meta-analyses about PA and exercise interventions in the natural environment. PICOS criteria were drafted to guide the search (see Table 1). A search strategy was developed using keywords and search terms retrieved from papers on the topic. PubMed and Scopus Electronic databases were searched with keywords and search strings organised in blocks (see Table 2). The search was limited to systematic reviews and meta-analyses in English published in the last 15 years. Thus, a narrative synthesis of the included reviews is outlined, as the statistical findings were outside this review's scope (Holland et al., 2021).

2.3. Results

The search revealed 1170 references. Two more articles were added by hand, searching as relevant to the topic. After duplicates were removed, 1008 references were found as potentially eligible. After screening the title and abstracts, 958 references were

excluded for reasons. The remaining 49 articles were full-text screened, and six reviews were retained.

Comparison conditions

The included studies employed various methods to compare GE interventions (Table 3). Bowler and colleagues (2010) included studies comparing GE to indoor exercise or urban outdoor exercise. Indoor environments were gyms and laboratories, whereas outdoor non-green environments involved streets and residential areas. Only a few studies compared the same activity in each environment. Thompson-Coon and colleagues (2011) conducted a review to compare the effects of GE vs indoor exercise. Indoor exercise was conducted in gyms, fitness facilities, laboratories, and a shopping centre. Two studies involved virtual reality as the green setting. Lahart and colleagues (2019) conducted a systematic review to investigate the effects of exercise performed in a natural outdoor or virtual environment compared with indoor exercise. Four trials lacked a non-green condition, wherein participants engaged in indoor exercise while watching a video of the same route being performed outdoors. Yen and colleagues (2021) conducted a systematic review and meta-analysis to examine the long-term influence of PA in natural settings on quality of life. Two studies involved PA intervention in aquatic environments. Only three trials compared green or blue exercise with PA conducted in non-green settings; the remaining studies involved other types of control groups such as occupational therapy, social activities, or waitlists. Wicks and colleagues (2022) conducted a systematic review to compare the psychological health effects of GE with exercise in urban environments. Marini and colleagues (2022) conducted a systematic review to explore the effects of PA interventions in green and blue environments. However, four out of six studies lacked a comparison condition.

Green exercise effects

Most of the reviews focused on the short-term effects of GE, reflecting a lack of long-term studies (for detailed findings, see Table 4).

Short-term effects. Bowler and colleagues (2010) found that GE yielded greater benefits for self-reported emotions, particularly in reducing negative emotions such as

sadness and anger, compared to exercise in non-natural outdoor settings. While the studies in their review examined GE's effects on attention, cardiovascular health, immune system functioning, and PA levels, the benefits were modest. Tranquillity levels were significantly higher after exposure to natural settings than after urban outdoor environments, but not compared to indoor exercise. Thompson-Coon and colleagues (2011) compared the effects of PA in natural environments versus indoors on psycho-physical well-being, primarily focusing on running and walking activities. Walking in natural settings showed significant improvements in various mood aspects, such as enjoyment, satisfaction, and intentions to repeat the outdoor activity. Running outdoors was associated with lower anxiety, depression, anger, hostility, and fatigue compared to indoor running, although two studies did not report benefits. Due to study heterogeneity and small sample sizes, the authors refrained from drawing conclusive evidence in support of GE. A meta-analysis by Lahart and colleagues (2019) showed mixed results of GE benefits compared to exercising in artificial or indoor environments. Significant short-term effects were found on the affective value and enjoyment of PA. In Wicks and colleagues' review (2022), twenty-two out of twenty-four primary studies examined the short-term effects of GE. In most of the studies (n=22), participants engaged in walking. Six meta-analyses with data from nine primary studies showed a significant effect of GE for the six outcomes investigated, though the heterogeneity of the results was considerable (Table 5).

Long-term effects. Upon excluding studies featured in multiple reviews, it was found that 26% of the primary studies delved into the long-term effects of GE. Interventions spanned from 10 weeks to one year. Within this subset, two observational studies focused on clinical populations (Bowler et al., 2010). In three long-term trials, GE was compared with indoor exercise with a similar training volume (Lahart et al., 2019). The meta-analysis investigated the long-term impacts of GE on positive emotional states, depressive symptoms, fatigue perception during exercise, cardiac indicators, PA engagement, weight, body mass index, and body fat percentage, involving data from two trials. The results demonstrated a significant effect exclusively on post-activity perceived exertion: participants engaging in GE reported slightly less exertion compared to indoor exercise. However, PA characteristics varied among the three trials: running, a

combination of strength and aerobic exercises, or cycling. Additionally, one trial included a clinical sample. A systematic review examined the long-term influence of PA in natural settings, including blue spaces, on quality of life (QL) (Yen et al., 2021). A meta-analysis of four randomised controlled trials did not find a significantly larger influence of green and blue exercise on general QL as measured by mental and physical health questionnaires. However, analysis based on six out of eight studies showed significant benefits of green and blue exercise activities on the psychological and physical health components of QL (Yen et al., 2021). Wicks and colleagues (2022) found that only two out of twenty-four primary studies assessed the effects of repeated GE sessions, and no conclusive results about long-term effects were reported. In their review focusing on the long-term effects of PA interventions in green and blue space settings, Marini and colleagues (2022) revealed that engagement in green and blue exercise yielded better responses in participants' mood and well-being compared to exercising or resting in urban environments. However, this finding was based on two studies with differing characteristics. Vert and colleagues (2020) investigated the long-term benefits of PA in blue spaces (a seafront route to a breakwater), while Song and colleagues (2015) assessed the physiological and psychological short-term effects of GE by having participants walk in an urban park during the fall season. Overall, walking was the primary PA intervention in two out of the six studies included, while the remaining studies involved combined exercises such as body strength training and aerobic workouts.

Green space assessment

Fourteen studies, accounting for 20.1% of the total, evaluated the benefits of PA interventions in natural settings such as woodlands, grasslands, or forests, all featuring trails and footpaths. Then, interventions often took place in urban parks (15%) or university campuses (12%), with both environments varying in the extent of greenness. Eight studies (12%) picked environments with water elements, such as lakes and rivers. Outdoor exercise stations were utilised as GE in 6% of the studies. Another 12% of the studies involved indirect exposure to natural environments, using virtual reality and views of nature scenes. Other GE conditions included beaches, harbours, seas, hiking areas, urban public parks, and tree-lined urban roads.

Objective environmental measures. Among the objective environmental measures, air temperature was the most reported (33.3%). Humidity was the second most frequently recorded (18.2%). Illumination levels (lux) were documented in 9.1% of studies, and noise levels were reported in 6.1% of studies. Wind speed, greenness rate, rainfall, sunlight exposure, and heat were less commonly measured.

Subjective environmental measures. Regarding the subjective assessment, 9% of the studies utilised the Perceived Restorativeness Scale (PRS) (Pasini et al., 2014) to evaluate the natural environment's restorative potential. Nisbet et al. (2011) adapted the Positive and Negative Affect Scale (PANAS) by adding elements related to fascination, curiosity, and interest to assess the environment's restorative capacity. The semantic differential (SD) method was employed in 7.5% of studies to gauge participants' environmental perceptions. One study examined the sense of presence in virtual green environments, while another study assessed perceived naturalness.

3. Discussion

This review aimed to synthesize current studies on the interplay between nature exposure and physical activity, focusing on methodological approaches and assessment metrics for the natural environment. Reviews on green exercise (GE) yielded mixed results, reflecting variability in short-term and long-term effects, likely influenced by diverse comparison methods, heterogeneous physical activity characteristics, and shortcomings in environmental assessment. Admittedly, this review has the limitation of focusing on a small number of reviews. The selection criteria led to a limited pool of studies, which may pose an issue of over-reliance on specific findings. However, the insights gained from this review provide essential guidance on key methodological issues in studying the benefits of green exercise and nature exposure.

The predominance of cross-sectional studies calls for longitudinal and robust experimental designs to unravel the complexities of the interrelation between exposure to nature and PA (Remme et al., 2021). Among the long-term effects of GE, a notable impact was observed only on perceived exertion levels (Lahart et al., 2019) and sub-components of quality of life (Yen et al., 2021). However, inconsistent comparison

conditions in these studies — such as resistance training with outdoor equipment or combined aerobic exercises as GE condition (Marini et al., 2022; Lahart et al., 2019; Yen et al., 2021) — may hinder the generalizability of the long-term results.

Results also highlight overlooked aspects such as biodiversity in green settings (Bowler et al., 2010) and the limited variety of green spaces utilised for PA (Thompson Coon et al., 2011). Reviewed studies often lacked objective nature measures and focused on subjective assessments by primary authors (Bowler et al., 2010) or mixed green spaces and blue spaces (Yen, 2021; Marini, 2022). Yen et al.'s (2021) meta-analyses failed to demonstrate significantly greater benefits of GE on overall quality of life, potentially due to overlooked factors like aesthetic preferences and environmental variables. While Lahart et al. (2019) found inconclusive evidence regarding the superiority of GE over non-green alternatives, short-term analyses showed the potential benefits on affective valence and enjoyment compared to indoor or non-green activities. Thus, methodological issues like poor descriptions of natural environments and limited subjective measures of environmental perceptions compromise the quality of evidence supporting GE.

Only a small portion (9%) of primary studies assessed the perceived restorative potential of natural settings, indicating a gap in understanding participants' environmental preferences and perceptions. Nonetheless, perceptions of the physical environment are crucial for understanding the relationship between environment and PA (Brownson et al., 2009), influencing engagement in GE (Menardo et al., 2022; Petrunoff et al., 2022). For example, outdoor thermal comfort (OTC) can significantly affect how people perceive and use outdoor spaces, influencing participation in outdoor activities and overall urban livability, particularly in the context of climate change (Chen & Ng, 2012).

Future Directions

Researching the efficacy of GE presents unique challenges, as it necessitates concurrent assessments of PA and nature exposure. An optimal approach involves monitoring PA levels through self-reports and contextually using device-based measures (Ding et al., 2020). Self-report tools, while valuable for exploring social and environmental aspects such as the perception of the activity's setting (Sattler et al., 2021), should be complemented with objective methods to ascertain attitudes towards PA

(Steene-Johannessen et al., 2016). Implementing standardised PA measurements is essential to combat the pandemic of physical inactivity (Pratt et al., 2020) and pursue the WHO goal of reducing inactivity levels (WHO, 2018). As such, Ecological Momentary Assessment (EMA) allows for real-time collection and transmission of self-reported data on emotions, behaviours, and environmental perceptions, enabling the examination of environmental factors that contribute to PA maintenance (Rhodes et al., 2019).

Furthermore, future studies should explore various environmental features: the objective quality of physical settings, perceptions of restoration potential, perceived biodiversity, ecological quality, outdoor thermal comfort and aesthetic preference. In addition, future research should include meta-analyses to assess whether specific natural environments provide distinct health benefits. While the current literature often compares green spaces with urban or indoor environments, evaluating how different types of natural settings, such as urban parks versus wilderness areas, affect health outcomes for participants engaging in physical activity would be valuable.

In addition to the health benefits of green exercise, future research should explore its potential to foster pro-environmental behaviours. Evidence suggests that regular contact with nature strengthens environmental awareness and encourages behaviours aimed at protecting the environment (Mackay & Schmitt, 2019). Understanding how green exercise can promote individual well-being and pro-environmental attitudes could offer valuable insights for advancing public health and sustainability initiatives.

However, the ongoing impacts of climate change, including increased urban heat stress, may alter the efficacy of green and blue spaces in promoting health, with different types of green spaces potentially providing distinct benefits for mental health and climate resilience (WHO, 2021). In addition, the perception and use of green spaces can vary depending on urban context and climate. In warmer climates, high temperatures may discourage outdoor exercise, whereas in more temperate areas, green exercise tends to be more common (Delgado-Serrano et al., 2024). Thus, it is crucial that future research investigates how different types of natural environments may offer varied health benefits, especially in the context of changing climatic conditions.

4. Conclusion

The journey to quantify the health benefits of nature exposure is ongoing, and the field has yet to reach a consensus on the most predictive nature exposure measures (MacIntyre et al., 2019). Future studies should aim for precision in evaluating these metrics' accuracy and identifying specific natural elements for measurement (Frumkin et al., 2017). Current research often portrays natural spaces as static entities, primarily focusing on their visual aspects (Bamberg et al., 2018). This perspective may overlook the dynamic human-environment interaction over time and the nuanced impact of biodiversity and restoration potential on well-being (Fuller et al., 2007).

The prevalent 'green versus urban' framework in studies of restorative environments may be too simplistic, potentially obscuring which specific environmental features confer health benefits (Van den Berg et al., 2014). The ecological diversity within green spaces is a promising research area, as it is closely tied to the restorative benefits of nature exposure (Wood et al., 2018). Research has shown that higher biodiversity levels within urban and peri-urban green spaces contribute to increased perceptions of restorativeness and well-being, emphasising the importance of ecological diversity in promoting mental and physical health benefits (Carrus et al., 2015). Furthermore, integrating regenerative urban design and biophilic principles into green spaces enhance their ability to foster healthful living while addressing climate resilience and sustainability (Lencastre et al., 2023). Thus, research that disentangles how different natural settings interact with PA to foster healthful living is a clear need for research.

This review highlights the multifaceted nature of GE and its effects on mental and physical health. While we understand some short-term benefits, the long-term impacts and the most effective environmental settings for promoting these benefits remain unclear. The contributions of subjective and objective measures of environmental attributes to GE outcomes require further investigation. Future research should integrate diverse methodologies, including EMA and advances in wearable technology, to capture the interplay of behaviour, environment, and time (Sattler et al., 2021; Dunton, 2017). Moving forward, it is crucial to expand our metrics beyond 'green' to encompass the broader spectrum of ecological features that enhance the restorative potential of natural

environments. Only through a comprehensive understanding can we fully leverage the power of GE to combat physical inactivity and improve global health outcomes, as outlined by the WHO (2018).

Supplementary materials

Table 1. PICOTS criteria guiding the electronic search.

Population	Healthy adults
Intervention	PA carried out outdoors or in a natural environment
Comparator	PA carried out indoors or in an urban environment or control activities
Outcome	Physical well-being and performance Psychological health Quality of life
Timing	15 years limit
Design	Experimental studies

Table 2. Keywords and research strategy.

Phyisical Activity	(exercis* OR "PA" OR "physical activities" OR "physical exercis*" OR "exercise training" OR "green exercise")
Environment	(nature OR "natural environment*" OR outdoor OR "green space" OR "green spaces" OR greenspace)
Outcome	(health OR "mental health" OR "physical health" OR "mental well-being" OR "physical well-being")

Table 3. Summary of the comparison condition, type of activity, and green exercise environments of the interventions included in the considered reviews.

review	studies	green conditions	comparation conditions	activities	green condition environments
Bowler et al. (2010)	25	natural outdoor	outdoor urban environments indoor	walking running wilderness backpacking gardening passive-sedentary activity mixed activities	parks university campuses nature reserve wildlife reserve wilderness forest garden
Thompson Coon et al. (2011)	11	natural outdoor	indoor	running walking	university/college campus sidewalks/walking paths forest country park described as 'outdoor', no further details are provided
Lahart et al. (2019)	28	natural outdoor indoor virtual natural	indoor	walking running cycling dancing combined strength and aerobic training	woodland gardens parks
Yen et al. (2021)	8	natural outdoor	urban outdoor indoor control group with no activity	aerobic training cycling walking hiking free activities	parks urban green areas sea beach marina
Wicks et al. (2022)	24	natural outdoor	urban outdoor	running walking	forest woodland grasslands regenerated landfill nature reserve urban park bamboo forest
Marini et al. (2022)	6	natural outdoor	urban outdoor no activity or daily routine	walking strength and resistance training	urban park outdoor fitness station exercise parks blue and urban environments

Table 4. Summary of the characteristics of the reviews and their main findings

review	studies	short-term findings	long-term findings
Bowler et al. (2010)	25	Reduced negative emotions (anger, fatigue, sadness). Less consistent results on anxiety and tranquillity. A positive small effect was also found on tests of attention. Confidence intervals overlapped zero after adjusting for pre-test measurements on attention and fatigue. Feelings of tranquillity after exposure to nature were more positive than after exposure to an outdoor built environment, but not in comparison to an indoor environment. Comparing the outcomes before and after the activity, positive changes were found in feelings of anxiety, energy, anger, fatigue, and sadness.	NA
Thompson Coon et al. (2011)	11	Walking in a natural environment compared to walking indoors: greater feelings of revitalisation and positive engagement. Decreased tension, confusion, anger, and depression and increased energy. However, the results suggested that feelings of calmness and tranquillity may be decreased following outdoor exercise. Participants reported greater enjoyment and satisfaction with the outdoor activity and intended to repeat the activity later. After running outdoors, compared to running indoors, less anxiety, depression, anger, hostility, and fatigue were reported. However, no benefits were reported in the other two studies involving running as PA.	NA
Lahart et al. (2019)	28	Compared with indoor exercise, acute bouts of outdoor green exercise may favourably influence affective valence and enjoyment but not emotion, perceived exertion, exercise intensity, and biological markers.	In a meta-analysis of three longitudinal trials, the only statistical finding was slightly lower post-intervention perceived exertion with green vs indoor exercise.
Yen et al. (2021)	8	NA	Green and blue exercise had no significant effect on the general QoL. Green and blue PA revealed a small to moderate significant impact on physical and a small and significant impact on mental health

Wicks et al. (2022)	24	Meta-analysis showed large or moderate effect sizes were obtained for anxiety, fatigue, and positive affect, but considerable heterogeneity was also evident. For vigour, a large effect favouring the natural environment had low heterogeneity. A moderate effect was found for anger, with low heterogeneity. The meta-analysis for depression revealed a small effect in favour of the natural environment but with considerable heterogeneity.	NA
Marini et al. (2022)	6	PA interventions carried out in an outdoor green–blue space natural environment can have a positive impact on a healthy population, both after a few weeks of intervention or after several weeks and can be an effective strategy to enhance and promote healthy lifestyles	NA

Table 5. Results of meta-analyses conducted by Wicks and colleagues (2022)

outcome	**participants (studies)**	**effect estimate**	**I^2**
anxiety	720 (7)	-6.59	91%
fatigue	697 (5)	-1.98	79%
positive affect	115 (2)	0.59	92%
vigor	697 (5)	3.28	15%
anger/hostility	697 (5)	-0.57	30%
depression	697 (5)	-0.34	74%

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Study 2. Exploring Emotional and Physiological Benefits of Moderate Green Exercise: A Randomized Controlled Comparison of Natural and Built Environments

Abstract

Introduction. Exercising in natural environments (i.e., green exercise) has been suggested to provide more significant physiological and psychological health benefits compared to urban or indoor environments (Gladwell et al., 2012). This study evaluated the psychological and physiological restorative effects of a 1-hour light-to-moderate intensity exercise session.

Methods. In a randomized crossover design, 25 healthy male subjects (M = 26.3, SD = 4.3) performed a 1-hour walk at a controlled pace (6 km/h) in three different environments: natural (G), urban (U) and indoor (I). Questionnaires for psychological assessment were administered to investigate the feeling of restoration, the emotional states, enjoyment of physical activity and intention to repeat in future. Physiological indices, including salivary cortisol, heart rate, and heart rate variability, were assessed before and after the intervention.

Results. Mixed model analyses revealed significant effects of the environment on psychological and physiological outcomes. Participants reported higher relaxation, greater positive emotions, and lower anxiety in the natural (G) environment compared to urban (U) and indoor (I) environments. Negative emotions were also reduced in G relative to I, with U showing intermediate effects. Restoration outcomes (Restorativeness PRS; Psychological Restoration, ROS) and enjoyment of physical activity (PACES) were consistently higher in G than in both U and I. Perceived exertion was lower in G compared to I, with no differences between G and U. Physiologically, cortisol levels, heart rate, and heart rate variability (RMSSD) differed by environment, with G showing a more favourable recovery profile compared to U and I. However, no interaction effects were observed for physiological measures, suggesting these responses were consistent over time across conditions.

Conclusions. The findings demonstrate that light-to-moderate intensity exercise in a natural environment provides clear psychological and physiological benefits, including enhanced relaxation, lower anxiety, and improved stress recovery compared to indoor and urban settings. While the natural setting showed a distinct advantage, the contrast between urban and natural environments was less pronounced for some outcomes, emphasizing the

need for further research to understand these differences better. These results reinforce green exercise's restorative and stress-relieving potential, highlighting its value as a resource for promoting mental well-being and supporting physical activity adherence in public health strategies.

1. Introduction

The steady rise of global urbanization is transforming the landscapes people inhabit, with the urban population projected to grow from 55% in 2020 to 68% by 2050 (WHO, 2016). As cities expand, access to green spaces—critical for health and well-being—faces increasing pressure from urban infrastructure. This shift diminishes the quantity and quality of green spaces, reducing their potential as restorative settings (WHO, 2021). Insufficient access to natural areas is particularly concerning given the broad physical and mental health benefits linked to these environments, such as reduced risks of cardiovascular conditions, improved mood, and lower stress levels (Shanahan et al., 2016; White et al., 2021).

Alongside reduced green spaces, sedentary lifestyles pose a significant health risk. Physical inactivity increases the risks of non-communicable diseases, including obesity, cardiovascular disease, and certain cancers (Bull et al., 2020; Warburton et al., 2006). Despite the well-known benefits of physical activity (PA), policies promoting it often fall short, leaving sedentary behaviors a major public health concern (Pratt et al., 2020).

In response to these challenges, there has been growing interest in green exercise (GE)—exercise performed in natural settings (Pretty, 2004; Pretty et al., 2003). GE promotes healthy lifestyles by encouraging PA maintenance throughout life (Eigenschenk et al., 2019). Combining exercise and nature amplifies benefits, fostering positive psychological outcomes and long-term adherence to PA (Hartig et al., 2014; Pretty et al., 2005).

This approach builds on the well-documented effects of natural settings, shown to lower stress, enhance mood, and improve overall health, including reduced blood pressure and increased well-being (Bratman et al., 2015; Nguyen et al., 2023). Two key frameworks, Attention Restoration Theory (ART) (Kaplan & Kaplan, 1989; S. Kaplan, 1995) and Stress Recovery Theory (SRT) (Ulrich, 1983), explain how nature facilitates restoration. While ART suggests natural settings engage involuntary attention, allowing cognitive resources to replenish, SRT focuses on affective responses, proposing that nature reduces stress by promoting positive emotions and lowering arousal.

Physiological evidence supports these theories. Nature exposure enhances parasympathetic nervous system (PNS) activity, indicated by increased heart rate variability (HRV), aiding autonomic relaxation (Gladwell et al., 2012). Active engagement with nature, like walking in a forest, further boosts HRV compared to urban environments (Kobayashi et

al., 2018). Even during stress, viewing natural scenes improves PNS recovery compared to urban settings (Brown et al., 2013).

Reviews comparing GE to non-natural settings report mixed results. Some studies show GE reduces negative emotions, such as sadness and anger, more effectively than exercise in urban areas, while increasing tranquility and enjoyment (Bowler et al., 2010; Thompson Coon et al., 2011). Short-term improvements in anxiety and fatigue have also been documented (Wicks et al., 2022). However, meta-analyses suggest no significant differences between PA in natural and indoor environments (Kelley et al., 2022; Lahart et al., 2019). Despite mixed results, enjoyment remains a key factor for exercise adherence, as positive experiences during PA support long-term commitment (Jekauc, 2015; Williams et al., 2006).

The relationship between exercise and affect remains complex and not fully understood (Ekkekakis & Brand, 2019). Acute bouts of PA are consistently linked to improved positive affective states (Reed & Ones, 2006), with moderate-intensity exercise increasing pleasure and perceived energy (Ekkekakis et al., 2011). GE introduces unique dynamics, as natural settings can evoke calming (Kinnafick & Thøgersen-Ntoumani, 2014) and activating responses (Niedermeier et al., 2017; Ryan et al., 2010).

However, methodological inconsistencies in GE research need addressing. Control environments vary widely, with some studies focusing solely on indoor settings, others including urban areas, and some combining mixed conditions (Lahart et al., 2019; Bowler et al., 2010; Wicks et al., 2022). Inconsistencies in PA types, ranging from walking to resistance training, further complicate comparisons. Additionally, few studies assess the perceived restorative qualities of settings despite their role in influencing PA engagement (Menardo et al., 2022; Petrunoff et al., 2022).

To address these gaps, our study incorporates validated measures to assess the environment and its perceived restorativeness (Pasini et al., 2014) and restoration (Korpela et al., 2008). Participants exercise in natural, urban, and indoor environments using a within-subject design, minimizing variability. Direct exposure to nature distinguishes our study, providing a clearer understanding of GE's psychological and physiological effects.

Aim

This study examines the influence of three environments—natural (G), urban (U), and indoor (I)—on psychological responses to controlled exercise. Physiological responses (e.g., cortisol, HR, HRV) are also assessed to confirm psychological findings, focusing on the stress relief and restorative benefits of natural settings.

Hypotheses:

- **Hp 1**: Exercise environments influence emotional states.
    - **Hp 1a**: Natural environments will elicit higher positive and lower negative emotions.
    - **Hp 1b**: Natural environments will reduce anxiety and promote relaxation.
- **Hp 2**: Natural environments improve physiological responses, including higher HRV, lower HR, and reduced cortisol.
- **Hp 3**: Perceived exertion will be lower in natural settings compared to urban and indoor environments.

2. Methods

2.1 Participants

Twenty-five male participants were recruited for this study (age: M = 26.3, SD = 4.3). They had an average Body Mass Index (BMI) of 22.9, maximum heart rate (HR max) of 191.29 bpm, VO_2 max of 4084 ml/min, and 55.8 mL/kg/min (see Supplementary Materials for details). According to the American College of Sports Medicine guidelines (2014), the average VO_2 max for 20–29-year-olds is 44 mL/kg/min, indicating this sample is highly fit or above average compared to the general population. A power analysis conducted in G*Power (version 3.1) indicated that 20 participants would be sufficient to detect moderate-to-large within-subject effects ($f = 0.30$) with 80% power at $\alpha = .05$. This threshold is supported by previous research findings suggesting that green exercise interventions commonly yield medium to large effects on emotional and restorative outcomes (see for systematic review, e.g., Wicks et al., 2022). Participants were recruited via digital advertisements posted on the websites of the Department of Engineering for Innovation Medicine and the Department of Human Sciences. The recruitment notices were made available to students and members of the public. Inclusion criteria were male gender, absence of chronic medical conditions, non-smoking status, and no medications affecting cardiovascular or psychological responses. All

participants provided written informed consent. The experimental protocol was approved by the University Ethics Committee.

2.2 Procedure

The study investigated the influence of three environments—natural (G), urban (U), and indoor (I)—on the physiological and psychological responses to a walking session (see Figure 1). The research was conducted at the CeRiSM laboratories in Rovereto. Participants visited the CeRiSM laboratories in Rovereto on four occasions: one preliminary assessment session followed by three experimental sessions in a randomized order.

Figure 1. Pictures of the three environments where participants performed the physical activity.

Note. On the left, natural (G; forest park of Rovereto); in the middle, urban (U; a city route through the centre of Rovereto); and on the right, indoor (I; the CeRiSM laboratory).

Preliminary session

The preliminary session, held before any experimental session, aimed to assess participants' physical fitness and psychological characteristics. Cardiorespiratory fitness was evaluated through a maximal treadmill test, preceded by a warm-up phase. Respiratory and cardiac data were recorded to determine fitness levels, which will be analyzed in a separate study. Following the treadmill test, participants completed questionnaires to assess individual

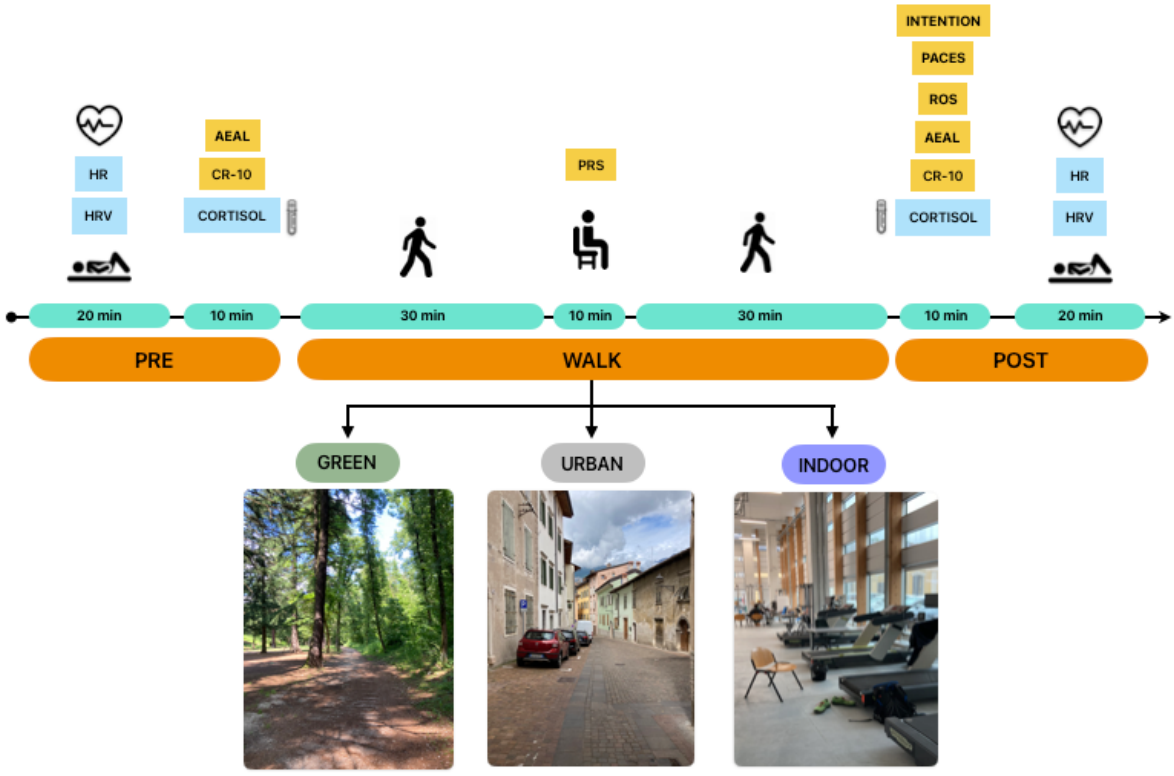
differences and psychological traits, including emotional intelligence and connection to nature. These data will contribute to additional analyses beyond the scope of this study.

Experimental Sessions

Participants completed three experimental sessions, each lasting approximately 2.5 hours, on separate days. A washout period of 7 to 15 days was maintained between sessions to ensure recovery and comparable environmental conditions. The interval was adjusted based on participant availability, weather forecasts, and minimize carryover effects due to fatigue or previous testing. To ensure balanced exposure and minimize order effects, the sequence of environmental conditions was randomized for each participant prior to data collection using randomization.org. All six possible orders of the three environments (Natural, Urban, Indoor) were represented and distributed evenly across the sample.

In each session, participants performed two 30-minute walking periods separated by a 10-minute seated rest, totaling 70 minutes of activity. The same routine was conducted across all environments (see Figure 2). For the natural and urban sessions, participants followed pre-defined outdoor routes totaling 6 km with 80 m elevation gain/loss. This route was simulated on a treadmill using incline adjustments for the indoor session.

Figure 2. Experimental session procedure.



Note: the figure displays the procedure repeated across the environments. HR: Heart Rate; HRV: Heart Rate Variability (RMSSD); CR-10: Borg's rate of perceived effort; AEAL: Achievement Emotions Adjective List; PRS: Perceived Restorativeness Scale; ROS: Restoration Outcome Scale; PACES: Physical Activity Enjoyment Scale; Intention: ad hoc item.

Outdoor walking sessions were performed in small groups of 2–3 participants. Participants walked in line with approximately 4–5 meters between each individual. An experimenter walked at the front of the group to set the pace and ensure the pre-established speed of 6 km/h. Throughout all sessions, including walking and the mid-walk rest, interactions among participants and with the experimenter were minimized to social influence. In the indoor condition, each participant walked individually on a treadmill set to maintain a constant speed of 6 km/h. The treadmill followed a speed- and elevation-matched protocol to replicate the outdoor conditions as closely as possible. The experimenter manually adjusted the treadmill walk's elevation profile to mirror the outdoor routes' elevation gain and loss (totaling 80 meters), reproducing the sequence of ascents and descents encountered in the natural and urban settings.

Upon arriving at the laboratory, participants changed into appropriate clothing and wore a chest strap for heart rate monitoring. They rested supine on a medical bed for 20 minutes while cardiac indices (HR and HRV) were continuously recorded. Before beginning the exercise, participants completed a baseline emotional state questionnaire (AEAL) and provided a saliva sample to measure salivary cortisol levels. They also reported their perceived exertion level using the Borg CR-10 scale.

At the halfway point of the walk, participants paused for a 10-minute seated rest to evaluate the restorative quality of the environment by filling the Perceived Restorativeness Scale (PRS).

Upon completing the exercise, participants provided a second saliva sample. They completed questionnaires measuring perceived exertion (CR10), emotional state (AEAL), enjoyment of the activity (PACES-It), psychological restoration (ROS), and future intention to exercise in the same environment. A final 20-minute resting phase allowed the recording of HR and HRV to assess post-activity recovery.

2.3 Measures

Restorativeness. The Perceived Restorativeness Scale (PRS) (Hartig, Kaiser, et al., 1997; Hartig, Korpela, et al., 1997; Pasini et al., 2014), grounded in Kaplan and Kaplan's Attention Restoration Theory (ART), was used to assess each environment's restorative qualities. The PRS evaluates four core dimensions: *Being Away* (escape from routine or demands), *Fascination* (effortless attention), *Coherence* (organization and comprehensibility), and *Scope* (opportunities for exploration). Participants rated statements on an 11-point Likert scale (0 = not at all, 10 = very much), providing a comprehensive measure of restorative potential. Internal consistency was strong, with McDonald's ω of 0.88, 0.85, and 0.93 for the indoor, natural, and urban environments, respectively.

Psychological restoration. The Restoration Outcome Scale (ROS; Korpela et al., 2008) assessed immediate restorative experiences in each environment. The scale includes six items across key areas: relaxation, attention restoration, and clearing one's thoughts. Participants rated statements like "I am calm" and "I am able to forget everyday worries" on a 7-point Likert scale, with higher scores reflecting greater restoration. The ROS is widely validated for measuring nature's emotional and cognitive effects (Pasanen et al., 2018),

showing strong internal consistency with McDonald's ω of 0.93, 0.77, and 0.97 for indoor, natural, and urban environments, respectively.

Emotional state. The Achievement Emotions Adjective List (AEAL; Raccanello et al., 2022) measured emotional states based on the circumplex model of activation and valence. A total of 14 items were used. Participants rated each item on a 5-point Likert scale (1 = not at all, 5 = very much). Initially developed for educational contexts, the AEAL is adaptable to other domains, including sports, where it effectively captures performance-related emotions that influence motivation and experience (see Results and Supplementary Table 2).

Perceived exertion. Perceived exertion was assessed before and after the walk using the Borg Category Ratio Scale (CR-10; Borg, 1998). The scale ranges from 0 (nothing at all) to 10 (maximal exertion) and above for absolute maximum exertion (Foster et al., 2001).

Enjoyment of physical activity. The Physical Activity Enjoyment Scale (PACES-It; Carraro et al., 2008), validated in Italian, assessed enjoyment. It includes 16 items rated on a 7-point Likert scale from 1 ("totally disagree") to 7 ("totally agree"), with higher scores indicating greater enjoyment. This scale helps evaluate how different settings influence the pleasure of exercise and its potential impact on adherence. Internal consistency was excellent, with Cronbach's α of 0.95, 0.88, and 0.96 for indoor, natural, and urban environments.

Intention to exercise. Participants' intentions to engage in future PA in similar environments were measured using a single ad-hoc item. They rated their intention on a 7-point frequency scale ranging from 1 ("Never") to 7 ("More than three times a week"). This self-reported measure captured participants' behavioral intentions, serving as an indicator of exercise adherence.

Heart Rate and Heart Rate Variability. Cardiac indices were continuously monitored for 20 minutes before and after the walk using a Polar H10 heart rate monitor while participants rested supine. Heart Rate Variability (HRV) was analyzed using the RMSSD time-domain index, which estimates vagally mediated HRV changes (Malik et al., 1996). Using a moderate error correction filter, data were processed with Kubios HRV software (Version 3.5.0, Biosignal Analysis and Medical Imaging Group, Kuopio, Finland).

Cortisol. As a stress marker, salivary cortisol concentrations were measured before and after walking using Salivette® (Sarstedt). Samples were centrifuged for 5 minutes immediately after collection and stored at -18°C for later analysis at the University.

2.4 Analyses overview

To investigate the impact of time (pre, post) and environment (natural = G, indoor = I, urban = U) on dependent variables such as emotions, cardiovascular indices, and perceived exertion, linear mixed modelling (LMM) with residual maximum likelihood estimations was employed. This method, widely used in restorative environments research (Oswald et al., 2023; Suko & Korpela, 2024), incorporates both fixed and random effects, accounting for the hierarchical structure of the data and within-subject variability.

For emotions, perceived exertion (CR-10), and cortisol, pre- and post-walk measurements were included in the linear mixed models. Heart rate (HR) and heart rate variability (RMSSD) were assessed across five time points: pre-walk and 5, 10, 15, and 20 minutes post-walk, allowing for a more detailed examination of recovery trajectories. Cortisol and RMSSD values were log-transformed before analysis.

Repeated measures ANOVA was used to analyze ROS and PRS scores, with the environment (natural, urban, indoor) as a within-subject factor. Post-hoc pairwise comparisons with Bonferroni correction were performed to analyze significant effects ($p < .05$).

Participants' intentions to engage in future PA in each environment were assessed using a non-parametric Friedman's ANOVA due to the non-normal distribution of intention scores. Pairwise comparisons with the Wilcoxon signed-rank test and Bonferroni correction explored differences between environments.

All mixed model analyses were conducted in Jamovi using the GAMLj module (version 2.6.6). In the main text, we report β coefficients and p-values to emphasize the strength and significance of the effects. Full model outputs, including model fit indices (AIC, BIC, log-likelihood), marginal and conditional R^2, and variance components (random effects, ICC), are provided in the Supplementary Materials to facilitate transparency and interpretation. Additional analyses, including repeated-measures ANOVA and non-parametric tests, were conducted using Jamovi and R Statistical Software (version 4.3.1). Descriptive statistics and post-hoc results are presented in the Supplementary Materials.

3. Results

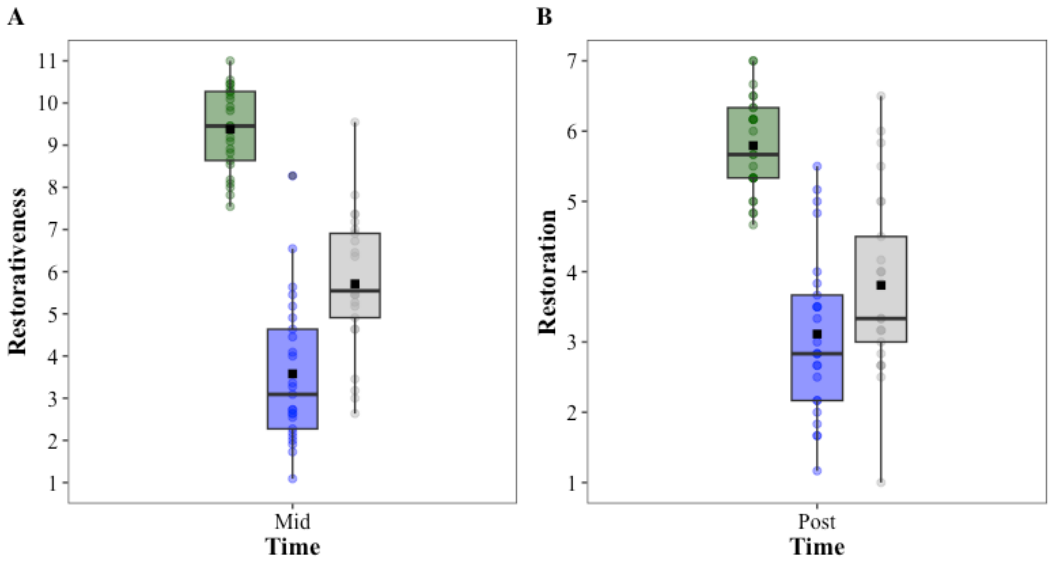
3.1 Psychological outcomes

3.1.1. Restoration

Results showed that the perceived restorativeness (PRS) varied significantly across the different environmental conditions (F (2,48) =105.9, $p < .001$, $\eta^2 = 0.82$, Figure 3). Post hoc comparisons showed that participants perceived the natural environment as the most restorative, followed by the urban and the indoor (all *ps* < .001).

Restoration outcomes (ROS) differed significantly across environments (F (2,48) = 38.03, $p < .001$, $\eta^2 = 0.61$); Figure 3). Post hoc comparisons indicated that the natural environment yielded significantly higher restoration scores than urban and indoor settings (*p*s < .001). At the same time, no significant difference was found between U and I ($p = .104$).

Figure 3. Perceived restorativeness (PRS) and psychological restoration (ROS) for each of the three environments.



Note: the plot displays the reported levels of perceived restorativeness (PRS; Panel A) and psychological restoration (ROS; Panel B) for each environment. Perceived restorativeness (PRS) was assessed during the 10-minute stop in the middle of the walk while participants were immersed in each of the three environments. The psychological restoration (ROS) was assessed at the end of the walk. Environments are represented by different colors: green for the natural environment, grey for the urban environment, and blue for the indoor environment.

3.1.2. Emotions

Emotions were assessed using a short version of the Achievement Emotions Adjective List (AEAL; Raccanello et al., 2022), grounded in the circumplex model of affect. This model categorizes emotions along two dimensions: activation (activating/deactivating) and valence (positive/negative), resulting in four distinct groups: positive activating emotions (PAE; i.e., happy, satisfied, optimistic), positive deactivating emotions (PDE; i.e., relaxed, relieved), negative activating emotions (NAE; i.e., anxious, angry, embarrassed), and negative deactivating emotions (NDE; i.e., demoralized, bored).

For this study, participants responded to a total of 14 items. Ten items measured one specific emotion within the circumplex categories. Additionally, three items were used to enhance reliability for the key target emotions of relaxation and anxiety. Relaxation was assessed with the items relaxed, calm, and tranquil, while anxiety was measured with anxious, worried, and nervous.

This tailored version of the AEAL allowed for calculating composite scores for each emotional category while providing a robust and detailed evaluation of relaxation and anxiety as primary outcomes.

Positive Emotions (PE). Our results revealed a significant main effect of the environment ($F(2,120) = 6.36$, $p = .002$). Participants reported significantly higher positive emotions in G compared to U ($\beta = -0.36$, $p = .005$) and I ($\beta = -0.40$, $p < .001$), confirming Hp 1a. While no significant effect of time alone was found ($p = .190$), there was a significant interaction effect of time and environment on positive emotions ($F(2,110) = 6.67$, $p = .002$; see Figure 4). Specifically, positive emotions decreased more in I compared to G from pre to post ($\beta = -0.90$, $p < .001$). The decrease in positive emotions in U was marginally significant compared to G ($\beta = -0.46$, $p = .068$). No significant changes were found in G and U from pre to post.

Positive activating emotions (PDE). The analysis showed a significant effect of the environment on positive activating emotions ($F(2,120) = 3.52$, $p = .033$). Participants reported lower positive activating emotions in I compared to G ($\beta = -0.37$, $p = .010$). No statistically significant difference between U and G ($p = .105$) existed. While no main effect of time was observed ($p = .628$), there was a significant interaction between time and environment ($F(2,120) = 5.32$, $p = .006$, see Figure 4). Participants in I showed a greater

reduction in positive activating emotions post-walk than G (β = -0.84, p = .002). No significant interaction was found in U compared to G (p = .459).

Positive deactivating emotions (PAE). The analysis revealed significant main effects of both time (F (1,120) = 10.57, p = .001) and environment (F (2,120) = 7.57, p < .001) on positive deactivating emotions. Post-walk, participants experienced a significant reduction in positive deactivating emotions compared to pre-walk levels (β = -0.41, p = .001). Participants reported significantly lower positive deactivating emotions in I (β = -0.48, p = .003) and U (β = -0.56, p < .001) compared to G. A significant interaction between time and environment was also observed (F (2,120) = 5.95, p = .003, see Figure 4). Participants in I experienced a larger reduction in positive deactivating emotions post-walk than G (β = -1.0, p = .002). Similarly, participants in U showed a significant reduction in these emotions post-walk compared to G (β = -0.84, p = .008).

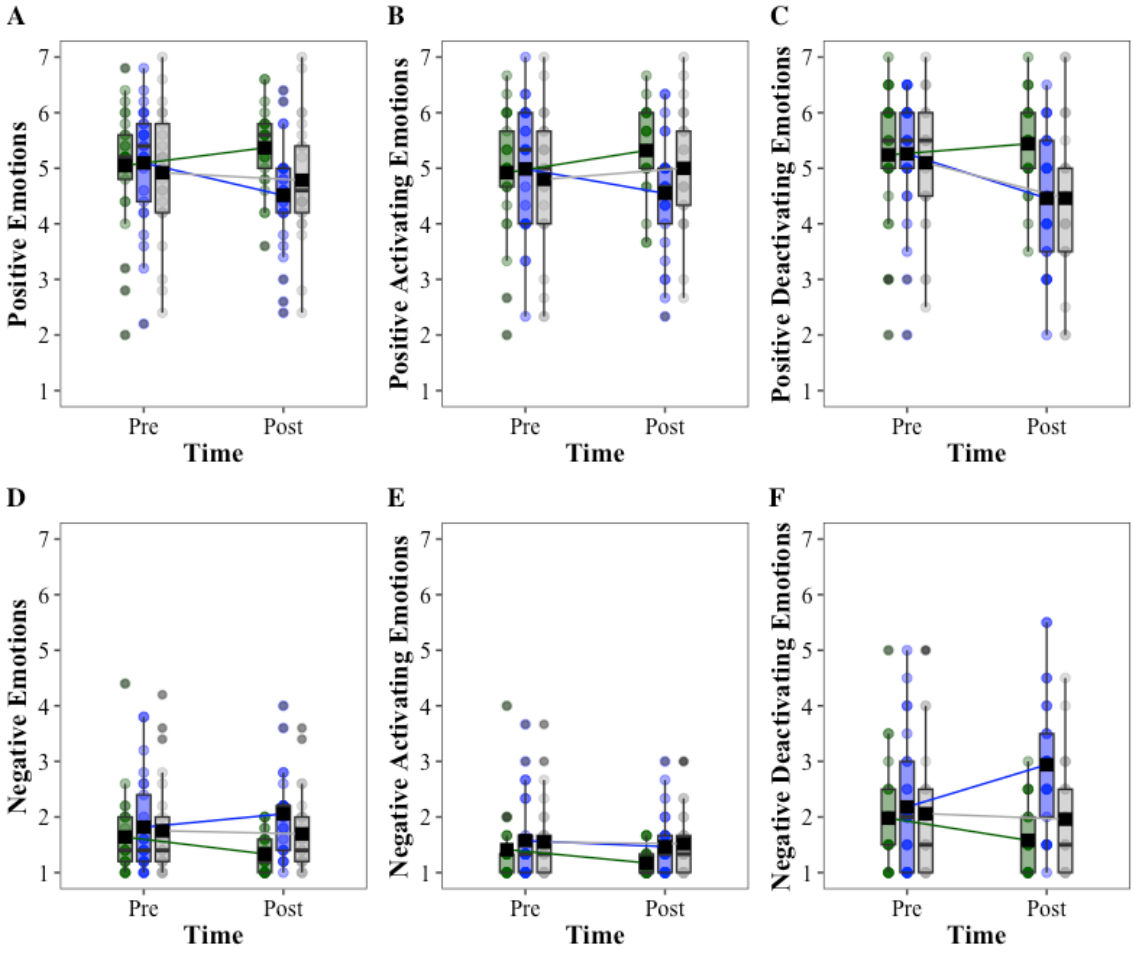
Negative Emotions (NE). The analyses showed a significant main effect of the environment on negative emotions (F (2,120) = 11.81, p < .001). Participants reported lower levels of negative emotions in G compared to I (β = -0.45, p < .001) and U (β = -0.24, p = .012), confirming Hp 1a. There was no significant main effect of time (p = .596). However, a significant interaction between time and environment was found (F (2,120) = 4.36, p = .015, see Figure 4). Negative emotions decreased more from pre to post in G than I (β = -0.54, p = .004). No significant interaction was found for U compared to G (p = .181). A significant decrease was found in G from pre to post exercise (β = -0.30, p = .021).

Negative activating emotions (NAE). The analysis revealed a significant main effect of the environment on negative activating emotions (F (2,120) = 5.65, p = .005). Participants reported higher negative activating emotions in both I (β = 0.23, p = .006) and U (β = 0.24, p = .003) compared to G. No main effect of time (p = .060) or significant interactions were found between time and environment (p = .408).

Negative deactivating emotions (NDE). The analysis revealed a significant main effect of the environment on negative deactivating emotions (F (2,120) = 15.31, p < .001). Participants reported higher negative deactivating emotions in I compared to G (β = 0.78, p < .001). No significant differences were found between U and G (p = 0.115). No main effect of time was found (p = .465). A significant interaction between time and environment was observed (F (2,120) = 8.64, p < .001). Participants in I reported an increase compared to G in

negative deactivating emotions from pre- to post-walk (β = 1.16, p < .001). No significant effect was found in U compared to G (p = 0.303).

Figure 4. Positive and negative activating and deactivating emotions pre- and post-activity in green, urban and indoor environments.



Note: the top panels show the interactions between time and environment for overall positive emotions (PA; panel A), positive activating emotions (PAE; panel B), and positive deactivating emotions (PDE; panel C). In the bottom panels, there are the interactions between time and environment for overall negative emotions (NE; panel D), negative activating emotions (NAE; panel E), and negative deactivating emotions (NDE; panel F). Environmental conditions are represented by different colors: green (natural environment), grey (urban environment), and blue (indoor environment).

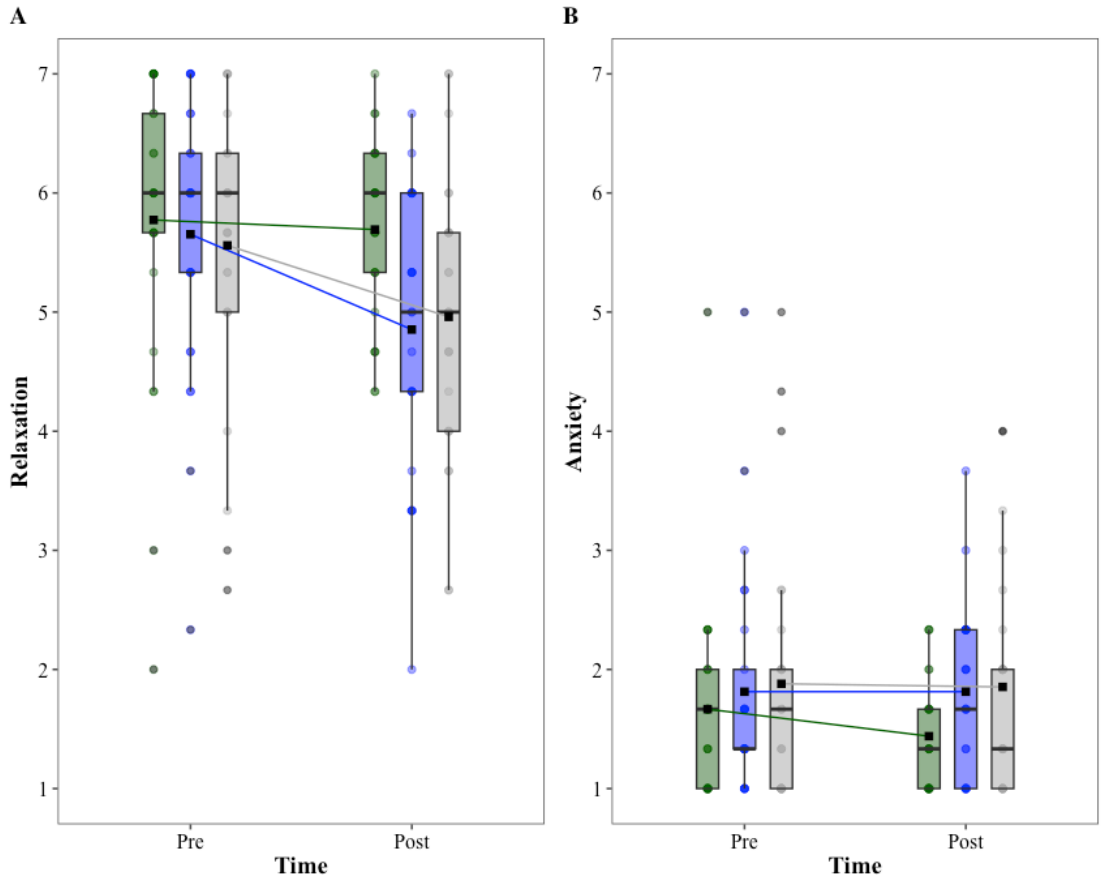
Relaxation. Our study revealed a significant main effect of environment on relaxation (F (2,120) = 7.08, p = .001), with participants in G reporting higher relaxation levels compared to both I (β = -0.48, p = .001) and U (β = -0.47, p = .002). We also found a significant main effect of time on relaxation (F (2,120) = 17.06, p < .001), with relaxation that

decreased from pre to post exercise across conditions (β = -0.49, p < .001). Our results also showed a significant interaction between time and environment (F (2,120) = 3.23, p = .043, see Figure 5), indicating that relaxation decreased more in I than in G from pre to post (β = -0.72, p = .015). No significant interaction was found for U compared to G (p = .078).

Anxiety. The analysis revealed a significant effect of the environment on anxiety levels (F (2,120) = 4.50, p = .013). Participants reported higher anxiety in I compared to G (β = 0.26, p = .022) and in U compared to G (β = 0.31, p = .006). There was no significant effect of time (p = .356) and no significant interaction between time and environment (p = .542).

These results confirmed Hp 1b, demonstrating that natural environments promote relaxation and maintain lower anxiety levels than urban and indoor settings.

Figure 5. Relaxation and anxiety pre- and post-activity in green, indoor and urban environments.

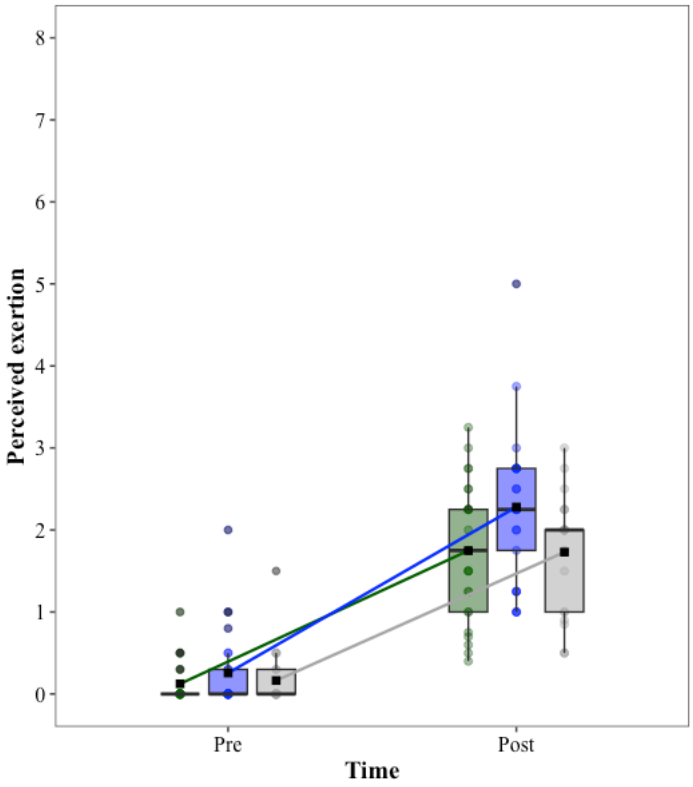


Note: the plot displays the interactions between time and environment for relaxation (panel A) and anxiety (panel B). Environmental conditions are represented by different colors: green for the natural environment, grey for the urban environment, and blue for the indoor environment.

3.1.3. Perceived exertion (CR-10)

The analysis of perceived exertion revealed a significant main effect of time ($F(1,120) = 333.18$, $p < .001$), indicating that participants reported higher levels of exertion post-exercise compared to pre-exercise ($\beta = 1.74$, $p < .001$). There was also a significant main effect of environment ($F(2,120) = 5.23$, $p = .007$), with participants reporting higher perceived exertion in I compared to G ($\beta = 0.33$, $p = .005$). No significant difference in perceived exertion was found between the U and G ($p = .925$). This finding partially supports Hp 3, as perceived effort was lower in natural settings than in indoor environments, though no significant differences emerged between natural and urban settings. The interaction between time and environment was not significant ($F(2,120) = 2.29$, $p = .106$).

Figure 6. Perceived exertion (CR-10) before and after the walk in green, urban, and indoor environments.

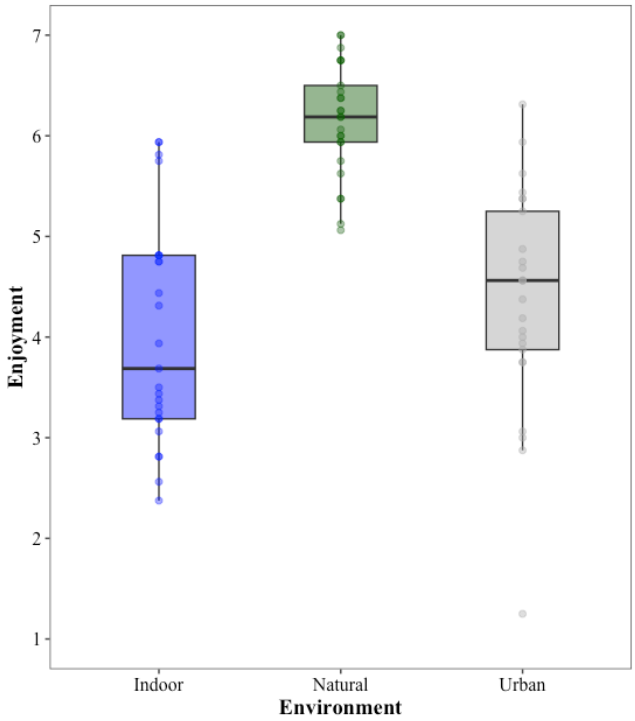


Note: the plot displays the interactions between time and environment for the perceived exertion (CR-10). Environmental conditions are represented by different colors: green for the natural environment, grey for the urban environment, and blue for the indoor environment.

3.1.4. Behavioral intentions and enjoyment of exercise

PACES (Physical Activity Enjoyment Scale). Enjoyment scores varied significantly across environmental conditions ($F(2,48) = 41.09$, $p < .001$, $\eta^2 = 0.63$, Figure 7). Aligning with Hp 1a, post-hoc analyses revealed that participants reported significantly higher enjoyment in G compared to both I and U (all ps $< .001$), with no significant difference between I and U settings ($p = .506$).

Figure 7. Enjoyment ratings of physical activity (PACES-it) across different environments.

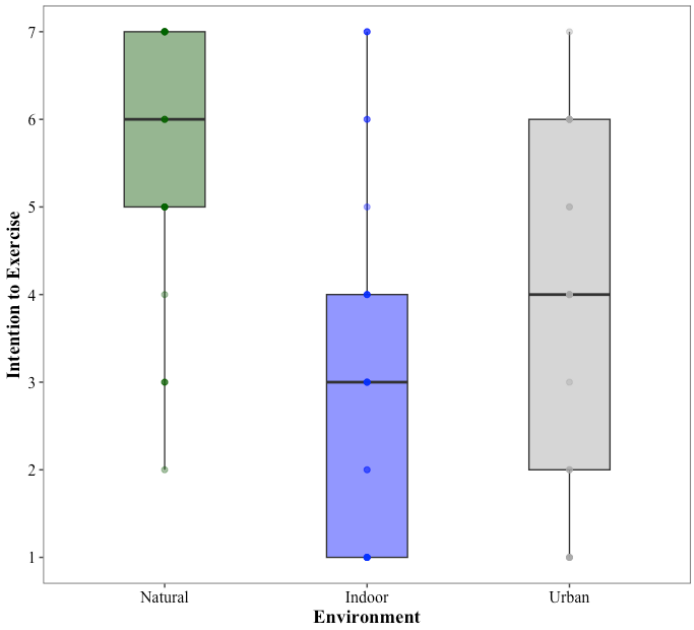


Note: Boxplot showing participants' enjoyment ratings (PACES-it) in each environment following physical activity. Environmental conditions are represented by different colors: green (natural environment), grey (urban environment), and blue (indoor environment).

Intentions. A Friedman test revealed a significant effect of the environment on participants' intention to engage in future PA within the same environment where they completed the experiment ($\chi^2(2) = 15.88$, $p < .001$, Kendall's $W = 0.318$, indicating a moderate effect; Figure 8). Post-hoc pairwise comparisons using the Wilcoxon signed-rank test with Bonferroni correction showed that the intention score was significantly higher in G

compared to I (p = .002, W = -2.31) and U (p = .004, W = -2.30) environments, aligning with Hp 1a No significant difference was found between I and U (p = 1.00).

Figure 8. Intention to repeat physical activity across different environments.



Note. Boxplot showing participants' intention to repeat physical activity in the same environment (natural, indoor, or urban), rated on a frequency scale. The scale ranges from 1 (never) to 7 (more than three times a week), with intermediate points: 2 (once a month), 3 (twice a month), 4 (once a week), 5 (twice a week), and 6 (three times a week).

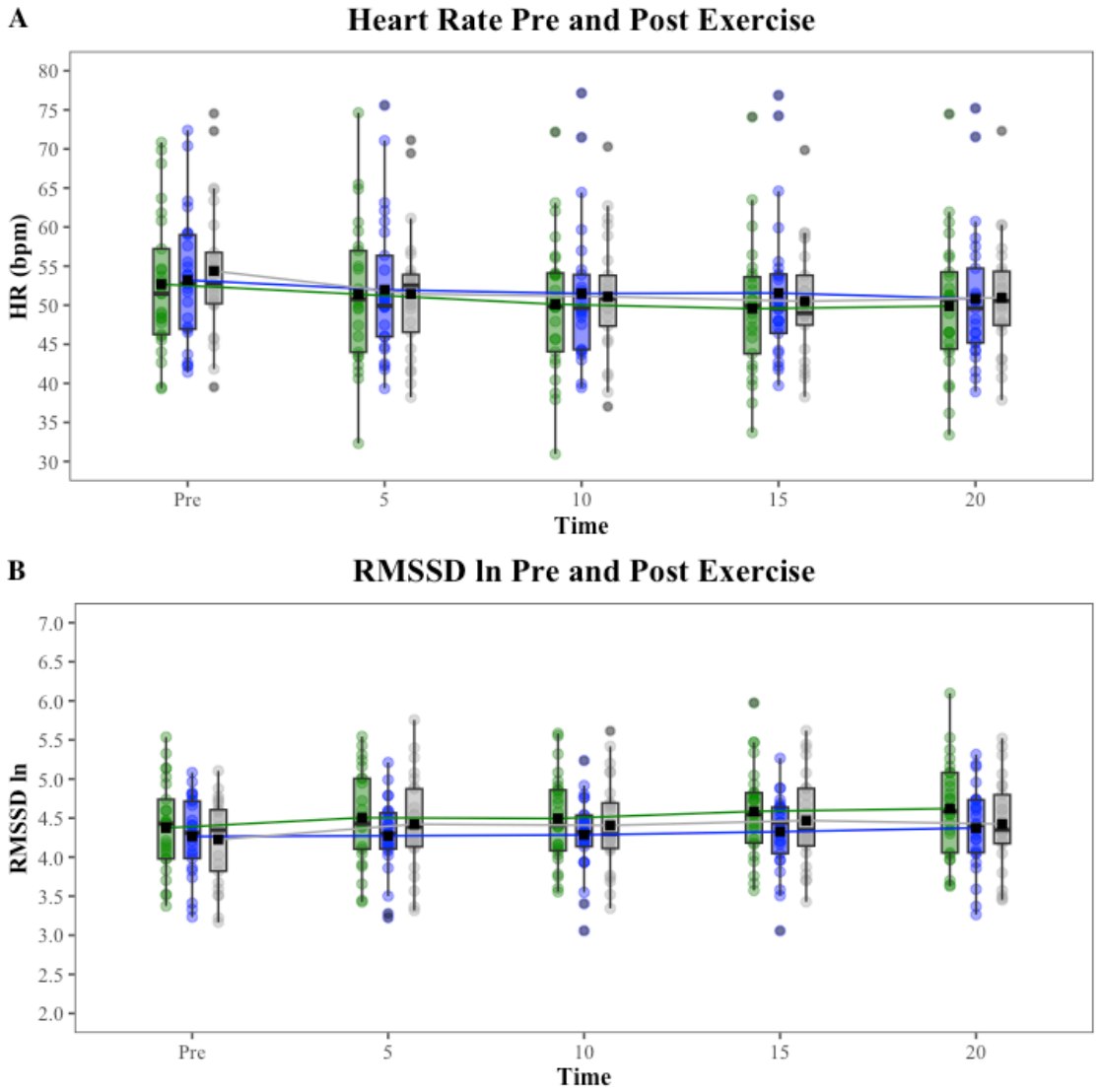
3.2 Physiological measures

Heart Rate. The analysis revealed significant effects of time on heart rate (F (4, 336) = 8.27, p < .001), indicating that HR significantly decreased across time points. Compared to the pre-walk baseline, HR was significantly lower at post-5 (β = -1.81, p = .002), post-10 (β = -2.52, p < .001), post-15 (β = -2.88, p < .001), and post-20 (β = -2.86, p < .001). A main effect of the environment was also found (F (2, 336) = 3.31, p = .038). HR was significantly higher in I compared to G (β = 1.08, p = .019) and in U compared to G (β = 0.95, p = .040), supporting Hp 2. No significant interactions between time and environment were found (p = .889).

RMSSD. The analysis revealed a significant effect of time on log-transformed RMSSD (F (4, 336) = 4.67, p = .001), with significant increases from pre-walk to 5 mins post

($\beta = 0.12$, $p = .020$), 10 mins post (Estimate = 0.11, $p = .026$), 15 mins post ($\beta = 0.17$, $p < .001$), and 20 mins post ($\beta = 0.19$, $p < .001$), showing a steady increase over time. Supporting further Hp 2, a significant main effect of the environment was found (F (2, 336) = 16.44, $p < .001$), with log-RMSSD being lower in I compared to G ($\beta = -0.21$, $p < .001$) and lower in the U compared to G ($\beta = -0.13$, $p < .001$). No interaction between time and environment was observed ($p = 0.784$).

Figure 9. Heart Rate (panel A) and ln RMSSD (Panel B) across different environments.

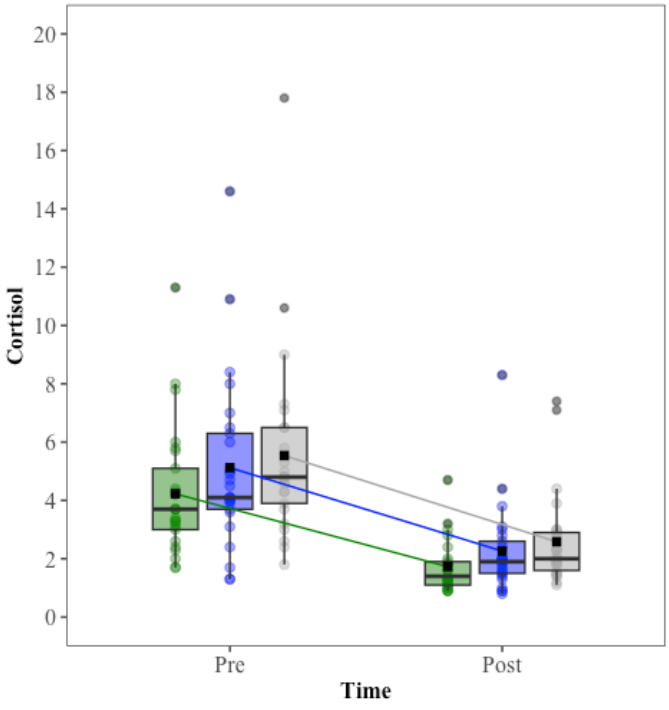


Note. Boxplots displaying participants' physiological responses - Heart Rate (Panel A) and log-transformed Heart Rate Variability (RMSSD, Panel B) - across three environmental conditions: natural (green), urban (grey), and indoor (blue). For each environment, values are shown for the pre-walk baseline (Pre) and four successive

time points during the 20-minute post-walk recovery phase (5, 10, 15, and 20 minutes).

Cortisol log. The analysis of log-transformed cortisol revealed a significant main effect of time (F (1, 120) = 209.10, $p < .001$), showing a substantial decrease in cortisol levels from pre- to post-walk across all conditions ($\beta = -0.82$, $p < .001$). Additionally, a significant main effect of the environment was observed (F (2, 120) = 10.43, $p < .001$). Cortisol levels were significantly higher in I compared to G ($\beta = 0.19$, $p = .009$) and in U compared to G ($\beta = 0.32$, $p < .001$). These results confirm Hp 2, demonstrating that natural environments are associated with lower cortisol levels, reflecting reduced physiological stress. No significant interaction between time and environment was found ($p = .730$).

Figure 10. Cortisol levels pre and post exercise across different environments.



Note. Boxplot showing participants' salivary cortisol levels across the three environments, represented by different colors: green for the natural environment, grey for the urban environment, and blue for the indoor environment.

Table 1. Summary of main effects and interactions for all dependent variables.

Outcome	Effect of Time	Effect of Environment			Time * Environment
	Pre vs Post	G vs I	G vs U	U vs I	
PRS	—	↑ in G	↑ in G	↑ in U	—
ROS	—	↑ in G	↑ in G	ns	—
PE	ns	↑ in G	↑ in G	ns	Yes
PDE	↓ post	↑ in G	↑ in G	ns	Yes
PAE	ns	↑ in G	ns	ns	Yes
NE	ns	↓ in G	↓ in G	ns	Yes
NAE	ns	↓ in G	↓ in G	ns	ns
NDE	ns	↓ in G	ns	ns	Yes
Relaxation	↓ post	↑ in G	↑ in G	ns	Yes
Anxiety	ns	↓ in G	↓ in G	ns	ns
CR-10	↑ post	↓ in G	ns	ns	ns
PACES	—	↑ in G	↑ in G	ns	—
Intentions	—	↑ in G	↑ in G	ns	—
HR	↓ post	↓ in G	↓ in G	ns	ns
RMSSD	↑ post	↑ in G	↑ in G	ns	ns
Cortisol	↓ post	↓ in G	↓ in G	ns	ns

Note: the table reports significant main effects of time, environment, and their interaction for each dependent variable. Symbols indicate whether the effect was statistically significant ($p < .05$). For significant effect of the environment, post hoc comparisons are briefly summarized, showing which environmental conditions differed significantly (G = green; I = indoor; U = urban). For non-significant results, "ns" is reported.

4. Discussion

This study examined the effects of different environmental contexts—natural, urban, and indoor—on both psychological outcomes (e.g., affective states, restoration, perceived restorativeness, enjoyment, and intention to exercise) and physiological responses (e.g., heart rate, heart rate variability, and cortisol) during moderate-intensity PA. Participants completed one hour of exercise in each environment, and their responses were assessed physiologically and through self-report measures. We hypothesized that natural environments would lead to greater psychological restoration, more positive emotional states, lower perceived exertion, and improved physiological recovery compared to urban and indoor settings.

Psychological outcomes

Restoration

Participants perceived the natural environment as significantly more restorative than indoor and urban settings, with the urban environment rated as moderately restorative but surpassing the indoor setting. These results emphasize the superior restorative potential of natural settings over built environments.

The PRS assesses key environmental qualities that promote restoration, such as fascination (effortless attention), compatibility (alignment with individual goals), extent (perceived scope), and being away (escape from routine; Kaplan & Kaplan, 1989; S. Kaplan, 1995). In contrast, the ROS measures immediate restorative effects, including relaxation, attention recovery, and the ability to clear one's thoughts (Korpela et al., 2008, 2010). Together, these tools provide a comprehensive understanding of how natural environments facilitate psychological recovery.

The higher perceived restorativeness of natural settings aligns with Attention Restoration Theory (ART), which suggests that environments rich in fascination and free from cognitive demands restore directed attention (Collado et al., 2017). Natural environments inherently offer these qualities, enabling a sense of psychological distance from daily routines and fostering coherence and mental space (Menardo et al., 2021).

The elevated ROS scores observed in natural settings further reinforce this, reflecting enhanced emotional and cognitive restoration following activity. This aligns with studies like Takayama et al. (2014), which found that walking in forests significantly improved ROS outcomes compared to urban settings, where distractions often hinder restorative experiences.

The consistency between PRS and ROS results underscores the integrated benefits of natural environments. They possess attributes conducive to restoration and effectively translate these into measurable psychological recovery. These findings add to the growing evidence base highlighting the positive impacts of nature exposure on mental health and stress reduction (Hyvönen et al., 2023).

By contrast, while urban and indoor environments offer some restorative benefits, their capacity for fostering recovery appears more limited. This suggests a critical need to incorporate natural elements into urban design and indoor spaces to enhance their restorative potential, especially when individuals engage in exercise or other forms of PA.

Emotions

Participants reported notably higher positive and lower negative emotions in the natural environment compared to urban and indoor settings. While no overall effect of time emerged, a significant interaction between time and environment revealed that positive emotions declined post-activity in the indoor setting, a trend less pronounced in the urban environment but absent in the natural environment. In contrast, negative emotions remained relatively stable but were consistently lowest in the natural setting. Post-walk increases in negative emotions were most prominent indoors, whereas urban environments remained closer to the green setting.

These findings underscore the emotionally restorative potential of natural environments, where individuals experience more positive and fewer adverse emotional outcomes than in urban and indoor spaces. Importantly, these results align with prior studies (Hartig et al., 2003; Mayer et al., 2009) and a meta-analysis demonstrating that even brief contact with nature enhances positive affect and moderately reduces negative affect, promoting overall emotional well-being (McMahan & Estes, 2015). These results highlight the value of natural environments for sustaining positive emotional states during and after PA. For practitioners designing exercise programs, incorporating outdoor settings can enhance psychological outcomes and motivation, contributing to better adherence and long-term mental health benefits. Participants also reported significantly greater relaxation in the natural environment, with the sharpest decline occurring indoors post-activity. Similarly, anxiety levels were consistently lower in natural settings compared to urban and indoor environments, though no significant time-related changes emerged in any condition. These results emphasize the synergistic effects of movement and restorative environments, where

natural settings promote sustained relaxation and lower baseline anxiety. This aligns with prior research on GE, highlighting its ability to enhance emotional well-being through the combined influence of PA and nature exposure (Kotera et al., 2021; Wicks et al., 2022). For exercise and health psychology, these findings are particularly relevant for populations managing stress, anxiety, or mood disorders, as natural settings offer a dual intervention for physical and mental health.

Further analysis along the activation-deactivation axis revealed distinct emotional patterns across environments:

Positive activating emotions (PAE) were significantly higher in natural settings, fostering happiness, satisfaction, and optimism. Positive deactivating emotions (PDE) were also strongest, emphasizing calming and tranquil qualities. Urban settings provided intermediate benefits for PAE and PDE, while indoor environments consistently elicited the lowest levels, lacking energizing or soothing effects. Negative emotions were mitigated most effectively in natural environments. Negative activating emotions (NAE) were highest indoors and moderately present in urban environments. Negative deactivating emotions (NDE) were lowest in natural settings but increased post-walk indoors, highlighting the limited capacity of indoor spaces to support psychological well-being.

These patterns indicate that natural environments provide a unique combination of activation and relaxation, supporting energizing emotions (important for motivation) and calming emotions (essential for stress recovery). These findings suggest that green settings optimize psychological outcomes, improving mood and recovery for athletes, recreational exercisers, or individuals in stress-reduction programs.

Perceived exertion

Furthermore, participants reported higher perceived exertion after the walk in the indoor environment, while natural and urban settings showed comparable levels. These findings partly align with prior research: for example, Rogerson et al. (2016) found no difference in exertion during outdoor and indoor cycling, potentially due to passive exposure to the outdoor environment. Similarly, Lahart et al. (2019) noted that lower perceived exertion in GE emerged mainly in longitudinal studies, while acute studies yielded mixed results. Wicks et al. (2022), in a meta-analysis comparing GE with urban PA, highlighted the consistent benefits of GE for increasing energy and reducing fatigue. However, heterogeneity

in measurement tools complicates direct comparisons. In short, our results suggest that nature's restorative and distracting qualities may mitigate perceived exertion. Still, this effect appears to depend on PA type and engagement factors. Also, lower perceived exertion in green settings may contribute to greater enjoyment and adherence to PA programs. This might have implications for health promotion initiatives, where green spaces can encourage individuals to engage in regular PA without the added psychological burden of exertion.

Behavioral intentions and enjoyment of exercise

Our findings provide novel insights into how environmental settings influence the enjoyment of PA and intentions for future engagement. Using a rigorous methodological approach, which assessed well-characterized natural, urban, and indoor environments, this study highlights the specific attributes of natural settings that enhance exercise experiences.

Consistent with prior reviews (Lahart et al., 2019), participants reported the highest levels of enjoyment in the natural environment. This reinforces the idea that GE amplifies the positive experience of PA. Enjoyment is a key determinant in sustaining regular PA, as it fosters motivation and satisfaction, which are critical factors for long-term adherence. Our study is among the first to compare behavioral intentions across diverse environmental settings systematically. Participants expressed a significantly greater intention to repeat PA in natural environments, with higher anticipated frequency compared to urban and indoor settings. This finding underscores the long-lasting impact of GE, as its perceived benefits extend beyond the immediate session to shape future behavior.

No significant differences in intention were observed between urban and indoor settings. This suggests that natural environments' unique restorative and engaging qualities are central to encouraging long-term adherence to PA. These results diverge slightly from Rogerson (2016), which underscores the importance of methodological differences. While Rogerson's study may have used less immersive or controlled conditions, our research incorporated light-to-moderate intensity walking in real-world environments. This approach aimed to capture the dynamic and context-rich benefits of GE.

Our results emphasize that PA type and environmental context are pivotal in shaping behavioral intentions. The findings highlight the unique motivational value of natural settings, which enhance the immediate enjoyment of PA and foster a greater willingness to maintain such behavior over time.

Physiological outcomes

Our findings provide further evidence for the role of environmental settings in shaping physiological recovery following PA. Across all environments, cortisol levels significantly decreased post-walk, reflecting stress recovery. However, cortisol levels remained consistently lower in the natural environment compared to indoor and urban settings, suggesting a stronger restorative effect. These results align with studies by Park et al. (2007), which also reported significant cortisol reductions after exposure to nature.

In contrast, studies such as Tyrväinen et al. (2014) and Gidlow et al. (2016) found no significant differences in cortisol reduction between environments. Such discrepancies may stem from methodological differences. First, our study employed individually paced, light-to-moderate intensity exercise, whereas Tyrväinen et al. used group walking at controlled speeds, potentially introducing social dynamics that could influence stress responses. Second, Tyrväinen's sample included middle-aged females, who may exhibit lower cortisol reactivity due to hormonal factors (Kudielka et al., 2004), contrasting with our younger male participants, who are more comparable to those in Park et al. (2007). Finally, our inclusion of a distinctly restorative natural environment likely enhanced the observed effects, highlighting the importance of clear environmental contrasts in studying the stress-relieving potential of nature.

Heart rate (HR) also decreased over time in all conditions, reflecting ongoing physiological recovery. Participants in the natural environment displayed consistently lower HR than in indoor and urban settings, supporting the idea that natural environments facilitate autonomic recovery. These results contrast with previous studies, such as those by Gidlow et al. (2016), which found uncertain environmental effects on HR, emphasizing the variability of findings in this area. Similarly, heart rate variability (HRV), measured through log-transformed RMSSD, significantly increased during the recovery period, with the highest values observed in the natural environment. This suggests enhanced parasympathetic activation in green settings, consistent with the stress-reducing properties attributed to natural environments (Brown et al., 2013; Gladwell et al., 2012). However, not all findings align with this pattern. For example, Gidlow et al. (2016) reported inconclusive HRV responses across environments. Scott et al. (2021) observed a counterintuitive decrease in HRV and an increase in HR during immersion in nature compared to urban or control settings. This

unexpected shift toward sympathetic activation highlights the complexity of physiological responses and suggests that individual or situational factors may moderate these effects.

These findings suggest that natural environments may support physiological recovery during light-to-moderate exercise, as indicated by lower heart rate, higher HRV, and reduced cortisol levels compared to urban and indoor settings. However, it is worth noting that while the environment had a significant effect, no interaction between time and environment emerged for any of the physiological indices. This points to a partial dissociation between physiological markers and participants' self-reported psychological restoration, particularly the marked improvements in perceived restoration (ROS), relaxation, and affective states observed after the walk in the natural setting.

This dissociation, already reported in literature (Scott et al., 2020), challenges the original Stress Recovery Theory (SRT) assumptions, which posits a direct alignment between affective and physiological responses to natural environments. Although SRT and Attention Restoration Theory (ART) offer practical frameworks for interpreting nature exposure's immediate affective and cognitive benefits, they often conceptualize individuals and environments as separate entities, focusing primarily on internal recovery from stress or attentional fatigue.

Recent theoretical developments have proposed a transactional and integrative approach to enrich these perspectives. The ecological dynamics framework (Araújo et al., 2019) emphasizes the person–environment system as the unit of analysis. According to this view, nature experiences are not simply the result of passive exposure but emerge from dynamic, embodied engagement with the affordances offered by natural settings. These affordances—more varied and less constrained than those in built environments—enable meaningful interactions that may enhance psychological functioning, motivation, and overall well-being during and after physical activity.

This framework helps explain why, in our study, natural environments elicited higher enjoyment and stronger behavioral intentions, despite the relatively subtle physiological differences across settings. It suggests that the restorative benefits of green exercise are not solely tied to stress recovery but also reflect a deeper person–environment synergy that facilitates positive emotional and motivational states.

Practical implications

These findings underscore the potential of GE for enhancing cardiovascular recovery and stress reduction and promoting greater enjoyment and engagement in PA. Such benefits hold significant implications for both athletic recovery and general public health.

For athletes and avid sports practitioners, incorporating natural environments into recovery protocols could accelerate physiological and psychological restoration, leading to improved performance and a reduced risk of burnout. GE has been shown to facilitate parasympathetic activation (Gladwell et al., 2012; Brown et al., 2013) and reduce cortisol levels (Park et al., 2007), which are key markers of stress recovery. This aligns with evidence suggesting that exposure to nature enhances mental relaxation and cognitive restoration, which are critical for maintaining consistent athletic performance (Hartig et al., 2003; Takayama et al., 2014).

GE can be a powerful motivator for the general population, particularly those who are moderately active or new to exercise. By making PA more enjoyable and less physically demanding (Wicks et al., 2022; Lahart et al., 2019), natural environments help lower perceived barriers to exercise. Increased enjoyment fosters a positive relationship with PA (Ekkekakis et al., 2011; Jekauc, 2015), improving adherence and encouraging long-term behavioral changes toward a healthier lifestyle.

From an exercise and health psychology perspective, these findings highlight the importance of affective responses, such as enjoyment, stress relief, and perceived effort, in shaping exercise adherence. Positive emotional experiences during PA are strongly linked to sustained motivation and long-term engagement (Williams et al., 2006; McMahan & Estes, 2015), making GE a promising strategy for addressing physical inactivity and improving mental well-being (Kotera et al., 2021).

Additionally, our results emphasize the potential value of integrating natural elements into urban design and public health strategies. Creating accessible green spaces has increased PA levels and improved mental health across diverse populations (Thompson et al., 2012; Shanahan et al., 2016). Promoting outdoor group activities in these spaces can provide inclusive opportunities for exercise, fostering social connection while improving physical and mental health outcomes (Hyvönen et al., 2023; Pasanen et al., 2018).

Future research should explore the long-term effects of GE interventions and investigate how the restorative qualities of natural environments can be optimized for specific populations, including those with chronic health conditions, mental health challenges, or

limited access to outdoor spaces (Menardo et al., 2021; Gidlow et al., 2016). Tailoring GE programs to meet these unique needs may amplify its benefits and address disparities in PA participation.

Limitations and future studies

This study has several limitations that should be addressed in future research. The sample consisted of 25 male participants with varying fitness levels, which may limit the generalizability of findings to broader populations, including women, older adults, and individuals with diverse fitness backgrounds. However, by including participants with different activity levels, we added variability to the sample, providing valuable insights into how individuals perceive and respond to various environments.

While representative of a typical city setting, the urban environment selected yielded relatively high fascination scores on the PRS, suggesting qualities that may enhance its restorative potential compared to more stressful urban areas. This setting was intentionally chosen as a real-world context free from overwhelming stressors such as heavy traffic or excessive noise. This approach addresses a common limitation in the literature, where appealing natural environments are contrasted with stressful urban settings. By selecting an engaging yet not overly stressful urban environment, the study provides a more balanced comparison, ensuring that observed benefits of nature reflect its inherent restorative qualities rather than unfavorable urban conditions. Nonetheless, future studies should examine a broader range of urban settings to better capture their variability and influence on restorative outcomes.

Temperature differences between environments may have influenced participants' physiological and psychological responses. While the study prioritized ecological validity by maintaining real-world conditions, future research could better control thermal comfort to isolate environmental effects.

Although participants were screened for familiarity with the study locations, prior exposure cannot be entirely ruled out. To minimize this risk, efforts were made to recruit individuals from diverse regions, enhancing the robustness of the findings.

Additionally, participants reported high relaxation and low negative emotions at baseline, which may have influenced subsequent measurements. However, these baseline

states reflect participants' natural disposition and indicate that the study design effectively captured authentic responses to the environments.

Despite these limitations, the study provides valuable evidence of the restorative potential of natural environments during PA. Future research with larger and more diverse samples, varied urban contexts, and controlled thermal conditions will help build on these findings and further advance our understanding of GE and its benefits.

5. Conclusion

This study highlights the important role of environmental context in shaping psychological and physiological responses to PA. Our findings demonstrate that natural environments yield superior benefits, enhancing perceived restoration, enjoyment, and intentions to engage in future activity. Participants reported greater positive emotions, lower negative emotions, and higher relaxation in natural settings compared to indoor environments, which emerged as consistently less favorable. However, the comparison between urban and natural environments revealed more nuanced results. Specific psychological outcomes, such as anxiety and some deactivating emotions, showed limited differentiation between the two. This suggests that the restorative advantages of nature over urban settings may depend on specific outcomes, highlighting the need for further investigation into the mechanisms underlying these effects.

Physiological measures provided strong support for the stress-relieving properties of nature. Participants in the green environment exhibited lower heart rates, lower cortisol levels, and higher HRV compared to indoor and urban settings, reinforcing nature's role in facilitating autonomic recovery. Notably, the absence of significant time-environment interactions for physiological variables indicates that nature's stress recovery effects are consistent over time, further underscoring its robustness.

The novelty of this study lies in its rigorous comparison of natural, urban, and indoor settings, integrating both psychological and physiological measures to provide a comprehensive understanding of environmental influences. While the benefits of nature are clear across multiple domains, the subtle differences observed in the urban-natural comparison suggest an opportunity to explore how urban environments can be optimized to enhance their restorative potential.

In conclusion, engaging in PA in natural environments is a powerful resource for promoting psychological well-being and physiological recovery. These findings advocate for the greater integration of natural spaces in urban planning and public health strategies. They also highlight the need for future research to further differentiate the unique contributions of urban and natural settings to health and well-being.

Data availability statement

The dataset generated and analyzed during the current study is available on the Open Science Framework (OSF) at https://osf.io/rfxgm/?view_only=e2bc0f4b02db422788a4d8ac0070e1ce

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Supplementary Materials

Supplementary Table 1. Detailed participant characteristics

	M	SD
Age	26.28	4.35
Heigh	179.31	4.98
Weight	73.61	8.36
BMI	22.86	2.00
HR max	191.29	7.25
VO_2 max	4084.01	496.33
VO_2 max / kg	55.77	6.38
VE max	165.38	22.60
Rf max	63.03	8.38
HR at 6 km/h	101.06	13.91
VO_2 6 km/h	1382.03	207.46
VO_2 at 6 km/h / kg	18.78	1.88
VE at 6 km/h	35.15	5.33
Rf at 6 km/h	23.00	5.56
% VO_2 max	34.14	5.46
% HR max	52.80	6.72

Supplementary Table 2. Achievement Emotions Adjective List

Valence		Achievement emotions	Italian	English
Positive	Activating	Enjoyment	*Contento*	*Happy*
			Felice	Cheerful
			Divertito	Joyful
		Pride	Orgoglioso	Proud
			Soddisfatto	*Satisfied*
			Fiero	Content
		Hope	Speranzoso	Hopeful
			Fiducioso	Confident
			Ottimista	*Optimistic*
	Deactivating	Relaxation	*Rilassato*	*Relaxed*
			Calmo	*Calm*
			Tranquillo	*Tranquil*
		Relief	*Sollevato*	*Relieved*
			Alleggerito	Lightened
			Rassicurato	Comforted
Negative	Activating	Anxiety	*Ansioso*	*Anxious*
			Preoccupato	*Worried*
			Nervoso	*Nervous*
		Anger	*Arrabbiato*	*Angry*
			Irritato	Irritated
			In collera	Furious
		Shame	Mi vergnogno	Ashamed
			Imbarazzato	*Embarrassed*
			A disagio	Uncomfortable
	Deactivating	Hopelessness	Sconsolato	Hopeless
			Demoralizzato	*Demoralized*
			Sfiduciato	Discouraged
		Boredom	*Annoiato*	*Bored*
			Stufo	Tired
			Tediato	Fatigued

Note. In italic items used in this study. For relaxation and anxiety, three items were used.

Supplementary Table 3. Summary of mixed models information for all outcomes

	AIC	BIC	LogLikel	R^2 Marginal	R^2 Conditional	random components				
						ICC	subj var	subj SD	residual var	residual SD
PE	353.40	389.18	-174.55	0.06	0.67	0.64	0.69	0.83	0.38	0.62
PAE	375.71	410.60	-185.26	0.04	0.63	0.62	0.72	0.85	0.67	0.45
PDE	413.37	446.75	-203.33	0.10	0.60	0.55	0.74	0.86	0.61	0.78
NE	261.76	301.21	-130.56	0.08	0.64	0.61	0.33	0.58	0.21	0.46
NAE	215.74	257.03	-108.47	0.05	0.58	0.56	0.21	0.46	0.16	0.40
NDE	390.83	425.12	-192.52	0.13	0.60	0.54	0.61	0.78	0.53	0.72
REL	398.17	432.16	-196.04	0.09	0.63	0.59	0.76	0.87	0.54	0.73
ANX	316.61	353.86	-156.89	0.03	0.59	0.58	0.43	0.66	0.31	0.56
RPE	293.42	331.60	-145.76	0.66	0.72	0.17	0.07	0.26	0.34	0.58
HR	2156.55	2201.38	-1050.31	0.02	0.82	0.82	60.30	7.77	13.20	3.62
lnRMMSD	256.34	377.19	-138.21	0.04	0.74	0.73	0.23	0.48	0.09	0.29
lnCL	169.88	212.99	-86.46	0.43	0.72	0.52	0.13	0.36	0.12	0.35

Supplementary Table 4. Means (standard deviations) and main effects for emotions (AEAL).

	Green		Urban		Indoor		Time	Env	E*T
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**			
PE	5.05 (1.11)	5.37 (0.72)	4.92 (1.16)	4.78 (1.08)	5.10 (1.10)	4.51 (1.01)	.190	.002	.002
PDE	5.24 (1.25)	5.44 (0.81)	5.10 (1.16)	4.46 (1.34)	5.26 (1.16)	4.46 (1.17)	.001	<.001	.003
PAE	4.92 (1.10)	5.32 (0.77)	4.80 (1.27)	5.00 (1.08)	4.99 (1.14)	4.55 (1.08)	.628	.033	.006
NE	1.64 (0.73)	1.34 (0.37)	1.75 (0.90)	1.70 (0.72)	1.82 (0.86)	2.06 (0.73)	.596	<.001	.015
NDE	1.98 (0.97)	1.58 (0.62)	2.0 (1.24)	1.96 (0.97)	2.18 (1.22)	2.94 (1.24)	.465	<.001	<.001
NAE	1.41 (0.62)	1.17 (0.26)	1.55 (0.72)	1.52 (0.61)	1.57 (0.75)	1.47 (0.56)	.060	.005	.408
REL	5.77 (1.28)	5.69 (0.75)	5.56 (1.21)	4.96 (1.17)	5.65 (1.15)	4.85 (1.19)	<.001	.001	.043
ANX	1.67 (0.86)	1.44 (0.47)	1.88 (1.11)	1.85 (0.92)	1.81 (0.96)	1.81 (0.71)	.356	.013	.542

Note. PE: positive emotions; PDE: positive deactivating emotions; PAE: positive activating emotions; NE: negative emotions; NDE: negative deactivating emotions; NAE: negative activating emotions; REL: relaxation; ANX: anxiety.

Supplementary Table 5. Means (standard deviations) and main effects for physiological variables.

	Green					Urban					Indoor					Time	Env	E*T
	Pre	Post				Pre	Post				Pre	Post						
		5	10	15	20		5	10	15	20		5	10	15	20			
HR	52.7 (8.9)	51.4 (9.3)	50.1 (9.0)	49.6 (8.6)	49.9 (8.9)	54.4 (8.6)	51.5 (8.1)	51.1 (7.7)	50.5 (7.2)	51.0 (7.3)	53.2 (8.5)	52.0 (9.1)	51.5 (9.0)	50.5 (7.2)	50.8 (8.8)	<.001	.038	.889
RMSSD ln	4.37 (0.59)	4.50 (0.60)	4.49 (0.58)	4.59 (0.60)	4.62 (0.63)	4.22 (0.54)	4.42 (0.61)	4.41 (0.58)	4.47 (0.59)	4.42 (0.59)	4.26 (0.51)	4.27 (0.47)	4.28 (0.48)	4.33 (0.49)	4.37 (0.53)	.001	<.001	.784
Cortisol ln	1.33 (0.48)	0.45 (0.44)				1.59 (0.48)	0.82 (0.49)				1.48 (0.58)	0.67 (0.53)				<.001	<.001	.730

Study 3. Restorative Potential of Indirect Nature Exposure Under Hypoxic Stress Conditions

Abstract

Introduction. Hypoxia, characterized by reduced oxygen pressure, is a psycho-physiologically stressful condition that alters cognitive and emotional states. In contrast, exposure to nature enhances well-being and facilitates stress recovery. This study investigated the psychological and physiological effects of indirect exposure to natural and urban environments under normoxic and hypoxic conditions, exploring whether nature imagery mitigates the impact of hypoxia.

Methods. Using a within-subjects randomized design, participants viewed natural or urban images for 10 minutes while resting in normoxia or hypoxia. Emotional states were assessed before (T1) and after (T2) exposure, and physiological markers, including heart rate and heart rate variability, were continuously monitored.

Results. Urban images elicited higher positive emotions compared to natural images. Hypoxia increased anxiety but had no effect on relaxation or positive emotions. Over time, anxiety decreased, and positive deactivating emotions increased, suggesting a calming effect of rest. Perceived restorativeness (PRS) significantly influenced outcomes, with higher PRS associated with greater relaxation, reduced anxiety, and enhanced positive emotions, even in hypoxic conditions.

Conclusions. Hypoxia induces stress, but individual perceptions of restorativeness can buffer its psychological impact. Indirect exposure to nature remains a valuable tool for emotional recovery, warranting further exploration in real-world and prolonged exposure contexts.

1. Introduction

Exposure to natural environments has long been associated with improved well-being and recovery from stress. Previous research has shown that nature exposure can enhance overall well-being (Hartig et al., 2014) and provide effective recovery from stressful events (Brown et al., 2014). Natural environments act as restorative settings, promoting the recovery of depleted psychological and physiological resources (Hartig, 2004) and fostering positive emotional states while reducing negative ones (McMahan & Estes, 2015). Importantly, the benefits of nature exposure extend beyond physical presence in such environments. Studies have demonstrated that indirect exposure, such as viewing images of natural landscapes, can also lead to improved emotional states and cognitive performance compared to viewing urban or abstract scenes (Berto, 2014; Ulrich, 1983; Ulrich et al., 1991). Even more dynamic forms of indirect exposure, such as virtual environments with nature sounds, have been shown to enhance stress recovery, with increased parasympathetic (PNS) activity observed in these settings (Annerstedt et al., 2013). Similarly, Gladwell et al. (2012) demonstrated in a controlled laboratory setting that viewing a 5-minute slideshow of natural scenes increased heart rate variability (HRV), a key marker of PNS activation, compared to built scenes. This result underscores the role of the autonomic nervous system in stress regulation and highlights the restorative potential of natural imagery, even without prior exposure to a stressor.

These findings emphasize the versatility of nature's restorative effects, even when experienced indirectly, highlighting its relevance for diverse settings and methodologies.

However, not all natural environments are inherently beneficial to human well-being. Specific settings, such as high-altitude mountain environments, pose significant physiological and psychological challenges due to hypoxia, a condition characterized by reduced oxygen availability in the atmosphere. Hypoxia can disrupt the body's homeostasis, impairing cognitive and physiological functions (Ruffini & Cera, 2020). It is associated with increased stress, reduced working memory and attention, and decreased mood and energy levels (Stavrou et al., 2018). Even short-term exposure to hypoxia, lasting less than one hour, has been shown to exacerbate fatigue and worsen mood (Li et al., 2020), while prolonged exposure can negatively affect sleep quality and recovery (de Aquino Lemos et al., 2012). Longest exposure at extreme simulated altitude impaired mood, decreasing vigor while increasing fatigue, especially for individuals with low emotional stability (Nicolas et al.,

2000). Anecdotal evidence confirmed anomalies in perceptual experiences (e.g., hallucinations) in climbers when higher altitudes (above 5000 m a.s.l.) were reached (Brugger et al., 1999). Several studies have confirmed the emergence and exacerbation of anxiety symptoms at high altitudes, assessed using various standardized scales (Burtscher et al., 2022). For instance, anxiety severity has been shown to increase significantly with altitude, as demonstrated in a study where every 100 m resulted in a partial increase in GAD-7 scores (Wang et al., 2023) Similarly, rapid ascent to 3700 m led to significant increases in anxiety symptoms, as measured by the SAS, although these levels generally remained within the normal range after acclimatization (Bian et al., 2013, 2019). At extreme altitudes, such as 5100 m or above, studies have reported significant effects on anxiety symptoms, with some participants experiencing moderate to severe (Ahmad & Hussain, 2017; Shah et al., 2020). Notably, during a 5372 m expedition, 98% of participants experienced anxiety symptoms at some point, with a peak incidence at 4670 m (Oliver et al., 2012). These findings collectively suggest that hypoxia and altitude-related stress significantly contribute to the emergence of anxiety symptoms, particularly during acute or rapid altitude changes.

Such findings underscore the potential duality of natural environments, which can both promote and hinder well-being depending on the specific characteristics of the setting.

Despite the adverse effects of hypoxia, natural environments, including indirect exposure through images, may remain pivotal in supporting stress recovery. Viewing natural images has been shown to activate the parasympathetic nervous system, promoting relaxation and restoring depleted resources (Scott et al., 2021). The potential for natural environments to counteract stress responses may persist even under challenging conditions such as hypoxia. This interplay between hypoxia and natural settings raises critical questions about how such environments influence psychological and physiological responses, particularly when nature exposure is indirect.

Aims

The current study investigates the effects of hypoxia and normoxia on psychological and physiological responses during exposure to natural and urban images. By exploring emotional states, relaxation, anxiety, and physiological markers, including heart rate and heart rate variability, the study seeks to understand whether indirect exposure to natural environments can mitigate the adverse effects of hypoxia. Adopting a hypoxic chamber to simulate a stressful environmental condition, this study aims to isolate the impact of exposure

to hypoxia from other sources of stress, such as exercise, cold, and danger. Hypoxic condition is expected to affect cardiac indices, increasing the heart rate and lowering the heart rate variability. This research aims to provide a nuanced understanding of the interplay between hypoxic conditions, environmental characteristics, and recovery, highlighting the potential for natural imagery to promote well-being even under physiologically challenging circumstances.

2. Methods

2.1 Participants

A total of 23 participants (age M = 25.4, SD = 3.7) were recruited through online advertisements and the university participant pool. Inclusion criteria required participants to be 18-35 years old, without a history of cardiovascular or respiratory conditions. Participants were compensated with course credits when applicable.

2.2 Materials

Images of environments. Twenty images of natural environments and twenty images of urban environments were selected from a previously validated database. These images were used to compose two distinct slideshows. The images were presented on a 24-inch monitor, with each image shown for 30 seconds, resulting in a total slideshow duration of 10 minutes for each type of setting. Each participant was exposed to both types of images (natural and urban), with the order of presentation randomly assigned for each session to eliminate any sequence bias.

Figure 1. Two example images of the natural and urban slideshow.

Hypoxia and Normoxia conditions. A hypoxic chamber (Hypoxico Inc.) was used to create hypoxia (14.7% O_2) and normoxia (20.9% O_2) conditions. The chamber was calibrated before each session to ensure accurate oxygen levels.

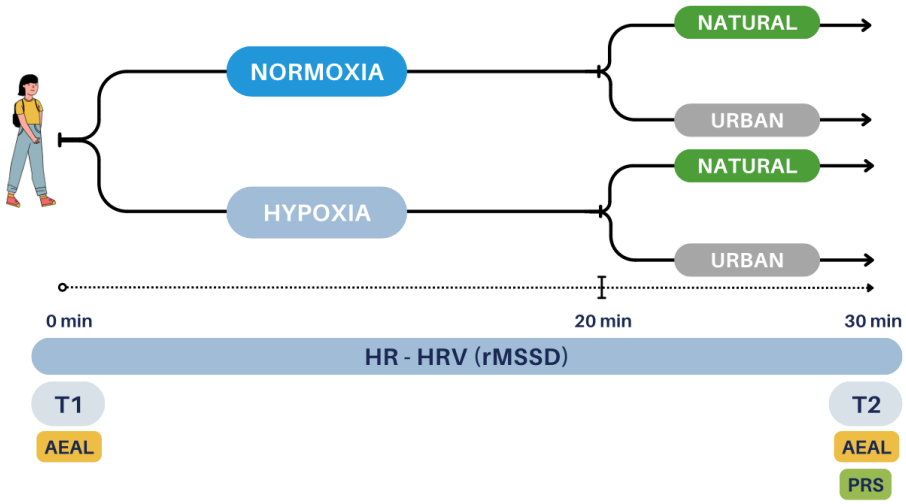
2.3 Procedure

This study employs a within-subjects design to explore the effects of three experimental factors: time, image setting, and oxygen condition. The image setting factor refers to the type of images shown to participants, with the slideshows alternating between the one composed of natural images and one depicting urban scenes. The urban images served as a control condition to compare the restorative effects of nature exposure, knowing their less restorative potential. The oxygen condition refers to the physiological environment in which participants were exposed, either normoxic (normal oxygen concentration) or hypoxic (reduced oxygen concentration) conditions.

Participants were exposed to both image settings (natural vs. urban) and oxygen conditions (normoxia vs. hypoxia), with the order of exposure randomized to control for sequence effects. This within-subjects design ensures that each participant experiences all conditions, allowing for direct comparison of the effects of image setting and oxygen condition on psychological and physiological outcomes.

The study was conducted at CeRiSM, the Sports, Mountain, and Health Research Center of the University of Verona, a laboratory equipped with a chamber able to recreate controlled hypoxic conditions.

Figure 2. Experimental procedure.



After the consent was obtained, participants were scheduled to visit the laboratory on four occasions to complete all the conditions required by the experiment in a randomized order: natural images under normoxia, natural images under hypoxia, urban images under normoxia, and urban images under hypoxia. Each session lasted approximately 1 hour. Upon arrival, participants were asked to report their baseline emotional state (AEAL). Afterwards, the participants, after being equipped with the necessary devices for monitoring physiological parameters, were guided to the laboratory and asked to lie down on an examination bed. The backrest of the bed was specifically inclined to allow proper positioning of the trunk and head and to ensure the participant maintained a comfortable position during the upcoming image viewing and throughout the experiment (see Figure 3).

Figure 3. Participant during the viewing phase of the experiment.

Physiological parameters were monitored using various non-invasive instruments. Cardiovascular data were measured breath-by-breath using an automated respiratory gas analysis system (Metabolimeter Quark PFT Ergo, Cosmed S.r.l., Rome, Italy). In this phase, participants wore a silicone mask covering their nose and mouth, which directed the incoming and outgoing airflow, and a finger pulse oximeter monitored oxygen saturation. Additionally, participants were monitored throughout the trial with a device designed to estimate cardiac output, stroke volume, and heart rate by applying ECG electrodes to the torso and neck (PhysioFlow, Manatec Biomedical, Ebersviller, France). However, in the present study only cardiac indices (HR and HRV) were used, while the other physiological indices were analyzed in a separate study.

After an initial 20-minute rest period (stabilization phase), participants were shown a slideshow consisting of either natural or urban images, depending on the sequence determined by the randomization procedure. The total duration of each slideshow was 10 minutes, with each image displayed for 30 seconds. Following the slideshow, participants completed questionnaires to assess the emotional responses induced by the image viewing, including a second assessment of emotional state (AEAL) and an assessment of the perceived restorativeness of the slideshows (PRS).

2.4 Measures

Emotional state. Pre- and post-images view, emotional states were assessed using a concise version of the Achievement Emotions Adjective List (AEAL; Raccanello et al., 2022)

based on the circumplex model of affect. This framework organizes emotions along two primary dimensions: activation (activating vs. deactivating) and valence (positive vs. negative), resulting in four distinct emotional categories: positive activating emotions (PAE; e.g., happy, satisfied, optimistic), positive deactivating emotions (PDE; e.g., relaxed, relieved), negative activating emotions (NAE; e.g., anxious, angry, embarrassed), and negative deactivating emotions (NDE; e.g., demoralized, bored). In this study, participants answered 14 items represented by a list of adjectives, with 10 adjectives targeting emotions across the circumplex categories. To ensure greater reliability for the main emotions of relaxation and anxiety, the extended version of the scale was used, which considers three items for each emotion. Therefore, relaxation was measured through the items "relaxed", "calm", and "tranquil", while anxiety was evaluated using the items "anxious", "worried", and "nervous". This adapted version of the AEAL enabled the calculation of composite scores for the four emotional categories while providing a detailed and reliable assessment of relaxation and anxiety as the primary outcomes of interest in this study. The internal consistency of the AEAL subscales, as measured by Cronbach's alpha, varied across conditions. For positive emotions, Cronbach's alpha ranged from 0.82 in the normoxia-natural images condition to 0.89 in the hypoxia-urban images condition. For negative emotions, Cronbach's alpha ranged from 0.52 in the normoxia-natural images condition to 0.75 in the hypoxia-urban images condition, indicating moderate to high reliability depending on the condition (see Supplementary Table 2).

Restorativeness. The Perceived Restorativeness Scale (PRS) (Hartig, Kaiser, et al., 1997; Hartig, Korpela, et al., 1997; Pasini et al., 2014), grounded in Kaplan and Kaplan's Attention Restoration Theory (ART), was used to assess each environment's restorative potential. The PRS evaluates four core dimensions: *Being Away* (escape from routine or demands), *Fascination* (effortless attention), *Coherence* (organization and comprehensibility), and *Scope* (opportunities for exploration). Participants rated statements on an 11-point Likert scale (0 = not at all, 10 = very much), providing a comprehensive measure of restorative potential. Internal consistency was strong, with McDonald's ω of 0.83 and 0.88, respectively, under normoxia and hypoxia for natural images and 0.95 for urban images under oxygen conditions.

Heart rate and heart rate variability. Cardiac indices, in particular heart rate and heart rate variability, were continuously monitored throughout the experiment while participants rested supine and viewed the slideshows. Heart Rate Variability (HRV) was

analyzed using the RMSSD time-domain index, which estimates vagally mediated HRV changes (Malik et al., 1996). Natural logarithm transformation was applied to the RMSSD index. Data were processed with Kubios HRV software (Version 3.5.0, Biosignal Analysis and Medical Imaging Group, Kuopio, Finland) using a moderate error correction filter.

3.2.5 Analysis overview

To investigate the impact of time (pre, post), oxygen (normoxia, hypoxia), and images (natural, urban) on dependent variables, linear mixed modelling (LMM) with residual maximum likelihood estimations was employed. This method, widely used in restorative environments research (Oswald et al., 2023; Suko & Korpela, 2024), incorporates both fixed and random effects, accounting for the hierarchical structure of the data and within-subject variability. Physiological data were preprocessed to remove artefacts and averaged over 1-minute intervals.

All mixed models were performed in Jamovi (GAMLj module, version 2.6.6), with full LMM details available in Supplementary Table 3. In the text, we report β coefficients and p-values to emphasize effect strength and significance.

3. Results

Table 1. Main effects of experimental conditions on emotional outcomes.

Emotion	Time	Oxygen	Images	PRS
Positive Emotions	x	x	↑U	↑
Positive Activating	↓	x	↑U	↑
Positive Deactivating	↑	x	↑U	↑
Negative Emotions	x	x	x	x
Negative Activating	x	x	x	x
Negative Deactivating	↑	x	x	x
Relaxation	x	x	x	↑
Anxiety	↓	↑H	x	↓

This table summarizes the effects of experimental conditions (time, oxygen, images, and PRS) on emotional outcomes. The direction of the effects is indicated as follows: ↑ denotes an increase, ↓ denotes a decrease, x indicates no significant effect, G refers to natural images, U refers to urban images, H indicates hypoxia, and N indicates normoxia.

Perceived restorativeness*.* The analysis revealed a significant effect of environment on the PRS total score ($F(1,158) = 630.62$, $p < .001$), with participants rating natural images significantly higher than urban images ($\beta = -4.94$, SE = 0.20, $t(158) = -25.11$, $p < .001$). No significant effect was found for the oxygen condition ($F(1,158) = 0.26$, $p = 0.609$), suggesting that the change in oxygen levels did not influence the restorativeness ratings of the images. The interaction between oxygen and the image setting was also not significant ($F(1,158) = 0.09$, $p = 0.771$).

Heart rate. The analysis revealed a significant main effect of oxygen condition on heart rate ($F(1,152) = 125.77$, $p < .001$), with participants exhibiting significantly lower heart rate under normoxia compared to hypoxia ($\beta = -9.86$, SE = 0.88, $t(152.1) = -11.21$, $p < .001$). No significant effects were found for the image setting ($p = .566$) or time ($p = .993$).

Marginal means showed an average heart rate of 56.9 bpm, 95% CI [53.6, 60.2] in normoxia, compared to 66.8 bpm, 95% CI [63.5, 70.0] in hypoxia, indicating a higher heart rate during oxygen deprivation.

Heart rate variability (lnRMSSD). The analysis revealed a significant main effect of oxygen condition on lnRMSSD (F (1,139) = 50.21, $p < .001$), with participants demonstrating lower heart rate variability under hypoxia compared to normoxia (β = -0.35, SE = 0.05, t (138.7) = -7.09, $p < .001$). No significant effects were found for the image setting ($p = .765$) or time ($p = .780$).

Positive Emotions. Analysis showed that the clustering of subjects explained a moderate amount of variance in positive emotions (ICC = 0.54). The results revealed a significant main effect of the image setting (F (2,164) = 7.78, $p = .006$). Participants reported significantly higher positive emotions viewing the urban images (U) compared to the natural images (U) ($\beta = 0.58$, SE = 0.21, t (164) = 2.79, $p = .006$). No significant effect of time was found ($p = .928$).

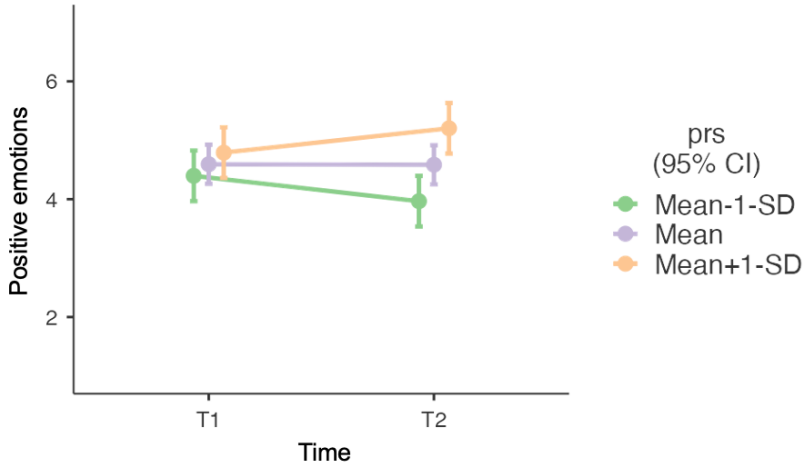
There was no significant interaction between oxygen and image setting ($p = .387$), indicating that the combination of normoxia and hypoxia did not significantly influence the effect of the environment on positive emotions. Likewise, the interaction between oxygen and time was not significant ($p = 0.480$), suggesting no change in positive emotions between T1 and T2 due to the oxygen condition. Similarly, the interaction between image setting and time was not significant ($p = 0.708$), indicating no differential changes over time between natural and urban environments.

The results revealed a significant main effect of PRS on positive emotions ($\beta = 0.14$, SE = 0.04, t (166.9) = 3.67, $p < .001$), indicating that higher perceived restorativeness was associated with more positive emotions overall. Interestingly, a significant interaction was found between time and PRS (F(1, 152) = 5.55, $p = .020$), suggesting that the effect of perceived restorativeness on positive emotions changed over time. Specifically, PRS had a stronger effect on positive emotions at T2 than at T1 ($\beta = 0.14$, SE = 0.06, t(151.9) = 2.36, $p = .020$).

The results revealed significant changes in positive emotions depending on participants' PRS scores. At T2, for participants with 1 SD under the mean of PRS, there was a significant decrease in positive emotions compared to T1 ($\beta = -0.43$, SE = 0.20, t (152) = −2.12, $p = .036$, see Figure 4), indicating a notable reduction in positive emotions over time

for individuals with lower perceived restorativeness. For participants with a 1SD above the mean of PRS, a significant increase in positive emotions was observed at T2 compared to T1 (β = 0.41, SE = 0.20, t (152) = 2.03, p = .044), suggesting that individuals who rated the images higher on PRS experienced a greater improvement in positive emotions over time. In contrast, for participants who reported a mean level of PRS from the view, no significant change in positive emotions was observed between T1 and T2 (β = −0.009, SE = 0.10, t (152) = −0.09, p = 0.928). These results indicate that higher perceived restorativeness led to a greater increase in positive emotions from T1 to T2.

Figure 4. Interaction between time and perceived restorativeness (PRS) on positive emotions.



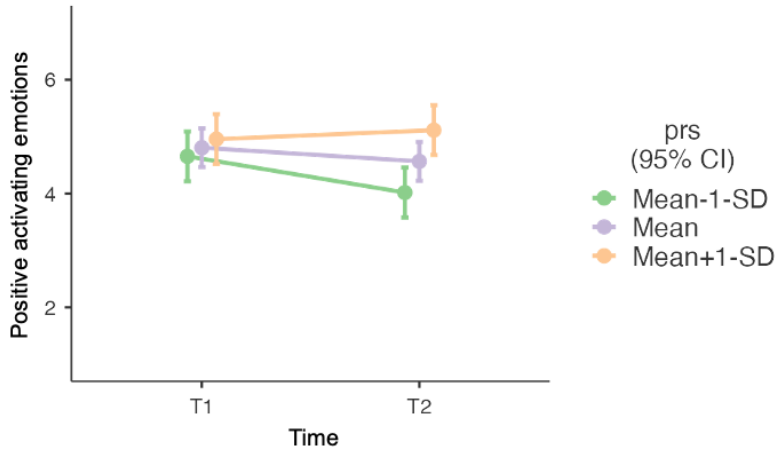
Positive activating emotions. A moderate amount of variance in positive activating emotions was explained by subject clustering (ICC = 0.54). Our mixed model analysis revealed significant effects of several factors on positive activating emotions. The images' setting effect was significant (F (1,164) = 5.71, p = .018). Specifically, participants reported higher positive activating emotions viewing urban images compared to the natural images (β = 0.51, SE = 0.21, t (164.1) = 2.39, p = .018). There was a main effect of time (F (1,152) = 6.04, p = .015). Participants reported a significant decrease in positive activating emotions from T1 to T2 (β = −0.24, SE = 0.10, t (151.9) = −2.46, p = .015).

Furthermore, PRS had a significant main effect (F (1,167) = 9.67, p = .002), indicating that higher perceived restorativeness was associated with increased positive activating emotions (β = 0.12, SE = 0.04, t (166.7) = 3.11, p = .002).

There were no significant interactions between oxygen and image setting (p = 0.653), oxygen and time (p = 0.770), or image setting and time (p = 0.660), suggesting that these factors did not significantly interact to influence positive activating emotions.

However, there was a significant interaction between time and PRS (F(1,152) = 4.80, p = .030). This interaction suggests that the change in positive activating emotions from T1 to T2 differed depending on the restorativeness scores participants assigned to the images (see Figure 5). Specifically, for participants who rated the images as low in restorativeness (1 SD below the mean), there was a significant decrease in positive activating emotions from T1 to T2 (β = −0.64, SE = 0.21, t (152) = −3.09, p = .002). For participants who rated the images as having average restorativeness, there was also a significant decrease from T1 to T2 (β = −0.24, SE = 0.10, t(152) = −2.46, p = .015). However, for participants who rated the images as highly restorative (+1 SD above the mean), there was no significant change in positive activating emotions from T1 to T2 (β = 0.16, SE = 0.21, t (152) = 0.77, p = .444). These findings indicate that participants who perceived the images as less restorative showed a significant decline in positive activating emotions over time, whereas those who rated the images as more restorative did not experience a significant change.

Figure 5. Interaction between time and perceived restorativeness (PRS) on positive activating emotions



Positive deactivating emotions. A moderate amount of variance in positive deactivating emotions was explained by subject clustering (ICC = 0.45). Mixed model analysis revealed significant effects of several factors on positive deactivating emotions. The

images' setting effect was significant (F (1,168) = 7.08, p = .009), indicating that participants reported higher positive deactivating emotions viewing the urban images compared to the natural images (β = 0.72, SE = 0.27, t (167.7) = 2.66, p = .009). The time effect was also significant (F (1,152) = 7.21, p = .008), suggesting that positive deactivating emotions increased from T1 to T2 (β = 0.34, SE = 0.13, t (151.9) = 2.68, p = .008).

Furthermore, PRS had a significant main effect (F (1,170) = 12.55, p < .001), indicating that higher perceived restorativeness was associated with higher positive deactivating emotions (β = 0.17, SE = 0.05, t (170.5) = 3.54, p < .001).

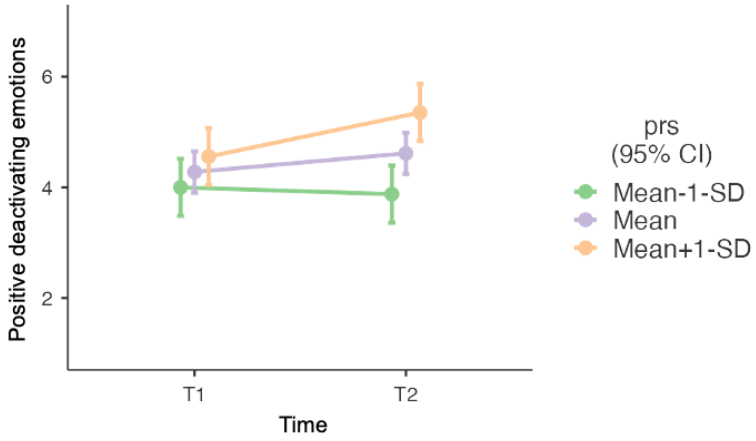
No significant interactions were found between oxygen and image setting (p = 0.259), oxygen and time (p = 0.312), or image setting and time (p = 0.837), suggesting that these factors did not significantly interact to influence positive deactivating emotions.

The interaction between time and PRS was marginally significant (F (1,152) = 3.85, p = .051), suggesting that the effect of PRS ratings on positive deactivating emotions changed over time. Specifically, the relationship between the restorativeness scores participants assigned to the images and positive deactivating emotions became more pronounced at T2 compared to T1 (β = 0.16, SE = 0.08, t (151.9) = 1.96, p = .051).

The simple effects of time were examined at different levels of PRS ratings. The results revealed significant changes in positive deactivating emotions from T1 to T2, depending on the participants' PRS ratings. For participants who rated the images as low in restorativeness (1 SD below the mean), there was no significant change in positive deactivating emotions from T1 to T2 (β = −0.12, SE = 0.27, t (152) = −0.46, p = .647). For participants who rated the images as having average restorativeness, there was a significant increase in positive deactivating emotions from T1 to T2 (β = 0.34, SE = 0.13, t (152) = 2.68, p = .008). For participants who rated the images as highly restorative (1 SD above the mean), there was a significant increase in positive deactivating emotions from T1 to T2 (β = 0.80, SE = 0.27, t (152) = 3.00, p = .003).

These results suggest that PRS ratings significantly moderated the change in positive deactivating emotions over time, with higher PRS ratings leading to a more substantial increase in positive deactivating emotions from T1 to T2.

Figure 6. Interaction between time and perceived restorativeness (PRS) on positive deactivating emotions



Negative emotions. A moderate amount of variance in negative emotions was explained by the clustering of subjects (ICC = 0.53). Results revealed a significant main effect of time (F (1, 152) = 7.23, p = .008). Participants reported significantly higher negative emotions at T2 compared to T1 (β = 0.22, SE = 0.08, t (151.9) = 2.69, p = .008) across all conditions. No significant main effects of image setting (p = .516) or oxygen (p = .394) were found. Regarding PRS, no main effect was observed (p = .729). Additionally, there were no significant interactions between oxygen and image setting (p = .843), oxygen and time (p = .866), and image setting and time (p = .889).

Negative activating emotions. No significant main effects or interactions were found for negative activating emotions. Specifically, neither the main effects of oxygen, image setting, time, or PRS nor their interactions had a significant impact on negative activating emotions (all $p > 0.05$).

Negative deactivating emotions. A moderate amount of variance in negative deactivating emotions was explained by subject clustering (ICC = 0.49). Mixed model analysis revealed a significant effect of time (F (1,152) = 28.46, $p < .001$), indicating that participants reported higher negative deactivating emotions at T2 compared to T1 (β = 0.62, SE = 0.12, t (152) = 5.34, $p < .001$). No main effect of image setting (p =. 392), oxygen (p = .848), or PRS (p = .888) was found.

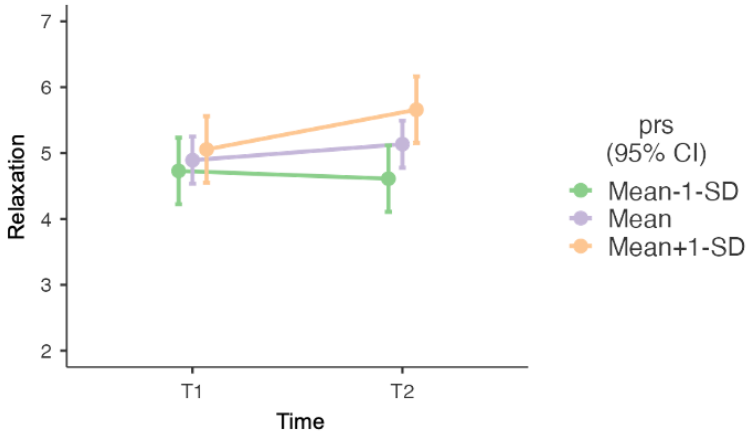
No significant interactions were found between oxygen and image setting (p = .577), oxygen and time (p = .560), or image setting and time (p = .881), suggesting that these factors did not significantly interact to influence negative deactivating emotions.

Relaxation. A moderate amount of variance in relaxation was explained by the clustering of subjects (ICC = 0.45). Our mixed model analysis revealed that oxygen did not significantly influence relaxation (p = .298), suggesting that changes in oxygen levels did not lead to significant differences in relaxation. Similarly, the image setting also did not have a significant effect on relaxation (p = 0.298). The time effect (T2 vs T1) showed a marginally significant trend (β = 0.24, SE = 0.13, t (151.4) = 1.93, p = 0.055), suggesting that relaxation increased slightly from T1 (M = 4.89, CI [4.53, 5.25]) to T2 (M = 5.13, CI [4.78, 5.49]), although this difference did not reach statistical significance. No significant interactions were found between oxygen and image setting (p = 0.935), oxygen and time (p = 0.221), or image setting and time (p = 0.932), suggesting that the effects of these factors did not significantly interact in influencing relaxation.

There was a significant main effect of PRS on relaxation (F(1, 171) = 5.77, p = .017), indicating that higher perceived restorativeness was associated with greater relaxation (β = 0.12, SE = 0.05, t (171.5) = 2.40, p = 0.017).

Although the interaction between time and PRS was not significant (p = .126), examining the simple effects at different levels of PRS ratings revealed significant patterns. For participants who rated the slideshows as low in restorativeness (1 SD below the mean), no significant change in relaxation was observed from T1 to T2 (β = −0.12, p = .659). For participants who rated the slideshows as having average restorativeness, relaxation increased marginally from T1 to T2, not reaching significance (β = 0.24, SE = 0.13, t (151) = 1.93, p = .055). A significant increase in relaxation was found for participants who rated the slideshows as highly restorative (1 SD above the mean; β = 0.60, SE = 0.27, t (151) = 2.27, p = .025).

Figure 7. Interaction between time and perceived restorativeness (PRS) on relaxation



Anxiety. A moderate amount of variance in anxiety scores was due to subject clustering (ICC = 0.46). Our mixed model analysis revealed a significant effect of oxygen on anxiety ($\beta = -0.23$, SE = 0.10, t (151.6) = −2.19, $p = .030$), indicating that participants in the hypoxia condition reported higher anxiety levels compared to those in the normoxia condition. The time effect was also significant ($\beta = -0.21$, SE = 0.10, t (151.6) = −2.04, $p = .043$), suggesting that anxiety decreased slightly from T1 to T2. However, no significant effects were found for image setting ($p = 0.188$) or interactions between oxygen and image setting ($p = 0.103$), oxygen and time ($p = 0.963$), and image setting and time ($p = 0.987$).

The PRS main effect was significant ($\beta = -0.08$, SE = 0.04, t (169.8) = −2.07, $p = .040$), indicating that higher perceived restorativeness was associated with lower anxiety levels. No interaction between time and PRS was observed ($p = .457$).

4. Discussion

The purpose of this study was to investigate the emotional and physiological responses to hypoxia and normoxia during indirect exposure to natural and urban image settings. Specifically, the study aimed to test whether natural images could mitigate the negative emotional and physiological effects of hypoxia compared to urban images. Emotional states, in particular relaxation and anxiety, and physiological markers, such as heart rate and heart rate variability, were examined to explore the interplay between hypoxic conditions, perceived restorativeness (PRS), and environmental characteristics. The study

sought to provide insights into the potential restorative benefits of natural imagery under physiologically challenging conditions by isolating hypoxia as the primary stressor in a controlled laboratory setting.

Oxygen condition

The analysis of cardiac indices revealed a significant physiological impact of hypoxia, with participants showing higher heart rate and lower heart rate variability under hypoxic conditions compared to normal oxygen levels conditions. These findings were largely expected, as previous research demonstrated that hypoxia triggers a cascade of systemic adaptations, including an acute cardiovascular response characterized by increased heart rate (Burtscher et al., 2022; Favret & Richalet, 2007). The substantial increase in heart rate under hypoxia in this study underscores the physiological strain induced by oxygen deprivation, even in a resting position and over a relatively short period.

However, in this study, the effects of hypoxia on physiological indices were only partially reflected in emotional outcomes. No significant effects of hypoxia were observed on self-reported negative emotions, contrasting with findings from another study combining rest and hypoxia exposure (Stavrou et al., 2018). It is important to note that the study by Stavrou et al. examined the effects of hypoxia over a much longer duration, with participants reporting higher negative affect after 14 and 21 days of bed rest in hypoxic conditions. Ruffini and Cera (2020), on the other hand, observed increased positive emotions and no significant effects on negative emotions in climbers after a real-world mountain ascent. However, in that context, physical activity and direct exposure to the natural environment likely played a role in influencing participants' emotional states.

In this study, hypoxia significantly increased anxiety, which is notable given the opposing effect of time, as participants generally reported reduced anxiety after 30 minutes of lying down. The reduction in anxiety over time suggests that passive recovery and the absence of external stressors can have a calming effect. The interplay between the physiological stress of hypoxia and the time-related calming effect highlights the complex relationship between physiological stress responses and conscious emotional experiences, particularly in passive experimental settings. This finding underscores the importance of integrating physiological measures with self-reported emotional states to provide a more comprehensive understanding of stress and recovery processes.

Image setting

Regarding the effect of image setting, the findings revealed that urban images elicited higher positive emotions, both activating and deactivating, than natural images. This result is surprising, as it contrasts with the established literature emphasizing the restorative potential of natural environments in promoting positive emotions and reducing stress (McMahan & Estes, 2015; Kaplan & Kaplan, 1989).

One possible explanation lies in the specific characteristics of the urban images used in this study. Although they were rated significantly lower on the Perceived Restorativeness Scale (PRS), both in total score and in fascination dimension, their content may have included features perceived as more engaging or stimulating, such as architectural details, vibrant colors, or cultural significance. These elements might have triggered positive emotional responses, even if participants consciously perceived the settings as less restorative. Moreover, participants may have associated urban images with familiar contexts, making them emotionally engaging from the outset.

Another noteworthy point is the baseline variation observed at T1, where positive emotions were already higher for urban images compared to natural images. This suggests the possibility of pre-existing biases or expectations influencing emotional responses. These initial differences could have amplified the unexpected pattern observed at T2, where urban images continued to elicit higher positive emotions.

Despite this surprising result, it is important to note that image setting did not significantly influence relaxation or anxiety. This highlights the nuanced nature of emotional responses to environmental stimuli, suggesting that while urban images may evoke higher positive emotions, their restorative effects are limited in comparison to natural settings, particularly in terms of reducing stress or promoting relaxation.

The unexpected direction of the effect might also reflect the statistical influence of PRS in the models, as the inclusion of this covariate may have absorbed variance that would otherwise be attributed to the image setting factor.

Perceived Restorativeness (PRS)

The role of perceived restorativeness emerged as a critical factor across multiple outcomes, highlighting its influence on emotional responses. Higher restorativeness ratings of the images were consistently associated with increased positive emotions (both activating and

deactivating), greater relaxation, and lower anxiety, suggesting that subjective perceptions of restorative potential play a pivotal role in shaping responses to environmental stimuli.

The interaction between PRS and time further underscores its importance. Participants who perceived the images as highly restorative experienced significant increases in positive emotions and relaxation over time, while those with low PRS reported decreases. This suggests that the restorative potential of an environment may not only depend on its objective characteristics but also on how individuals subjectively perceive and interpret it.

It's important to note that since PRS reflects the subjective evaluation of the image setting, which participants had not yet experienced at T1, it should be considered conceptually and temporally as a predictor of emotional states at T2 only. Therefore, we focused on the relationship between PRS and emotional responses measured after the exposure (T2), rather than interpreting interactions with time.

Interestingly, PRS also appeared to buffer against the physiological stress of hypoxia, as participants who rated the images as more restorative reported lower anxiety levels, even under oxygen-deprived conditions. This aligns with prior research suggesting that restorative environments can mitigate the adverse effects of stressors, providing psychological relief even in challenging contexts (Hartig, 2004; McMahan & Estes, 2015).

A key finding of this study is the partial dissociation between physiological and emotional outcomes. While hypoxia had a clear and significant impact on physiological markers—increasing heart rate and reducing heart rate variability—its effects on emotional outcomes were more limited, with anxiety being the only affected variable. This highlights the complexity of the stress-recovery process, where physiological strain does not always translate into conscious emotional experiences, particularly in passive experimental settings.

Moreover, the passive nature of the task likely contributed to the limited activation of negative emotions, even in the most physiologically stressful condition (hypoxia + urban images). The absence of an active stressor or demanding task might have created a relatively neutral baseline, minimizing the potential for strong negative emotional responses.

These findings underscore the importance of integrating physiological measures with self-reported emotional states to capture a more comprehensive picture of stress and recovery. While physiological indices like heart rate and HRV provide valuable insights into autonomic responses, self-reported emotions reflect a different dimension of the stress-

recovery process, shaped by subjective perceptions (e.g., perceived restorativeness) and contextual factors (e.g., passive task setting).

Limitations

This study provides valuable insights into the interplay between hypoxic stress, nature exposure, and emotional responses. However, certain limitations should be acknowledged. First, the experimental design involved participants resting in a semi-supine position for 30 minutes, likely reducing the elicitation of negative emotions. Resting itself is inherently calming and may have mitigated the potential for urban images and hypoxia to evoke strong negative responses, limiting the contrast between conditions.

Second, while hypoxia was expected to increase stress levels, the passive nature of the task and the absence of additional stressors (e.g., cognitive or physical challenges) likely dampened the overall impact of hypoxia on emotional outcomes. This suggests that the experimental conditions, even in the worst-case scenario of hypoxia combined with urban imagery, were not sufficiently stressful to elicit robust emotional changes.

Finally, the study focused on relatively short exposure durations (30 minutes of rest, of which 10 minutes for image viewing), which may not fully capture the cumulative effects of prolonged exposure to hypoxia or natural imagery. Future research could explore longer durations and more active tasks to better understand the dynamic interplay between these factors. These limitations highlight the need for caution when generalizing findings to more ecologically valid or stressful scenarios and suggest directions for further research to build on these results.

5. Conclusion and future directions

This study highlights the complex interplay between physiological and emotional responses to environmental and hypoxic conditions. The findings suggest that while short-term acute hypoxia induces clear physiological strain, its emotional impact is less pronounced, particularly in passive settings. The stimuli's perceived restorativeness emerged as a key moderator, influencing positive emotions, relaxation, and anxiety across conditions. However, the unexpected findings regarding urban images call for further investigation into the characteristics of stimuli that drive emotional responses beyond their restorative value.

Future research should consider active tasks or more engaging stressors to explore better the relationship between physiological stress and the emotional recovery potential of nature. Additionally, extending exposure durations or incorporating more active nature exposure provides deeper insights into the restorative potential of nature under hypoxic conditions. Finally, examining individual differences in emotional regulation and environmental preferences may help explain the variability in responses observed in this study.

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Supplementary Materials

Supplementary Table 1. Means, standard deviations and reliability indices of PRS scales across conditions.

oxygen	images	Mean	SD	McDonald's ω
normoxia	natural	9.62	0.94	0.83
hypoxia	natural	9.67	0.81	0.88
normoxia	urban	4.63	2.15	0.95
hypoxia	urban	4.79	2.06	0.95

Supplementary Table 2. Means, standard deviations and reliability indices of AEAL scales across conditions.

			pre			post		
	oxygen	images	M	SD	α	M	SD	α
positive	normoxia	natural	4.57	0.87	0.85	4.90	0.92	0.82
	hypoxia	natural	4.43	1.15	0.88	4.65	1.02	0.87
	normoxia	urban	4.66	0.88	0.83	4.43	1.08	0.88
	hypoxia	urban	4.71	1.08	0.89	4.35	1.07	0.89
negative	normoxia	natural	1.79	0.81	0.71	1.81	0.65	0.65
	hypoxia	natural	1.76	0.82	0.80	1.95	0.71	0.52
	normoxia	urban	1.76	0.64	0.66	2.15	0.69	0.59
	hypoxia	urban	1.90	1.06	0.87	2.17	0.85	0.75

Supplementary Table 3. Summary of mixed models parameters for all outcomes

						random components				
	AIC	**BIC**	**LogLikel**	**R^2 Marginal**	**R^2 Conditional**	**ICC**	**subj var**	**subj SD**	**residual var**	**residual SD**
PE	432.11	494.34	-215.88	0.09	0.58	0.54	0.49	0.70	0.43	0.65
PAE	437.19	499.14	-218.28	0.08	0.58	0.54	0.52	0.72	0.44	0.66
PDE	522.87	580.11	-258.76	0.11	0.51	0.45	0.58	0.76	0.73	0.85
NE	363.98	429.90	-183.66	0.04	0.55	0.53	0.33	0.57	0.30	0.54
NAE	367.29	432.97	-185.19	0.03	0.44	0.43	0.23	0.48	0.31	0.56
NDE	497.91	556.53	-246.98	0.09	0.54	0.49	0.60	0.78	0.62	0.79
REL	521.07	578.39	-257.90	0.09	0.47	0.42	0.52	0.72	0.73	0.85
ANX	451.49	512.62	-225.02	0.06	0.49	0.46	0.42	0.65	0.49	0.70
HR	1251.02	1268.78	-603.10	0.23	0.68	0.58	49.20	7.01	35.70	5.98
HRV	162.57	237.22	-87.79	0.11	0.68	0.64	0.18	0.42	0.10	0.31
PRS	670.73	694.22	-331.46	0.71	0.80	0.31	0.79	0.89	1.78	1.33

Note. PE: positive emotions; PDE: positive deactivating emotions; PAE: positive activating emotions; NE: negative emotions; NDE: negative deactivating emotions; NAE: negative activating emotions; REL: relaxation; ANX: anxiety; HR: heart rate; HRV: heart rate variability; PRS: perceived restorativeness scale.

Discussion

The interplay between physical activity, nature exposure, and psychological well-being represents a complex and multifaceted area of research. Despite its growing importance, this field is still characterized by significant methodological challenges. This thesis aimed to explore the psychological and physiological benefits of natural environments, focusing on green exercise. Through a series of studies, this research sought to investigate how active and passive exposure to natural settings influences stress recovery, affective states, and overall well-being.

The first study of this thesis provided a comprehensive review of the existing literature on green exercise, highlighting key methodological gaps and offering a foundation for experimental studies. Specifically, it sought to describe both the short- and long-term effects of green exercise while monitoring objective and subjective environmental measures. The second study focused on a field experiment investigating the psychological and physiological restorative effects of a 1-hour light-to-moderate intensity exercise session in urban and natural environments. Finally, the third study examined the role of indirect exposure to nature in supporting recovery from physiological stressors, particularly hypoxia, through passive exposure to nature via images.

The central thread of this project was exploring the beneficial impact of nature exposure through both active and passive means while simultaneously considering both physiological and psychological outcomes, with particular attention to emotional responses. This discussion will also reflect on the restorative potential of the environments used in the studies. The findings of these three studies provide valuable insights into how different types of environmental exposure—active and passive—can influence psychological and physiological well-being. By considering both the real-world contexts of green exercise and the more controlled conditions of exposure to nature images, this thesis offers a unique contribution to understanding nature's impact on health.

A key finding from the literature review (Study 1) was the variability in the effects of green exercise, with studies showing mixed results across both short-term and long-term outcomes. This variability was attributed to differences in the methodologies employed, including the types of physical activities examined, the environmental settings used, and the measures of nature exposure. Many studies employed inconsistent comparison conditions,

such as varying types of exercise or mixed types of green and blue spaces, which compromised the generalizability of the findings. Despite these limitations, the review highlighted the positive short-term effects of green exercise on emotional outcomes and enjoyment compared to indoor or non-green activities. The review also underscored the importance of considering environmental perceptions, particularly the perceived restorative potential of natural environments. Only a small portion of studies included restoration measures, signalling a significant gap in understanding how participants perceive the restorative qualities of green spaces. While the existing literature points to the potential benefits of green exercise, the methodological challenges identified in the review call for more refined research designs that integrate both the investigation of environmental perceptions and consistent comparison conditions. These findings set the stage for the experimental studies in this thesis, which aim to address these gaps by investigating the effects of green exercise and the potential restorative role of indirect nature exposure.

This thesis focused on a field experiment to examine physical activity's psychological and physiological restorative effects across different environmental contexts—natural, urban, and indoor. This study was designed to address the methodological gaps identified in the literature review by incorporating validated psychological assessments and physiological markers, including heart rate variability (HRV). The aim was to comprehensively analyze how environmental settings influence psychological outcomes such as restoration, affective states, and enjoyment while simultaneously evaluating physiological responses such as heart rate (HR), cortisol levels, and HRV.

A key strength of this study was the rigorous methodological approach adopted, using the Perceived Restorativeness Scale (PRS) for a thorough and valid assessment of the perceived restorative qualities of the natural and urban environments. This enabled a robust comparison between these settings, emphasizing their potential for psychological restoration compared to the indoor environment. The selection of environments for this experiment was carefully considered to ensure ecological validity. Rather than comparing a lush natural environment with a degraded urban one, we chose a realistic urban setting—a central area of a small Italian town—to reflect a more typical, real-world context. This decision was intentional to ensure the results could be generalized to everyday urban settings, where individuals typically engage in physical activity. The natural environment selected, though not excessively pristine, was carefully chosen to represent an environment rich in restorative qualities, ensuring that both settings were comparable in terms of their potential to support

psychological restoration and as a venue for physical activity. The key findings from this study reinforced the hypothesis that natural environments would provide superior restorative effects compared to urban and indoor settings. Participants reported significantly greater psychological restoration in the natural environment, as assessed by both the Perceived Restorative Scale (PRS) and the Restorative Outcomes Scale (ROS), in line with a recent meta-analysis (Menardo et al., 2021). These results support the thesis's central hypothesis, highlighting nature's restorative potential in facilitating psychological recovery while performing physical activity.

One of the key aspects of green exercise is the potential for natural environments to reduce perceived exertion of physical activity, which is thought to enhance motivation and improve adherence to exercise (Loureiro & Veloso, 2017). For example, previous research has suggested that when participants are instructed to exercise at a fixed perceived exertion level, often measured with Borg's RPE scale, they work at higher levels in terms of speed or physiological indices (Olsson et al., 2024). Other studies showed how when participants are free to set their activity pace, they exercise harder in terms of heart rate yet report lower perceived effort (Focht, 2009). Surprisingly, this research showed no significant difference in perceived exertion between physical activity in natural and urban environments. Participants reported higher perceived exertion indoors when using the treadmill, which confirms that indoor activities, especially those involving stationary exercise equipment, can impose a greater psychological burden. One potential explanation for the lack of difference between the natural and urban environments in terms of perceived exertion could lie in the concept of optic flow and the attentional demands of different environments. As Rogerson et al. (2019) suggested, outdoor environments typically offer greater optic flow—a visual cue associated with the expanding flow on the retina as individuals move through space. This increased optic flow is thought to reduce perceived exertion by providing a more immersive and less cognitively demanding experience. In contrast, indoor exercise on stationary equipment, such as treadmills or cycle ergometers, does not offer visual flow, which may make the exercise more mentally demanding as participants focus more on their internal states, increasing perceived effort. Still, the unexpected finding in this study was the absence of a significant difference in perceived exertion between the natural and urban environments. This contrasts the assumptions of restorative environments, such as the Attention Restoration Theory (ART), which suggests that natural settings are less demanding for directed attention, providing greater opportunities for recovery. The thesis results did not indicate a clear

advantage of natural environments over urban settings in lowering perceived exertion. This could be attributed to several factors. The low perceived exertion in all three environments may have obscured differences between natural and urban settings, possibly due to the relatively fit sample. When the intensity of the exercise is low, it is possible that the differences in the environments are not sufficiently large to elicit noticeable changes in perceived effort.

Additionally, both urban and natural settings in this study provided relatively calm and manageable conditions for walking, which might have reduced the impact of environmental differences on the participants' perceived exertion. It's also important to note that for this study, the routes in the two outdoor environments were matched as much as possible regarding altimetric profile and walking distance. Additionally, the walking pace was controlled for all participants to ensure consistency, with the experimenter using GPS to monitor and adjust the pace. These measures helped standardize the physical demand of the exercise, which may have minimized any differences in perceived exertion between the two environments. Interestingly, while the natural environment was perceived as more restorative than the urban environment (as measured by the Perceived Restorative Scale), this difference in perceived restorativeness did not translate into a significant difference in perceived exertion. This suggests that while perceived restorativeness may influence psychological recovery and emotional states, it may not directly impact the perception of physical effort during exercise.

This study provided an opportunity to investigate the physiological effects of green exercise with robust methods commonly used in sports science and physiology, focusing on cortisol levels, heart rate (HR), and heart rate variability (HRV). The results have contributed to clarifying conflicting findings in the literature on green exercise, specifically regarding its benefits on physiological outcomes (Gidlow et al., 2016; Noseworthy et al., 2023). While previous studies have shown contrasting results (Niedermeier, Grafetstätter, et al., 2017), this research suggests that nature exposure during physical activity results in better physiological recovery than in urban and indoor environments. Cortisol levels decreased across all environments from pre- to post-exercise, but lower levels were observed in the natural environment. This supports prior research indicating that nature exposure promotes stress recovery by lowering cortisol (Park et al., 2007; Gladwell et al., 2012). Participants showed lower HR and higher HRV during recovery after exercising in the natural environment, reflecting better autonomic recovery and parasympathetic activation than in urban and indoor

environments. These results are consistent with studies showing that exposure to nature can enhance autonomic recovery, further supporting the role of nature in facilitating physiological recovery from physical exertion (Gladwell et al., 2016).

Moreover, participants expressed a greater intention to engage in future physical activity in natural environments, emphasizing the role of green exercise in fostering long-term engagement with exercise. The study's findings highlight the motivational benefits of natural environments, with enjoyment being the key determinant of future behavioral intentions. These results reinforce the thesis objective of exploring how nature exposure can promote not only immediate psychological recovery but also sustained engagement with physical activity (Loureiro & Veloso, 2017).

This intention to engage in future healthy behavior and be more active is also sustained by the greater affective benefits that green exercise could offer compared to exercise in other non-green environments. Participants reported significantly higher positive and lower negative emotions exercising in the natural environment compared to urban and indoor environments. This aligns with previous research on green exercise (Barton & Pretty, 2010; Lahart et al., 2019), demonstrating that nature contributes to emotional well-being by enhancing positive affect and reducing negative affect. Specifically, positive emotions increased post-walk in the natural setting, with no significant change in urban and indoor environments. The breakdown of positive emotions into activating and deactivating dimensions revealed that the natural environment led to an increase in positive deactivating emotions (such as calmness and relaxation). In contrast, these emotions decreased in both urban and indoor settings. Negative emotions, already low pre-exercise, are further reduced in the natural environment after the activity. Participants in the indoor environment experienced a rise in negative emotions after exercise. The natural and urban settings contributed to a decrease in negative deactivating emotions, with the natural setting showing a stronger reduction.

Regarding target emotions of relaxation and anxiety, participants reported higher relaxation levels in the natural environment, with the smallest decline post-exercise compared to indoor settings, where relaxation levels dropped significantly. Although anxiety showed no significant time effect, it was consistently lower in the natural environment, further supporting nature's restorative and calming effects. Urban and indoor environments, on the

other hand, were associated with higher anxiety levels, which may hinder the overall emotional recovery process.

This thesis has also demonstrated that, from a physiological standpoint, exercise in natural environments offers greater benefits in terms of recovery, given the positive effects on physiological markers. In terms of psychological restoration, it is clear that the natural environment stands out as offering greater benefits compared to urban and indoor environments. These clear findings regarding physiological markers and psychological restoration were somewhat replicated in the emotional self-reports, with the most observable benefit being positive emotions, especially deactivating ones. This was further confirmed by examining the target emotion of relaxation, which remained constant after exercise in the natural environment but decreased in the other environments. While the physiological outcomes strongly support the potential of nature to facilitate recovery, the emotional self-reports mirrored this trend, particularly concerning relaxation and deactivating positive emotions.

A secondary aim of this thesis was to assess the restorative properties of natural environments in mitigating the stress effects of hypoxia, a condition characterized by reduced oxygen levels in the air. Hypoxia triggers an automatic stress response in the body, which activates a series of physiological adaptation mechanisms. However, in terms of psychological outcomes, the results indicate that the only significant effect of hypoxia was on anxiety: participants reported higher anxiety levels in the hypoxic condition compared to the normal oxygen condition. Broadly, positive and negative emotions, particularly relaxation, were not significantly influenced by the brief and passive exposure to hypoxia. This finding is exciting since anxiety levels decreased from pre- to post-exposure across oxygen conditions. The lack of significant emotional responses to hypoxia could be attributed to the brief nature of the exposure, the passive mode of interaction, and the absence of other typical stressors associated with hypoxia, such as intense physical activity, elevation, or high-altitude environmental challenges.

As for the effect of viewing natural images, contrary to expectations, they did not positively impact any psychological outcome or even physiological indices. Urban images were associated with significantly higher positive emotions. This lack of positive effects from natural images, or the lack of expected negative impacts from urban images, could be explained by the state of calm and relaxation experienced by participants across all

conditions. Pre-exposure scores for positive emotions were already high, and the significant effect of time showed an increase in deactivating emotions, both positive and negative. The absence of a task or a preceding stressor might have affected the ability of natural images to generate stress recovery and enhance participants' emotional states.

Regarding the regenerative potential of the images, using the Perceived Restorativeness Scale (PRS) clearly showed that the two slideshows were evaluated quite differently. Participants rated the natural images as having a higher restorative potential in terms of the overall score and its core subdimension, *fascination*. These results align with existing literature suggesting that natural environments generally have greater restorative potential than urban environments (Menardo, 2021). This thesis emphasizes the importance of assessing participants' perceptions of the environments they encountered, whether through active engagement or passive exposure. Environmental perceptions can significantly influence how individuals relate to both natural and other environments, and they play a critical role in shaping emotional and physiological responses. The results of Study 3 confirmed this. Higher restorativeness ratings of the images were consistently associated with increased positive emotions (activating and deactivating), greater relaxation, and lower anxiety. The interaction between perceived restorativeness and time further underscores this: participants who rated the images as more restorative experienced significant increases in positive emotions and relaxation over time, while those who rated the images as less restorative reported declines. This indicates that the restorative potential of an environment is not just dependent on its objective characteristics but also on how individuals perceive and interpret it. Interestingly, perceived restorativeness also appeared to shield against the physiological stress of hypoxia. Participants who rated the images as more restorative reported lower anxiety levels, even under oxygen-deprived conditions. This finding supports previous research indicating that restorative environments can alleviate the adverse effects of stressors, providing psychological relief even in challenging contexts (Hartig, 2004; McMahan & Estes, 2015).

A key finding of this thesis is the partial dissociation between physiological responses and self-reported emotional outcomes. In the case of active exposure to natural environments, there was a greater alignment between physiological and emotional reactions, likely due to the restorative benefits of nature. However, in the study involving hypoxia, where participants experienced passive exposure, this dissociation was more pronounced. Specifically, while hypoxia had a clear impact on physiological markers—raising heart rate

and lowering heart rate variability—its effects on emotional outcomes were more limited, with anxiety being the only significantly affected variable. Similarly, the natural images in the hypoxia study did not significantly impact physiological or emotional responses. These findings underscore the complexity of the stress-recovery process, suggesting that physiological strain does not always translate into emotional experiences, especially in passive experimental settings where engagement with the environment is minimal.

In this context, this thesis advances the research on nature exposure by exploring two modalities: passive and indirect exposure through viewing images and active and interactive exposure through engagement in physical activity in real-world settings. The findings suggest that the latter modality offers more promising benefits of nature exposure. Active engagement with natural environments during physical activity enhances physiological recovery and emotional well-being to a greater extent, highlighting the importance of direct interaction with nature for maximizing the restorative effects.

Implications

The results of this thesis underscore the significant benefits of green exercise, particularly in terms of psychological and physiological outcomes. Exposure to natural environments during physical activity enhanced both emotional well-being and recovery from physiological stress, supporting existing theories on the restorative potential of nature. The findings of this thesis also suggest that green exercise leads to greater enjoyment of physical activity compared to urban and indoor environments, as well as a stronger intention to repeat the exercise. This has significant implications for promoting an active lifestyle, as the increased pleasure and intention to exercise in nature could help individuals incorporate more outdoor activities into their routines.

These findings have important implications for urban planning, especially considering the increasing challenges of urbanization and the decreasing availability of green spaces in many cities. As cities continue to grow, it is crucial to prioritize integrating green spaces into urban environments, as they offer environmental benefits and improve public health by providing accessible areas for green exercise.

One key implication of this thesis is the need to consider how the design and accessibility of urban spaces can foster a stronger connection between people and nature. Nature connectedness has emerged as a critical factor in promoting individual well-being and

environmental sustainability (Mayer et al., 2009). A meta-analysis demonstrated that psychological connection with nature can be fostered by nature-based activities, such as mindfulness or outdoor exercise (Barragan-Jason et al., 2021). In turn, the stronger the psychological connection, the more it positively impacts individuals' attitudes and behaviors towards the environment, including pro-environmental actions (Mackay & Schmitt, 2019). This reciprocal relationship suggests that green exercise is a powerful tool to improve personal health and foster sustainable environmental behaviors. As urban spaces become more congested and urban dwellers less connected to nature, fostering this connection through intentional design becomes essential for individual well-being and collective sustainability efforts. Creating more opportunities for people to engage in green exercise, especially in urban environments, could facilitate a positive feedback loop. As individuals experience the well-being benefits of nature, they become more familiar with preserving these natural spaces.

Another key point emerging from the literature, including studies such as those by Hughes et al. (2019), is that children inherently have a stronger, more spontaneous connection with nature than adults. This intrinsic bond, often called biophilia (Kellert & Wilson, 1993), typically diminishes as individuals grow older and become more immersed in urban, technology-driven environments. The challenge, therefore, is to sustain and nurture this natural connection throughout life. This disconnection from nature may be linked to the modern urban lifestyle, where individuals often underestimate the emotional benefits of nature and actively avoid engaging with it. Research on affective predicting errors (Nisbet & Zelenski, 2011) has shown that adults often misjudge the level of pleasure they experience from spending time outdoors, leading them to underestimate the positive emotional impact of nature. If left unaddressed, this disconnection may have lasting implications for individual well-being and environmental sustainability.

Limitations and future studies

While this thesis provides valuable insights into the benefits of green exercise, several limitations should be acknowledged. One of the main constraints is the absence of a rest condition, which would have allowed for a more comprehensive comparison of the effects of physical activity per se versus the impact of exposure to nature. Including a rest condition would have helped isolate the influence of nature from that of the physical exercise itself. Additionally, due to the experimental design, emotional fluctuations during physical activity

could not be captured, as doing so would have compromised the standardization of the exercise across all participants. Future studies could benefit from investigating real-time emotional changes during green exercise. One approach to achieve this would be using single-item scales at various time points during the activity to monitor affective fluctuations. Such data would offer more profound insights into how emotions evolve during exercise in natural environments, further elucidating the dynamic relationship between physical activity and environmental exposure (Ekkekakis & Brand, 2019). This is crucial, as another important consideration is the potential phenomenon of affective rebound, where post-exercise mood improvements might not entirely reflect the overall emotional effect of the activity. This rebound effect suggests that the positive emotional changes observed after exercise could be misleading, and future studies should explore this possibility to better understand how emotional states are impacted by green exercise during and after the activity.

Another significant limitation is related to the types of physical activities involved in green exercise. While this research focused on the potential benefits of a moderate intensity walk, a more detailed exploration of varying intensities of exercise in natural settings is needed. Different levels of physical exertion are associated with distinct emotional patterns and understanding how these different intensities interact with nature exposure would provide a clearer picture of how exercise and the environment jointly affect emotional well-being.

Moreover, this research did not explore the wide range of individual and contextual variables that may influence the relationship between nature exposure and well-being. Individual factors, such as gender, socioeconomic status, and ecological knowledge, are important moderators in this field of study, as well as contextual aspects like accessibility to green spaces, familiarity with the environment, perceived safety, and cultural-social norms and values. For example, thermal comfort might play a significant role in moderating the effects of green exercise, as different weather conditions could affect the experience of physical activity in natural settings. The impact of these variables warrants further investigation to improve the generalizability of findings and tailor interventions to diverse populations.

In addition, using small, relatively homogenous samples in the studies reviewed may limit the generalizability of the results. Future research should consider larger, more diverse samples in terms of age, fitness levels, and demographic characteristics to strengthen the validity and applicability of the findings. Moreover, longitudinal studies would be beneficial

in consolidating the evidence and accounting for temporal changes in natural environments, mainly because natural settings, unlike urban environments, are subject to significant seasonal changes. For instance, walking in a forest during winter differs significantly from walking in the same forest during summer, especially regarding natural features. This variability underscores the need to go beyond a simple green versus urban comparison and account for differences between various natural environments.

Several limitations should be considered regarding the study of the restorative potential of nature exposure in the presence of a physiological stressor such as hypoxia. One key limitation stems from the experimental design, where participants rested in a semi-supine position for 30 minutes. This passive task likely reduced the elicitation of strong negative emotions, as resting is inherently calming. Consequently, this may have mitigated the potential for urban imagery and hypoxia to evoke pronounced emotional responses, limiting the contrast between conditions.

Furthermore, while hypoxia was expected to induce stress, the passive nature of the task and the absence of additional stressors such as cognitive or physical challenges possibly diminished the overall impact of hypoxia on emotional outcomes. This suggests that, even in the worst scenario of hypoxia combined with urban imagery, the experimental conditions were not sufficiently stressful to elicit robust emotional changes. Stavrou and colleagues' (2018) study has shown that emotional responses to stressors like hypoxia may require longer exposure times to manifest, particularly in passive settings. In contrast, physiological responses to hypoxia tend to occur quickly, with adaptation to oxygen deprivation happening within minutes. Therefore, the 30-minute exposure in this study was likely insufficient to capture the full emotional impact of hypoxia. Future studies could benefit from extending exposure durations to allow for a more robust assessment of the restorative effects of nature on emotional responses, particularly when combined with stress-inducing tasks.

Conclusion

In summary, the three studies presented in this thesis offer a comprehensive investigation into the psychological and physiological effects of exposure to natural environments through active engagement in physical activity (green exercise) and passive interaction, such as exposure to nature images. Study 1 provided a critical overview of the methodological challenges in studying green exercise and nature exposure, highlighting the

inconsistencies and gaps in current research and emphasizing the need for more rigorous and standardized approaches. Study 2 confirmed the restorative potential of green exercise by demonstrating the beneficial effects of physical activity in natural environments, revealing significant improvements in both emotional well-being and physiological markers of recovery. Study 3 introduced a novel perspective by investigating the effects of nature exposure within hypoxia, underscoring the importance of environmental perceptions in shaping emotional responses.

Collectively, these studies contribute valuable insights into the differential effects of active versus passive nature exposure, shedding light on how both types of exposure can influence stress recovery and emotional well-being. The findings indicate that active engagement with natural environments during physical activity produces more pronounced benefits, particularly in enhancing emotional states, fostering a stronger sense of psychological restoration, and facilitating physiological recovery. In contrast, passive exposure, such as viewing nature images, did not show the same magnitude of effects, particularly regarding emotional response.

Moreover, this thesis has demonstrated that green exercise leads to greater enjoyment of physical activity compared to urban and indoor settings and increases the intention to repeat the exercise. This has significant implications for promoting sustainable physical activity and improving mental health, as the enjoyment and intrinsic motivation associated with green exercise can be a powerful tool for fostering long-term participation in outdoor activities.

The methodological consistency of this thesis has advanced the understanding of nature's impact on health, employing validated self-report measures and objective physiological assessments to provide a comprehensive and nuanced picture of how environmental factors interact with physical activity. By integrating multiple dimensions of emotional and physiological outcomes, this research offers a more robust framework for studying the complex relationship between nature exposure and well-being.

Ultimately, the findings of this thesis underscore the importance of considering both the type and quality of nature exposure in health interventions. They suggest that urban planning, educational strategies, and public health policies should prioritize the integration of nature into daily life to enhance well-being and promote an active, sustainable lifestyle. Incorporating green spaces into urban environments and encouraging physical activity in

nature could be key components of strategies to combat urbanization's adverse effects on mental and physical health. Future research should continue to explore how nature exposure can be optimized to improve individual and community health outcomes.

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Study 1 has two co-authors, Stefano De Dominicis and Margherita Brondino and has been published in *Frontiers in Sports and Active Living*. Since *Frontiers* articles are published under the CC-BY license, which allows unrestricted use, distribution, and reproduction as long as the original authors and source are credited, the manuscript has been incorporated into this dissertation with proper citation:

Laezza L, De Dominicis S and Brondino M (2024) Reassessing green exercise research: unveiling methodological gaps and pathways for progress. *Front. Sports Act. Living* 6:1449059. doi: 10.3389/fspor.2024.1449059

Study 2 has several co-authors: Martina Vacondio, Alessandro Fornasiero, Barbara Pellegrini, Margherita Pasini, Margherita Brondino, and Stefano De Dominicis and has been submitted to *Psychology of Sport and Exercise* and is currently under review.

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