buildings

MDPI

Article

The Neurobiophilia Index

Mohamed Hesham Khalil * and **Koen Steemers**

Neurocivitas Lab, Department of Architecture, University of Cambridge, Cambridge CB2 1PX, UK; kas11@cam.ac.uk
* Correspondence: mhmhk2@cam.ac.uk

Abstract

This paper aims to establish the Neurobiophilia Index, a quantitative tool to assess environmental enrichment at the architectural scale based on neurobiological evidence. Using a literature review followed by an expert opinion workshop and deliberations, 10 items were identified: sky visibility, daylight, light/dark cycles, sound, odours, indoor plants, window green views, temperature, air quality, and materials. The index provides a symmetrical scoring system for each item based on the effect of its parameters on the brain: enrichment (+1), neutral (0), and harm (−1), facilitating assessment of architectural spaces and buildings to understand implications for neuroplasticity, with cognitive, mental health, stress recovery, and resilience outcomes. It is a useful tool for future research and provides a pathway toward advancing green building rating systems from sustainability to neurosustainability.

Keywords: environmental enrichment; built environment; biophilia; biophilic architecture and design; neuroarchitecture; brain health; plasticity

1. Introduction

The quality of the environment determines whether the brain develops adaptive or maladaptive changes. Environmental enrichment sustains adaptive brain plasticity, yet what constitutes enrichment in human environments has become increasingly unclear with the rapid shift from natural to built environments, particularly in indoor spaces.

The relationship between humans and nature is rapidly changing as populations shift from natural to built environments. A global systematic review of 100 case studies found that around 63% of longitudinal studies reported decreased nature connection, manifesting as reduced interest in nature, declining species identification abilities, and decreased participation in outdoor activities suggested to stem from urbanisation, loss of natural environments, and sedentary screen-based lifestyles [1]. By 2050, the United Nations projects 68% of the world's population will live in urban areas [2], and agent-based modelling suggests that even substantial interventions may not fully reverse declining nature connectedness until after 2050 [3]. While the heterogeneous nature of these changes suggests opportunities for targeted interventions [1], the challenge may be compounded by increasing indoor time. Over two decades ago, it was reported that time spent indoors is around 90% [4], a rate that has likely increased further. From around the same time of that study to 2022, daily indoor time in the USA increased by 1 h and 39 min [5]. Globally, time spent at home increased after the COVID-19 lockdown [6,7]. This unprecedented shift warrants careful assessment of architectural enrichment to restore the connection with nature.

Brain imaging research suggests that connection with nature through built environments is associated with adaptive brain responses. At the residential level, the integration

Check for updates

Academic Editor: Eusébio Z. E. Conceição

Received: 20 December 2025
Revised: 27 January 2026
Accepted: 31 January 2026
Published: 3 February 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

of natural elements in cities (e.g., tree cover density, sky visibility) associates with larger brain volumes [8–10]. Walking in forests, unlike in cities, reduces amygdala activity and facilitates acute stress recovery [11,12]. However, a systematic review reported no studies examining how indoor built environments specifically affect the human brain [13]. Given that people spend ≈90% of their time indoors, this research gap is critical and highlights an urgent need to assess enrichment at the architectural scale and develop methods to restore connections with nature in indoor environments.

In addition to the aforementioned brain imaging evidence explaining how nature affects brain volume, hippocampal neurogenesis provides a complementary mechanistic framework for understanding how nature nurtures the brain. In humans, neurogenesis persists into the tenth decade of life [14], but it drops in subjects with Alzheimer's disease [15,16] and neuropsychiatric disorders [17], suggesting that adult hippocampal neurogenesis may serve as a therapeutic target and provide stress resilience [18–20]; yet, how built environments affect human neurogenesis remains unclear. However, animal models can bridge this knowledge gap, as neurogenesis persists across species with convergent biological pathways [21,22]. These models demonstrate that neurogenesis is directly influenced by environmental parameters including lighting and temperature [23–27]. These factors can be architecturally controllable. This evidence base provides a framework for assessing how architectural enrichment can restore connections with nature in indoor environments to sustain adaptive brain plasticity.

These neurogenesis findings, alongside brain volume changes and neurotrophic factors, represent key mechanisms within the Neurobiophilia framework [28], which provides a neuroscience-informed foundation for understanding how nature affects the brain. The original biophilia hypothesis posited humans' innate tendency to affiliate with nature and life [29], and while this has been studied for four decades, it lacked neuroscientific grounding [30]. This gap was recently addressed by the theoretical establishment of Neurobiophilia [28]. This advancement provides a mechanistic basis for designing buildings that harness nature's enrichment, particularly given evidence that people across cultures and biomes consistently rate natural elements (trees, grass, plants, sky) as eliciting the most positive feelings [31], suggesting biophilia is a universal phenomenon that can inform architectural design.

Consequently, this paper develops the Neurobiophilia Index, a neuroscience-grounded assessment tool for evaluating environmental enrichment in buildings. This tool addresses a critical gap: existing biophilic design frameworks and green building rating systems lack neuroscientific foundations based on mechanisms such as neurogenesis and brain-derived neurotrophic factor, while people spend approximately 90% of their time indoors where environmental impacts on brain health remain unstudied. The Neurobiophilia Index can serve as a complementary assessment tool for green building rating systems, advancing sustainability to neurosustainability [32]. Ultimately, it provides architects, designers, and researchers with evidence-based criteria to conduct further research on focused populations and to create enriched indoor spaces that restore human-nature connections and support brain health.

2. Materials and Methods

This study employed a four-stage iterative methodology to develop the Neurobiophilia Index:

First, the index structure was based on five neuro-needs (5NNs) identified in the Neurobiophilia framework [28]: (1) neuroprotection, (2) neurophysiological regulation, (3) neurotrophic factors, (4) neurogenesis, and (5) neural responses to novelty. While the Neurobiophilia framework established seven neuro-needs (7NN), these five were selected as most applicable to architectural design interventions. A symmetrical scoring system was established for each enrichment item: enrichment parameters (+1), neutral/comfort parameters (0), and harmful parameters (−1). Parameters were classified qualitatively, quantitatively, or both based on literature-evidenced effects on the 5NNs.

Second, a non-systematic literature review was conducted due to the interdisciplinary nature of the topic and the lack of studies on buildings identified in an earlier systematic review [13]. Searches were conducted using Google Scholar with a snowballing strategy from September 2023 to September 2025. Search terms were interactions of each of the 5NNs with enrichment architectural keywords. Term for the 5NNs were neuroprotection (brain volume, neuroplasticity, cortical thickness, grey matter, white matter, brain atrophy, neuroinflammation); neurophysiological regulation (subiculum, amygdala, EEG, physiology); neurotrophic factors (brain-derived neurotrophic factor, BDNF); neurogenesis (adult hippocampal neurogenesis); and neural responses to novelty (EEG). Terms for enrichment items were spatial (building, layout, interior, ceiling height, window, skylight, spatial novelty); visual (outdoor view, sky view, lighting, plants, trees, vegetation, visual complexity, fractals); ambient (air quality, temperature, heat, odour, sound, soundscape, noise, material, wood); and social (interaction, connection, safety, diversity).

Third, a workshop with 14 experts in architecture or neuroarchitecture introduced participants to Neurobiophilia and the initial index version. Following interactive discussion, experts could optionally submit additional anonymous comments via an online form. Based on workshop feedback, and after deliberations by both authors, the identified items through the search process were kept or eliminated.

Fourth, both authors conducted final deliberations to streamline the 15-item version to the final index. While enrichment domains proved useful for identifying items through literature review, presenting items organised by domain rather than biophilic relevance resulted in scattered, impractical groupings that obscured nature connections. Items were therefore evaluated and reorganised based on direct biophilic relevance, based on the extent to which they facilitate human–nature connection through architectural design.

3. Results

The initial literature review identified 30 candidate items organised into four enrichment domains: spatial enrichment (n = 8: spatial affordance for physical activity, spatial complexity, space height:width ratio, window-to-wall ratio, sky view factor, spatial novelty [short-term and long-term], integrated outdoor experiences); visual enrichment (n = 8: visual complexity, visual clutter [density and organisation], visual contrast, fractals dimension, natural plant density, light intensity [morning and sleep]); ambient enrichment (n = 10: odours, sound source, noise level, temperature [daylong and brief], humidity, wind speed, air exchange, PM2.5 and PM10 levels); and social enrichment (n = 4: safety, density, connection, interaction).

Following expert workshop feedback and subsequent deliberations, the index was streamlined from 30 items to 15 items (5 spatial, 5 visual, 5 ambient). Workshop feedback identified several areas requiring improvement: item redundancy, parameters exceeding comfort levels without clear enrichment benefits, limited biophilic relevance for some items, difficulty visualising abstract variables without architectural context, and concerns regarding socio-cultural variability in parameter assessment.

Subsequent streamlining yielded 10 items that constitute the Neurobiophilia Index. This streamlining process involved: (1) combining related items across domains where they addressed the same biophilic element (e.g., window-to-wall ratio from spatial domain combined with outdoor green views from visual domain), (2) removing redundant items where multiple parameters achieved similar neurobiological effects (e.g., physical activity removed as passive heat exposure provides similar brain-derived neurotrophic factor benefits without combined excessive stress), (3) excluding items with unclear effects or limited universal applicability (e.g., visual complexity, which remains unclear and may not suit neurodivergent individuals), (4) removing impractical items (e.g., spatial novelty requiring reconfiguration, spatial complexity lacking clear biophilic connection), (5) excluding items now embedded within retained parameters (e.g., visual novelty captured through sky visibility dynamics and changing odours), and (6) avoiding drawing conclusions based on limited evidence until further evidence is available (e.g., space height:width ratio and length:width ratio).

The final Neurobiophilia Index comprises ten biophilic parameters: sky visibility, daylight, light/dark cycles, sound, odours, indoor plants, window green views, temperature, air quality, and materials. These items represent nature-based enrichment parameters with neurobiological evidence (Figure 1). The results are presented subsequently, followed by the scoring system presented in Table 1.

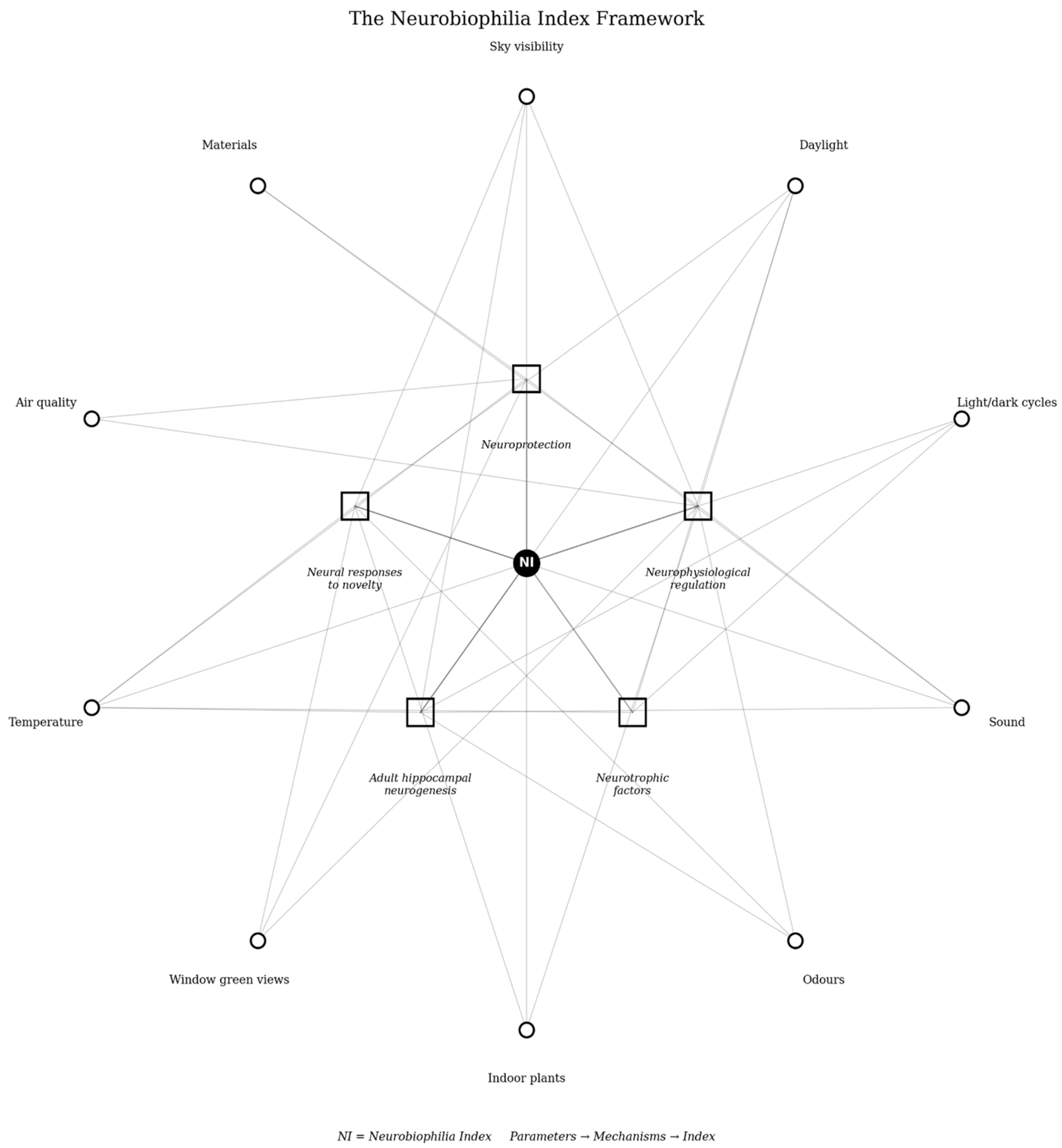

Figure 1. The Neurobiophilia Index framework, as established through the interconnected associations between the environmental enrichment variables and the human brain's primary 5NNs: (1) Neuroprotection, (2) Neurophysiological regulation, (3) Neurotrophic factors, (4) Neurogenesis, and (5) Neural responses to novelty.

Table 1. The Neurobiophilia Index.

Items	Item Scoring *		
	+1 pt	**0 pt**	**−1 pt**
1. Sky view factor	skylight or window view with a sky view factor ≥ 0.5 showing a sky with a dynamic changing pattern	skylight or window view with a sky view factor 0.3–0.4	no skylight or window, or either having a sky view factor < 0.3
2. Daylight	average exposure to <900 lux at daytime, with exposure to ≥10,000 lux for only 30 min/day without exposure to chronic discomfort glare	average exposure to <900 lux at daytime without exposure to chronic discomfort glare	chronic exposure to >900 lux at daytime, or chronic exposure to discomfort glare
3. Light/dark cycles	uninterrupted exposure to <0.1 lux for 7–9 h at nighttime	uninterrupted exposure to <1 lux for 7–9 h at nighttime	chronic exposure to >1 lux on average at night
4. Sound	dominant natural sounds in a <60 dBA surrounding, maintaining silence (or <30 dBA) during sleep or in focus spaces	mixed pleasant sounds; noise level is <60 dBA	chronic sound pressure levels ≥ 60 dBA regardless of source type, or prolonged complete auditory deprivation
5. Odours	daily or overnight changing natural odours (e.g., rose, orange, eucalyptus, lemon, peppermint, rosemary, and lavender) from a plant or diffuser source; odours must have positive valence	mixed or static natural odours with positive valence	no odours; or mixed or static odours associated with a negative valence
6. Indoor plants	13–24% density of natural indoor plants in a visual field, natural plants provide visual novelty across seasons, with natural biofiltration plants	≥1% natural indoor plants in a visual field	no natural indoor plants in a visual field
7. Window green views	window-to-wall ratio 40–80%, window green views = 45–75%, and greenery depth = 0.4–0.65	Window-to-wall ratio 30–90%, and window green views > 30%	window-to-wall ratio < 40% or >80%, or window green views < 30%
8. Temperature	average 18–24 °C/24 h + head-protected exposure to 26–36 °C for <1 h/day (sunroom, warm room, sauna, hot tub, etc.); UV-protected sun exposure is <2 h/day	average 18–24 °C/day; UV-protected sun exposure is <2 h/day	chronic exposure to <18 °C or >40 °C/24 h; UV-protected sun exposure or >2 h/day
9. Air quality	>0.5 h^{-1} air exchange via cross ventilation independently or with mechanical ventilation; wind speed is 0.3–0.8 m/s for moderate conditions or 1.0–2.0 m/s for hot, humid conditions; PM2.5 < 2 μg/m^3/24 h; PM10 < 7 μg/m^3/24 h	0.5 h^{-1} air exchange through one window open or through mechanical ventilation only. PM2.5 < 2 μg/m^3/24 h; PM10 < 7 μg/m^3/24 h	<0.5 h^{-1} exchange; PM2.5 > 2 μg/m^3/24 h; PM10 > 7 μg/m^3/24 h
10. Materials	natural wood + low VOCs	low VOC materials	high VOC materials

* To increase points, all conditions must be met in case there are multiple conditions.

3.1. Sky Visibility

The sky view factor (SVF) is a 0 to 1 parameter representing the fraction of sky visible from a specific ground point. In urban environments, Kühn et al. [8] reported that SVF, averaging 63.5% (range: 27.96–87.95%), was a significant predictor of prefrontal brain volume when analysed with tree cover and open green space. These findings warrant further investigation into whether interiors provide this enrichment.

To test whether SVF enriches indoor spaces, two EEG-based studies examined simulated sky lighting in offices, yielding complementary results. Yasukouchi et al. [33] found that artificial skylights (versus fluorescent lighting) reduced arousal and sympathetic activity while maintaining work performance. However, the skylight also had 35% higher melanopic illuminance, higher correlated colour temperature (CCT) (6200 K vs. 4800 K), and different spatial distribution, making it difficult to isolate sky perception from superior lighting characteristics. Schöllhorn et al. [34] tested nature-adapted lighting with simulated clouds in a better-controlled design (matching photopic lux while varying CCT and dynamics) and found no effects on alertness, cognitive performance, or cortisol, though dynamic sky lighting reduced perceived tension and concentration effort. These studies suggest that sky visibility or adapting its qualities, not yet fully identified, can lead to adaptive brain responses.

While lighting and temperature may be associated with sky visibility, the sky's enrichment quality extends beyond these factors. Yasukouchi et al. [33] showed that viewing a dynamic sky reduces perceived tension and effortful concentration. This hypothesis is supported by laboratory studies. Ramírez-Rodríguez et al. [35] report that changing environmental complexity maintains cognitive stimulation, enhances hippocampal neurogenesis, and reduces anxiety, regardless of the pattern of change.

While light and temperature are discussed later as separate items, 'sky visibility' is maintained in the Neurobiophilia Index as a separate visual enrichment item.

3.2. Daylight

Daylight intensity, not merely its presence, determines effects on brain-derived neurotrophic factor, adult hippocampal neurogenesis, and outcomes such as depression.

Bright light exposure (BLE) enhances hippocampal neurogenesis in animals. In rats, Hirakawa et al. [25] found that 10,000 lux for four weeks increased neurogenesis. Similarly, Kwon et al. [24] reported that 10,000 lux light exposure for 30 min/day over four weeks increased hippocampal brain-derived neurotrophic factor and neurogenesis.

In humans, a meta-analysis of 22 studies suggested that light at 10,000 lux and above reduced depressive symptoms compared to lower intensities [36]. Since hippocampal neurogenesis and depression are inversely associated [17,37], these findings converge. Additionally, Molendijk et al. [38] reported higher brain-derived neurotrophic factor levels in spring-summer periods, correlated with ambient sunlight.

While brief exposure to 10,000 lux benefits neurogenesis, chronic exposure to even moderate lighting levels may affect arousal differently. EEG studies show that office illuminance exceeding 1300 lux heightens arousal, while levels below 300 lux increase calmness, suggesting 700–900 lux is appropriate for offices [39]. This aligns with previous research suggesting 500–750 lux [40].

However, sunlight exposure has a critical threshold. Li et al. [41] reported that moderate sun exposure (~2 h) yielded adaptive responses, but prolonged exposure (>2 h) reduced brain, white matter, and grey matter volumes. UV irradiation and brain temperature may explain these maladaptive responses. BLE recommendations should account for adverse effects of prolonged sun exposure. Chronic UV irradiation induces neurogenesis deficits in animal models [42], suggesting both UV and brain heat contribute to maladaptive changes.

Therefore, the Neurobiophilia Index assesses architectural enrichment through daylight given the multidimensional nature of light: brightness, duration, and sun exposure.

3.3. Light/Dark Cycle

Lifestyles in built environments have altered light/dark cycles, which can have detrimental effects on the brain.

Constant light exposure adversely affects the brain. Fujioka et al. [23] found that three weeks of constant light versus standard 12 h/12 h light-dark cycles impaired neurogenesis in animals. Walker et al. [43] reported that mice exposed to 14 h of 150 lux:10 h of 5 lux at night for three nights (compared to 14 h of 150 lux:10 h of 0 lux) showed increased depressive behaviours and reduced neurotrophic and growth factors. Illuminance of 5 lux at night shows similar adverse effects, impairing brain-derived neurotrophic factor expression, increasing vulnerability to stress-induced oxidative damage, and affecting memory [44,45].

Even 2 lux at night can have adverse effects. Sangma and Trivedi [46] examined 30 days of 2 lux dim light at night versus 250 lux constant light, finding that 2 lux at night reduced brain-derived neurotrophic factor expression in the rat hippocampus, thalamus, and cortex, consistent with previous studies. While no studies report changes in brain-derived neurotrophic factor in humans in response to light at night, human research recommends sleep environments be as dark as possible, ideally below 1 lux to support physiology [47].

The Neurobiophilia Index draws on natural light/dark cycles as reference values. Illuminance of daytime twilight is estimated at 10 lux, while nighttime deep twilight has around 1 lux, decreasing further depending on moonlight: 0.1 lux in full moon, 0.01 quarter moon, 0.001 starlight, and 0.0001 overcast night [48].

3.4. Sound

The effect of sound on the brain is complex and depends on sound type, composition, silence, and noise level.

Natural sounds support psychophysiological restoration in outdoor environments [49,50]. Gould van Praag et al. [51] reported that natural sounds reduced autonomic stress compared to artificial sounds or silence. Li et al. [52] found that in mountainous urban parks where biological and human sounds constituted >84.4% of the soundscape, EEG measurements showed more restorative α-wave activity at birdsong-dominant sites than traffic-noise-dominant sites (56.7–68.4 dBA).

Studies on indoor environments support the relationship between sound composition and stress recovery. Frescura et al. [53] reported that lower sound levels (footsteps at 30 dB vs. 50 dB, speech at 24 dB vs. 42 dB) increased relaxation, though relaxing music showed the opposite pattern. Combined sounds produced higher relaxation than single sounds, and participants with low noise sensitivity showed larger α-EEG responses. Zhang et al. [54] tested nature sounds for recovery from traffic noise stress (80 dBA). The 50 dBA natural sound environment showed optimal restorative effects for most people, while 40 dBA had variable effects and 60 dBA exacerbated stress.

While chronic severe noise exposure causes neural damage in rats [55], the effects of silence are complex. Short-term silence enhanced adult hippocampal neurogenesis in rats, while ambient background auditory stimuli did not [56]. However, prolonged auditory deprivation can impair hippocampal neurogenesis through increased stress responses [57–59]. Thus, while silence may benefit humans during sleep, extended periods of auditory deprivation during waking hours may be detrimental.

https://doi.org/10.3390/buildings16030637

The Neurobiophilia Index accounts for these complex interrelationships when proposing assessment recommendations for indoor environments.

3.5. Odours

Olfactory enrichment with novelty can enhance neurogenesis in both the olfactory bulb and hippocampus [60]. Novelty was the critical element, as exposure to multiple odorants individually enhanced neurogenesis, but not exposure to mixed odours [61].

In humans, using an odorant diffuser with a different scent each night (rose, orange, eucalyptus, lemon, peppermint, rosemary, or lavender) for 2 h overnight improved cognitive and neural functioning by 226% compared to controls with no scent [62].

Individual odorants also have distinct effects. Pleasant scents such as peppermint, sweet orange, and lavender modulate brain oscillations and improve task performance. Peppermint enhances alertness and attention, sweet orange improves mood and performance [63], and lavender produces relaxation alongside improved cognitive flexibility [64]. Garden plant odours similarly produce heightened relaxation and attentional readiness, particularly when combined with congruent visual stimuli [65].

The Neurobiophilia Index considers interior odours as an enrichment factor, recognising their role in supporting adult hippocampal neurogenesis and neurophysiological regulation through specific odorant types.

3.6. Indoor Plants

Plant density in the visual field affects brain function, as evidenced by brain imaging studies linking tree cover to brain volumes in urban environments and EEG studies on vegetation density.

In urban environments, effective tree cover density typically ranges from 9–12% within 200–500 metre residential buffers [13]. Indoor vegetation shows restorative effects in indoor natural spaces [66]. Rhee et al. [67] found that indoor vegetation density shows a clear hierarchy for stress reduction and cognitive restoration, with 13–24% performing best, followed by 25–36% and 37–100%, while 1–12% provided moderate improvements over barren environments. Other studies support those findings [49,68].

Natural plants provide additional benefits beyond visual density. Plant types offering air purification through botanical biofiltration provide neuroprotective effects by reducing neurotoxicity [69,70]. Additionally, as discussed with sky dynamism, natural plants change seasonally, which may provide perception of visual novelty.

The Neurobiophilia Index suggests incorporating indoor plants through visual field density and plant type.

3.7. Window Green Views

Outdoor views are complex and based on multiple factors including the window green views percentage, greenery depth, and the previously introduced sky view.

While a VR-based EEG study found natural outdoor views elevated physiological arousal compared to no outdoor views or indoor wooden/curvilinear elements [71], another showed forest views evoked the most restorative neural responses, while city views induced overstimulation and park views evoked mindful engagement and partial restoration [72]. Another VR-based EEG study using the Window Green View Index (WGVI) found that 25–50% WGVI increased relaxation, with 29.13–39.94% WGVI optimal for stress recovery where the remaining ≈60% was sky visibility [73].

After accounting for sky visibility and outdoor green views, greenery depth appears important. Physiological measures identified an inverted U-shaped curve with preference peaking at 74% WGVI [74]. The study introduced greenery depth (GD), the relative distance of vegetation from the viewer (0 = touching window, 1 = horizon), as a key moderator, with middle distances (GD = 0.4–0.65) providing optimal restoration.

Window-to-wall ratio (WWr) also affects outdoor view effectiveness, while window orientation appears less critical. Kim et al. [75] found that in small rooms (14 m^2), ceiling height and WWr combinations that minimised arousal depended on room proportions: narrower rooms (width:length 1:1.6) performed best with lower WWr (60%), while squarer rooms (1.6:1) performed best with higher WWr (100%). Zhang et al. [76] studied WWr 0.2 to 0.8 in vertical and horizontal orientations. While larger WWr openings enhanced relaxation, excessive WWr proved detrimental: both overly large and overly small window openings produced non-optimal physiological relaxation. Window shape had limited physiological impact when WWr was similar.

The Neurobiophilia Index incorporates outdoor green views, accounting for interactions between sky visibility, window green view index, and greenery depth. Outdoor green views provide neuroprotective effects, as tree cover density is associated with larger brain volumes [13], and may offer greater novelty than indoor plants.

3.8. Temperature

Temperature effects on the brain depend on critical thresholds, with temperatures outside optimal ranges yielding adaptive or maladaptive responses.

While the thermal comfort range is 18–24 °C [77], brief exposure to non-severe passive heat can increase brain-derived neurotrophic factor levels and neurogenesis. Kirby et al. [78] showed that brain-derived neurotrophic factor increases by 90 pg/mL per 1 °C rise in ambient temperature (from 22 °C to 36 °C). Although physical activity is often suggested to increase brain-derived neurotrophic factor, passive heat exposure may be necessary. Brain-derived neurotrophic factor did not increase in humans during 180 min moderate-intensity walking in a 16 °C environment, but increased after similar exercise in a 32 °C environment [79]. Thus, acute exposure to moderate heat produces adaptive brain responses.

Evidence for heat-enhanced neurogenesis in humans comes from animal studies. Rats exposed to 1 h heat treatment (36 °C) for 7 days showed enhanced neurogenesis compared to controls at 25 °C [26]. Exposure to mild heat (38.5 °C) enhances neurogenesis in rats [80]. Human neurogenesis may benefit from exposure to similar conditions.

Despite assumptions that 32 °C causes stress, an EEG study of 10 stress conditions found that 30 °C ranked second-least stressful when combined with no irritant odours and natural sounds [81]. Conversely, 20 °C with irritant odours and traffic noise ranked most stressful [81]. These findings align with the physiological restorative effects of summer temperatures (26–32 °C) [82].

Prolonged or severe temperature exposure may produce maladaptive responses. While brief hot water immersion (42 °C for 20 min) increased BDNF [83], and daylong exposure to 40 °C ambient conditions elevated BDNF in younger and older adults [84], severe heat stress causing core body temperature to reach 42 °C induced oxidative damage to the hippocampus in rats [85]. Direct solar radiation on the head produces effects, with prolonged exposure to simulated sunlight (≈1000 W/m^2) elevating core temperature by 1 °C and impairing cognitive and motor performance at lower hyperthermia levels than ambient heat alone [86].

The Neurobiophilia Index recommends temperature ranges accounting for the complexity of brain–environment interactions.

3.9. Air Quality

Air quality in indoor spaces is determined by volatile organic compounds (VOCs) and particulate matter (PM) levels. Controlling these pollutants is essential for supporting adaptive brain responses and avoiding maladaptive changes. Additionally, air velocity can affect neurophysiological regulation.

PM is generally lower indoors than in urban outdoor environments, though high PM levels may impair brain-derived neurotrophic factor increases. Bos et al. [87] found that 20 min cycling near major traffic (PM10: 64.9 μg/m^3, PM2.5: 24.6 μg/m^3, ultrafine particles: 28,180/cm^3) inhibited exercise-induced brain-derived neurotrophic factor increases in untrained individuals (0.5% increase vs. 14.4% in clean indoor air with PM10: 7.7 μg/m^3, PM2.5: 2.0 μg/m^3, ultrafine: 496/cm^3). Similarly, Cassilhas et al. [88] reported that brain-derived neurotrophic factor has increased more with indoor exercise than outdoor exercise when PM was significantly higher outdoors. Thus, lower indoor PM levels generally provide safer conditions for brain health.

Indoor VOCs trigger maladaptive brain responses through pro-inflammatory mechanisms [89]. Higher VOC concentrations occur in housing and offices [90]. Hybrid ventilation (mechanical plus open windows) removes pollutants most effectively, with mechanical ventilation plus two open windows achieving lowest concentrations [91]. Maintaining air change rates above 0.5 h^{-1} through continuous ventilation is crucial for keeping VOC levels within health guidelines [92].

Air velocity affects brain responses. Li et al. [93] tested velocities of 0.3–1.6 m/s across 24–28 °C at ≈50% relative humidity, finding 27 °C with 0.3 m/s optimal. Maruyama et al. [94] tested 0.44–4.0 m/s under hot, humid conditions (30 °C, 70% RH) and found 2.0 m/s most pleasant, while very low (0.44 m/s) and very high (4.0 m/s) velocities were least pleasant. Higher temperature and humidity require increased air velocity, with preferred ranges of 0.3–0.8 m/s for moderate temperatures and 1.0–2.0 m/s for hot conditions.

The Neurobiophilia Index recommends maintaining low PM levels indoors, using reported thresholds as guidance pending further research. The Index also emphasises eliminating VOCs through air exchange mechanisms while considering optimal air velocity for thermal comfort.

3.10. Materials

Limited research on materials and brain health suggests wood has positive effects, while high-VOC materials have deleterious effects. Wooden interiors elicit relaxed attentional engagement, higher self-reported relaxation and positive affect, and enhanced cognitive performance [71]. Touching uncoated white oak wood promotes physiological relaxation more than marble, tile, or stainless steel [95]. Wood surface features such as colour, grain, and gloss influence human responses [96]. Conversely, high-VOC materials can likely harm the brain [97,98].

4. Discussion

The development of the Neurobiophilia Index represents a pivotal advancement in integrating neuroscience with architectural design, addressing a critical gap in current biophilic tools and green building standards. The design of this index is novel, as it is not derived from or overlapping with the structure of previous biophilia tools that lacked neuroscience-informed evidence [30]. Traditional biophilic tools and frameworks often emphasise perceptual and psychological benefits, often overlooking neurobiological mechanisms like neurotrophic factors or hippocampal neurogenesis that persists into the tenth decade of human life [14]. The Neurobiophilia Index is theoretically designed to benefit a broad range of building users and vulnerable populations, is designed to be suitably inclusive, shows flexible approaches for application, addresses future research based on the identified limitations, contrasts architectural enrichment with the unclear enrichment of urban environments, and finally urges green building rating systems to incorporate it as a means to advance from sustainability to neurosustainability.

4.1. Targeted and Vulnerable Populations

The Neurobiophilia Index is theoretically designed to benefit a broad range of building users, with particular relevance for vulnerable populations who spend extensive time indoors. Contemporary lifestyles have dramatically increased indoor time, with individuals in developed nations spending approximately 90% of their time in built environments [4–7]. This unprecedented shift has profound implications for brain health, as prolonged indoor exposure often coincides with reduced environmental enrichment that may contribute to the rising rates of cognitive decline, mental health disorders, and chronic stress.

The index provides biophilic means of enrichment that can compensate when other modalities are inaccessible. For individuals with mobility limitations who cannot engage in physical activity to increase brain-derived neurotrophic factor [99,100], passive heat exposure [83], through warm rooms, saunas, or sunrooms, may offer an alternative pathway to achieve similar neurobiological benefits. People with auditory impairments, who may be at increased risk of impaired neurogenesis due to reduced auditory stimulation, can still benefit substantially from olfactory enrichment. Bright light exposure can be additive enrichment for all populations. This compensatory framework ensures that no single disability precludes access to neurobiological enrichment.

Additionally, the index addresses contemporary health challenges such as the widespread impact of COVID-19 on olfactory function across many populations [101–103], providing diverse means of enrichment.

The index also recognises age-related differences in neurobiological responsiveness. While adult hippocampal neurogenesis may decline with age [21], it persists even in the tenth decade of life [14], which makes Neurobiophilia a lifelong passive supporter of neurogenesis. Older adults, who often spend more time at home, may particularly benefit from neurobiophilic design principles. Similarly, children and adolescents, whose brains are still developing, may show heightened sensitivity to environmental enrichment, making neurobiophilic design especially critical in educational settings.

4.2. Practical Application

The Neurobiophilia Index is designed for practical application across diverse building typologies, from residential homes to offices, schools, and healthcare facilities. The index can be applied at multiple scales: individual rooms (such as living rooms or bedrooms), entire dwellings (houses or flats), and non-residential buildings (office buildings, schools, etc.). This scalability ensures that the principles of neurobiophilic design can be applied with unique design solutions for every architectural space or intended building use. Practical implementation of the index parameters can take numerous forms, offering designers flexibility while maintaining evidence-based rigour.

a. For sky visibility, solutions include installing skylights, using tilted windows to increase sky view factor, or ensuring that window placement provides adequate views of the sky's dynamic patterns.
b. Daylight can be enhanced through strategic window placement, reflective interior surfaces, and supplementary bright light therapy lamps where natural light is insufficient; yet, while avoiding discomfort glare. The 30 min daily exposure to ≥10,000 lux can be achieved through morning sunlight exposure via east-facing windows or dedicated bright light therapy devices in winter.

c. Light/dark cycles can be supported through automated lighting systems that dim to <0.1 lux at night, blackout curtains or blinds in bedrooms, and the elimination of electronic devices with light-emitting displays from sleeping areas.
d. Acoustic design might include sound-masking systems that play natural soundscapes (birdsong, flowing water) in areas where external noise is problematic, while ensuring that bedrooms and focus spaces maintain silence or very low ambient sound levels (<30 dBA).
e. Olfactory enrichment can be implemented through daily or overnight rotation of natural scent diffusers, strategic placement of aromatic plants (lavender, rosemary, mint), or garden access with cross-ventilation to bring outdoor plant odours indoors.
f. Indoor plants should occupy 13–24% of the visual field, preferably with species that provide biofiltration (such as spider plants, peace lilies, or snake plants) and that change visually across seasons.
g. Window green views require careful consideration of window-to-wall ratios (40–80% for optimal benefit), window green view index (45–75%), and greenery depth (vegetation at middle distances of 0.4–0.65 on a 0–1 scale), simultaneously encouraging spending time outdoors where environmental enrichment can be greater.
h. Temperature enrichment can be achieved through dedicated warm spaces such as sunrooms, saunas, Turkish hammams, hot tubs, or Jacuzzis that allow brief, head-protected exposure to elevated temperatures (26–36 °C). These need not be permanent fixtures; even temporary solutions such as portable infrared saunas or warm water foot baths can provide neurobiological benefits.
i. Air quality management requires cross-ventilation combined with mechanical ventilation systems, maintaining air exchange rates above 0.5 h^{-1}, with appropriate wind speeds for thermal comfort (0.3–0.8 m/s for moderate conditions, 1.0–2.0 m/s for hot, humid conditions).
j. Material selection should prioritise natural wood with low volatile organic compound (VOC) emissions, avoiding high-VOC materials such as certain paints, adhesives, and synthetic furnishings.

Importantly, the index encourages multi-enrichment strategies that leverage synergies between parameters. Indoor plants provide both visual density and olfactory stimulation while also contributing to air purification. Gardens visible through windows offer visual novelty, greenery depth, and—with cross-ventilation—natural odours and sounds. Sunrooms can simultaneously provide sky visibility, natural daylight, temperature enrichment, and window green views. These multi-parameter solutions maximise neurobiological benefits while optimising spatial efficiency and cost-effectiveness.

The index is designed to be adaptable to different cultural contexts and climatic conditions. For instance, temperature enrichment strategies that are appropriate in northern European climates (saunas) may differ from those in Mediterranean regions (hammams) or tropical climates (shaded outdoor bathing areas). Similarly, appropriate vegetation densities and species selections will vary regionally. The core neurobiological principles remain constant, but their implementation can and should be tailored to local conditions, resources, and cultural practices.

4.3. Towards Neurosustainability: Future Integration with Green Building Rating Systems

The implications of the Neurobiophilia Index are profound for architecture and green building practices. This represents an advancement of sustainability to neurosustainability [32], prioritising brain health as part of sustainability efforts.

Current green building rating systems such as LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental

Assessment Method) primarily address energy efficiency, resource conservation, and basic indoor environmental quality (air quality, thermal comfort, lighting levels). The WELL Building Standard advances beyond traditional green building by incorporating health-focused criteria. The Neurobiophilia Index provides a framework for future integration into existing rating systems as a complementary assessment tool.

The economic implications are also significant. Cognitive decline and mental health disorders impose substantial societal costs, including healthcare expenses, lost productivity, and caregiver burden. If neurobiophilic design can delay cognitive decline onset by even a few years or reduce depression incidence by a modest percentage, the population-level health and economic benefits would be considerably sustainable.

4.4. Architectural Enrichment Versus Urban Enrichment

Spending time indoors is not a substitute for outdoor environmental enrichment, nor should it be. However, the quality of the outdoor environment is another critical factor that does not make time spent outdoors a better form of enrichment per se.

Based on a comprehensive review of restricted environmental enrichment studies in rodents [104], 2–3 h of daily enriched environmental exposure appears optimal for enhancing exploratory behaviours and cognitive performance. Translating this to human contexts, where approximately 90% of time is spent indoors, suggests that at least 2–3 h daily should ideally be spent in enriched outdoor environments.

However, urban outdoor environments often fail to provide adequate enrichment. Outdoor air pollution, traffic noise, grey spaces, and lack of greenery can significantly diminish the environmental enrichment potential of urban spaces [8–19,87,105,106]. These harsh conditions often suggest that urban environments with the aforementioned conditions may worsen or intensify complex mental disorders [107].

Therefore, it is vitally important to provide architectural enrichment using the Neurobiophilia Index principles, while simultaneously advocating for the same neurobiophilic design considerations in urban design. Indoor spaces must be designed to compensate for reduced outdoor time and to provide neurobiological support during the substantial portion of life spent within buildings. Concurrently, urban designers should follow similar principles. The goal is not to replace outdoor time with indoor enrichment but to ensure that both indoor and outdoor environments are enriched.

4.5. Limitations and Future Research Recommendations

While the Neurobiophilia Index represents a rigorous, evidence-based framework for neurosustainable design, several limitations must be acknowledged alongside a clear research agenda for future validation and refinement.

The methodology employed in developing this index was necessitated by the current state of the evidence base. A systematic review with meta-analysis was not feasible due to several factors. First, the multi-item nature of the index spans diverse environmental parameters that are rarely studied together in controlled experiments. Second, the evidence comes from multiple species (humans, rats, mice), making direct quantitative synthesis challenging (Figure 2). Third, the number of available studies for some parameters is limited, particularly for human neuroimaging or biomarker studies that directly measure hippocampal neurogenesis or brain-derived neurotrophic factor in response to architectural features. These methodological constraints do not invalidate the index but rather highlight the need for future empirical research specifically designed to test its predictions. The index provides testable hypotheses that can now be systematically investigated through controlled experiments and field studies.

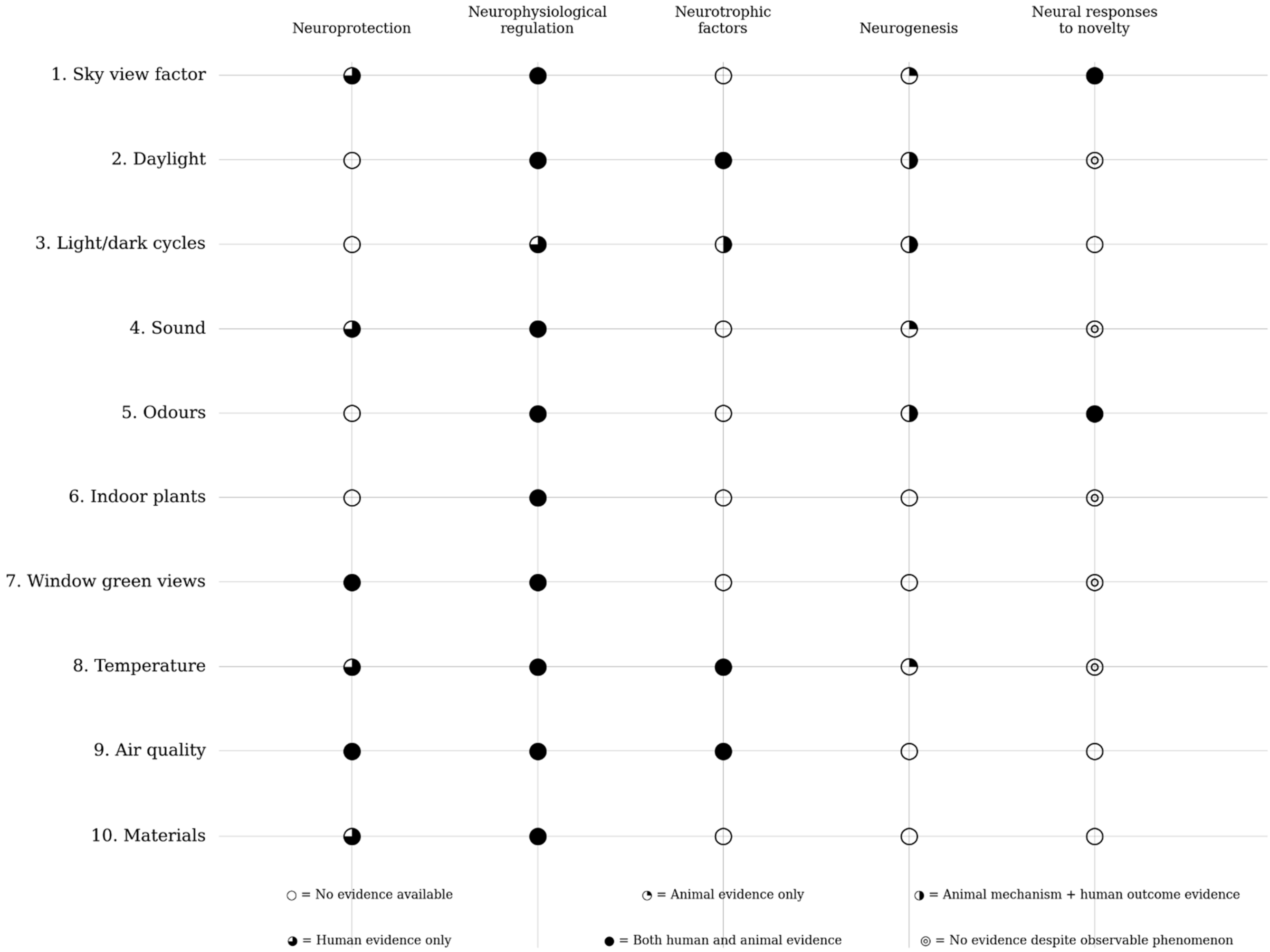

Figure 2. The Neurobiophilia Index: Cross-species evidence supporting the interrelationships between environmental enrichment and the brain's 5NNs.

The parameter ranges proposed in the index aim to accommodate variability, but optimal conditions within those ranges may differ across climates, cultures, and individual characteristics. Thermal preferences, acceptable vegetation densities, and acoustic comfort levels may vary between regions. For instance, appropriate temperature ranges for enrichment may differ across regions and cultures. Similarly, acceptable soundscape compositions may vary culturally, with some populations preferring more bustling acoustic environments and others favouring tranquillity. Still, it is expected that preferences should still fall within the provided broad enrichment ranges in the Neurobiophilia Index.

The index provides general parameters applicable to typical populations but does not yet account for individual differences comprehensively. Age, health status, and prior environmental exposures may influence individual responses to architectural enrichment in future applications. Future work should explore adaptations for specific groups, such as children in schools, older adults in residential care, or clinical populations recovering from neurological or psychiatric conditions.

Therefore, the Neurobiophilia Index can evolve through region-specific calibrations while maintaining its core neurobiological principles. Several research approaches are recommended:

1. The long-term effects of inhabiting buildings, as measured by the Neurobiophilia Index, can be assessed through longitudinal or cross-sectional studies that examine

changes in brain volume or function using structural or functional magnetic resonance imaging (MRI).

2. The acute exposure to buildings with contrasting scores provided by the Neurobiophilia Index can be tested using MRI to determine changes in amygdala activity or subiculum volume, using electroencephalography (EEG), in blood oxygenation levels using Functional Near-Infrared Spectroscopy (fNIRS), or serum/plasma brain-derived neurotrophic factor (BDNF) concentrations. For BDNF concentrations, it is recommended that testing be performed in blood serum or plasma, as the reliability of salivary assays varies [108–111]. However, using either method, peripheral concentrations are proxy measures of BDNF in the central nervous system in humans, as it is not feasible to test it in living humans [112].
3. Direct measurement of adult hippocampal neurogenesis in living humans is not feasible, but it can be done using postmortem samples in longitudinal studies. Otherwise, proxy measures of neurogenesis-relevant outcomes in healthy humans can be used, such as Alzheimer's disease and major depressive disorder.

While the Neurobiophilia Index has limitations inherent to its development, these limitations do not preclude its use. Rather, they indicate a research agenda that can progressively refine and validate the index. The current framework provides sufficient evidence-based guidance to begin implementing neurobiophilic design principles in different geographical contexts with different cultures or demographics. Sub-versions of the Neurobiophilia Index can evolve accordingly. Given the risk of cognitive decline and mental health disorders, and the substantial time spent indoors, the Neurobiophilia Index offers a timely, evidence-based approach for neurosustainability.

5. Conclusions

This study establishes the Neurobiophilia Index, a quantitative tool for assessing environmental enrichment at the architectural scale based on neurobiological evidence. The index theoretically provides ten evidence-based parameters: sky visibility, daylight, light/dark cycles, sound, odours, indoor plants, window green views, temperature, air quality, and materials. The index addresses a gap in current biophilic design tools that lacked neuroscience-informed evidence. Integration of the Neurobiophilia Index with green building rating systems would advance the field from sustainability to neurosustainability. Future empirical research can validate the index for specific populations while the current framework provides sufficient evidence-based guidance to begin implementing neurobiophilic design principles.

Author Contributions: Conceptualization, M.H.K.; methodology, M.H.K. and K.S.; validation, M.H.K. and K.S.; formal analysis, M.H.K.; investigation, M.H.K.; writing—original draft preparation, M.H.K. and K.S.; writing—review and editing, M.H.K.; visualization, M.H.K.; supervision, K.S.; project administration, M.H.K.; Funding acquisition, M.H.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research is part of a PhD thesis funded by Cambridge Commonwealth, European and International Trust and the Jameel Education Foundation.

Data Availability Statement: The original contributions presented in this study are included in the article.

Acknowledgments: The first author expresses his gratitude to the Cambridge Commonwealth, European and International Trust and the Jameel Education Foundation for funding his doctoral thesis and covering the open-access publication fees for this article. We also thank the experts who shared their valuable opinions, which helped refine the interpretations.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Soga, M.; Gaston, K.J. Global synthesis reveals heterogeneous changes in connection of humans to nature. *One Earth* **2023**, *6*, 131–138. [CrossRef]
2. Ritchie, H.; Samborska, V.; Roser, M. Urbanization. Our World in Data. 2024. Available online: https://ourworldindata.org/urbanization (accessed on 20 January 2026).
3. Richardson, M. Modelling nature connectedness within environmental systems: Human-nature relationships from 1800 to 2020 and beyond. *Earth* **2025**, *6*, 82. [CrossRef]
4. Klepeis, N.E.; Nelson, W.C.; Ott, W.R.; Robinson, J.P.; Tsang, A.M.; Switzer, P.; Behar, J.V.; Hern, S.C.; Engelmann, W.H. The National Human Activity Pattern Survey (NHAPS): A resource for assessing exposure to environmental pollutants. *J. Expo. Sci. Environ. Epidemiol.* **2001**, *11*, 231–252. [CrossRef]
5. Sharkey, P. Homebound: The long-term rise in time spent at home among US adults. *Sociol. Sci.* **2024**, *11*, 553–578. [CrossRef]
6. Shi, H.; Goulias, K.G. Long-term effects of COVID-19 on time allocation, travel behavior, and shopping habits in the United States. *J. Transp. Health* **2024**, *34*, 101730. [CrossRef]
7. Morris, E.A.; Speroni, S.; Taylor, B.D. Going nowhere faster: Did the COVID-19 pandemic accelerate the trend toward staying home? *J. Am. Plan. Assoc.* **2025**, *91*, 361–379. [CrossRef]
8. Kühn, S.; Schmalen, K.; Beijers, R.; Tyborowska, A.; Roelofs, K.; Weerth, C.D. Green is not the same as green: Differentiating between the Association of Trees and Open Green Spaces with Children's brain structure in the Netherlands. *Environ. Behav.* **2023**, *55*, 311–334. [CrossRef]
9. Kühn, S.; Düzel, S.; Mascherek, A.; Eibich, P.; Krekel, C.; Kolbe, J.; Goebel, J.; Gallinat, J.; Wagner, G.G.; Lindenberger, U. Urban green is more than the absence of city: Structural and functional neural basis of urbanicity and green space in the neighbourhood of older adults. *Landsc. Urban Plan.* **2021**, *214*, 104196. [CrossRef]
10. Kühn, S.; Banaschewski, T.; Bokde, A.L.; Buechel, C.; Quinlan, E.B.; Desrivieres, S.; Flor, H.; Grigis, A.; Garavan, H.; Gowland, P.; et al. Trees for brains: Current residential tree cover density and its association with brain structure in young adults. *J. Environ. Psychol.* **2023**, *89*, 102047. [CrossRef]
11. Sudimac, S.; Sale, V.; Kühn, S. How nature nurtures: Amygdala activity decreases as the result of a one-hour walk in nature. *Mol. Psychiatry* **2022**, *27*, 4446–4452. [CrossRef]
12. Sudimac, S.; Kühn, S. Can a nature walk change your brain? Investigating hippocampal brain plasticity after one hour in a forest. *Environ. Res.* **2024**, *262*, 119813. [CrossRef]
13. Khalil, M.H. Green Environments for Sustainable Brains: Parameters Shaping Adaptive Neuroplasticity and Lifespan Neurosustainability—A Systematic Review and Future Directions. *Int. J. Environ. Res. Public Health* **2025**, *22*, 690. [CrossRef] [PubMed]
14. Moreno-Jiménez, E.P.; Terreros-Roncal, J.; Flor-García, M.; Rábano, A.; Llorens-Martín, M. Evidences for adult hippocampal neurogenesis in humans. *J. Neurosci.* **2021**, *41*, 2541–2553. [CrossRef]
15. Tobin, M.K.; Musaraca, K.; Disouky, A.; Shetti, A.; Bheri, A.; Honer, W.G.; Kim, N.; Dawe, R.J.; Bennett, D.A.; Arfanakis, K.; et al. Human hippocampal neurogenesis persists in aged adults and Alzheimer's disease patients. *Cell Stem Cell* **2019**, *24*, 974–982. [CrossRef]
16. Moreno-Jiménez, E.P.; Flor-García, M.; Terreros-Roncal, J.; Rábano, A.; Cafini, F.; Pallas-Bazarra, N.; Ávila, J.; Llorens-Martín, M. Adult hippocampal neurogenesis is abundant in neurologically healthy subjects and drops sharply in patients with Alzheimer's disease. *Nat. Med.* **2019**, *25*, 554–560. [CrossRef] [PubMed]
17. Márquez-Valadez, B.; Gallardo-Caballero, M.; Llorens-Martín, M. Human adult hippocampal neurogenesis is shaped by neuropsychiatric disorders, demographics, and lifestyle-related factors. *Cell Stem Cell* **2025**, *32*, 1577–1594. [CrossRef] [PubMed]
18. Berger, T.; Lee, H.; Young, A.H.; Aarsland, D.; Thuret, S. Adult hippocampal neurogenesis in major depressive disorder and Alzheimer's disease. *Trends Mol. Med.* **2020**, *26*, 803–818. [CrossRef]
19. Alonso, M.; Petit, A.C.; Lledo, P.M. The impact of adult neurogenesis on affective functions: Of mice and men. *Mol. Psychiatry* **2024**, *29*, 2527–2542. [CrossRef]
20. Surget, A.; Belzung, C. Adult hippocampal neurogenesis shapes adaptation and improves stress response: A mechanistic and integrative perspective. *Mol. Psychiatry* **2022**, *27*, 403–421.
21. Spalding, K.L.; Bergmann, O.; Alkass, K.; Bernard, S.; Salehpour, M.; Huttner, H.B.; Boström, E.; Westerlund, I.; Vial, C.; Buchholz, B.A.; et al. Dynamics of hippocampal neurogenesis in adult humans. *Cell* **2013**, *153*, 1219–1227. [CrossRef]
22. Zhou, Y.; Su, Y.; Yang, Q.; Li, J.; Hong, Y.; Gao, T.; Zhong, Y.; Ma, X.; Jin, M.; Liu, X.; et al. Cross-species analysis of adult hippocampal neurogenesis reveals human-specific gene expression but convergent biological processes. *Nat. Neurosci.* **2025**, *28*, 1820–1829. [CrossRef]

23. Fujioka, A.; Fujioka, T.; Tsuruta, R.; Izumi, T.; Kasaoka, S.; Maekawa, T. Effects of a constant light environment on hippocampal neurogenesis and memory in mice. *Neurosci. Lett.* **2011**, *488*, 41–44. [CrossRef]
24. Kwon, S.J.; Park, J.; Park, S.Y.; Song, K.S.; Jung, S.T.; Jung, S.B.; Park, I.R.; Choi, W.S.; Kwon, S.O. Low-intensity treadmill exercise and/or bright light promote neurogenesis in adult rat brain. *Neural Regen. Res.* **2013**, *8*, 922–929. [PubMed]
25. Hirakawa, H.; Terao, T.; Hatano, K.; Shirahama, M.; Kugimiya, T.; Kohno, K.; Matsuta, H.; Shimomura, T.; Fujiki, M. Increased volume of the left hippocampal dentate gyrus after 4 weeks of bright light exposure in patients with mood disorders: A randomized controlled study. *Transl. Psychiatry* **2023**, *13*, 394. [CrossRef] [PubMed]
26. Koyama, Y.; Mukuda, T.; Hamasaki, S.; Nakane, H.; Kaidoh, T. Short-term heat exposure promotes hippocampal neurogenesis via activation of angiotensin II type 1 receptor in adult rats. *Neuroscience* **2018**, *385*, 121–132. [CrossRef] [PubMed]
27. Zhu, X.; Huang, J.; Wu, Y.; Zhao, S.; Chai, X. Effect of heat stress on hippocampal neurogenesis: Insights into the cellular and molecular basis of neuroinflammation-induced deficits. *Cell. Mol. Neurobiol.* **2023**, *43*, 1–13. [CrossRef]
28. Khalil, M.H.; Steemers, K. Neurobiophilia. *Brain Sci.* **2026**, *16*, 85. [CrossRef]
29. Wilson, E.O. *Biophilia*; Harvard University Press: Cambridge, MA, USA, 1986.
30. Tekin, B.H.; Izmir Tunahan, G.; Disci, Z.N.; Ozer, H.S. Biophilic design in the built environment: Trends, gaps and future directions. *Buildings* **2025**, *15*, 2516. [CrossRef]
31. Lefosse, D.C.; Duarte, F.; Sanatani, R.P.; Kang, Y.; van Timmeren, A.; Ratti, C. Feeling Nature: Measuring perceptions of biophilia across global biomes using visual AI. *npj Urban Sustain.* **2025**, *5*, 4. [CrossRef]
32. Khalil, M.H. Neurosustainability. *Front. Hum. Neurosci.* **2024**, *18*, 1436179.
33. Yasukouchi, A.; Maeda, T.; Hara, K.; Furuune, H. Non-visual effects of diurnal exposure to an artificial skylight, including nocturnal melatonin suppression. *J. Physiol. Anthropol.* **2019**, *38*, 10. [CrossRef]
34. Schöllhorn, I.; Deuring, G.; Stefani, O.; Strumberger, M.A.; Rosburg, T.; Lemoine, P.; Pross, A.; Wingert, B.; Mager, R.; Cajochen, C. Effects of nature-adapted lighting solutions ("Virtual Sky") on subjective and objective correlates of sleepiness, well-being, visual and cognitive performance at the workplace. *PLoS ONE* **2023**, *18*, e0288690. [CrossRef]
35. Ramírez-Rodríguez, G.B.; Gutiérrez-Vera, B.; Ortiz-López, L.; Vega-Rivera, N.M.; Meneses-San Juan, D.; Granados-Juárez, A.; Aquino, D.V.C.-D.; Castro-García, M.; Ramos, M.F. Environmental enrichment: Dissociated effects between physical activity and changing environmental complexity on anxiety and neurogenesis in adult male Balb/C mice. *Physiol. Behav.* **2022**, *254*, 113878. [CrossRef] [PubMed]
36. Seok, J.W.; Kim, J.D. Light Therapy for Older People with Depressive Symptoms: Systematic Review and Meta-Analysis. *J. Clin. Med.* **2024**, *13*, 6982. [CrossRef] [PubMed]
37. Boldrini, M.; Hen, R.; Underwood, M.D.; Rosoklija, G.B.; Dwork, A.J.; Mann, J.J.; Arango, V. Hippocampal angiogenesis and progenitor cell proliferation are increased with antidepressant use in major depression. *Biol. Psychiatry* **2012**, *72*, 562–571. [CrossRef]
38. Molendijk, M.L.; Haffmans, J.P.; Bus, B.A.; Spinhoven, P.; Penninx, B.W.; Prickaerts, J.; Voshaar, R.C.O.; Elzinga, B.M. Serum BDNF concentrations show strong seasonal variation and correlations with the amount of ambient sunlight. *PLoS ONE* **2012**, *7*, e48046. [CrossRef]
39. Payedar-Ardakani, P.; Gorji-Mahlabani, Y.; Ghanbaran, A.H.; Ebrahimpour, R. The impact of changes in daylight illuminance levels on architectural experiences in office environments using virtual reality and electroencephalogram. *J. Build. Eng.* **2024**, *96*, 110487. [CrossRef]
40. Tong, L.; Liu, N.; Hu, S.; Lu, M.; Zheng, Y.; Ma, X. Research on the preferred illuminance in office environments based on EEG. *Buildings* **2023**, *13*, 467. [CrossRef]
41. Li, H.; Cui, F.; Wang, T.; Wang, W.; Zhang, D. The impact of sunlight exposure on brain structural markers in the UK Biobank. *Sci. Rep.* **2024**, *14*, 10313. [CrossRef]
42. Yoon, K.N.; Kim, S.Y.; Ji, J.; Cui, Y.; Quan, Q.L.; Park, G.; Oh, J.-H.; Lee, J.S.; An, J.-Y.; Chung, J.H.; et al. Chronic ultraviolet irradiation induces memory deficits via dysregulation of the dopamine pathway. *Exp. Mol. Med.* **2024**, *56*, 1401–1411. [CrossRef]
43. Walker, W.H.; Borniger, J.C.; Gaudier-Diaz, M.M.; Hecmarie Meléndez-Fernández, O.; Pascoe, J.L.; Courtney DeVries, A.; Nelson, R.J. Acute exposure to low-level light at night is sufficient to induce neurological changes and depressive-like behavior. *Mol. Psychiatry* **2020**, *25*, 1080–1093. [CrossRef]
44. Fonken, L.K.; Kitsmiller, E.; Smale, L.; Nelson, R.J. Dim nighttime light impairs cognition and provokes depressive-like responses in a diurnal rodent. *J. Biol. Rhythm.* **2012**, *27*, 319–327. [CrossRef]
45. Namgyal, D.; Chandan, K.; Sultan, A.; Aftab, M.; Ali, S.; Mehta, R.; El-Serehy, H.A.; Al-Misned, F.A.; Sarwat, M. Dim light at night induced neurodegeneration and ameliorative effect of curcumin. *Cells* **2020**, *9*, 2093. [CrossRef]
46. Sangma, J.T.; Trivedi, A.K. Light at night: Effect on the daily clock, learning, memory, cognition, and expression of transcripts in different brain regions of rat. *Photochem. Photobiol. Sci.* **2023**, *22*, 2297–2314. [CrossRef] [PubMed]

https://doi.org/10.3390/buildings16030637

47. Brown, T.M.; Brainard, G.C.; Cajochen, C.; Czeisler, C.A.; Hanifin, J.P.; Lockley, S.W.; Lucas, R.J.; Münch, M.; O'hAgan, J.B.; Peirson, S.N.; et al. Recommendations for daytime, evening, and nighttime indoor light exposure to best support physiology, sleep, and wakefulness in healthy adults. *PLoS Biol.* **2022**, *20*, e3001571. [CrossRef] [PubMed]
48. Levels, R.L. Recommended Light Levels (Illuminance) for Outdoor and Indoor Venues. The Engineering Toolbox. Recommended Light Levels. 2020. Available online: https://www.engineeringtoolbox.com/light-level-rooms-d_708.html (accessed on 20 January 2026).
49. Zeng, C.; Lin, W.; Li, N.; Wen, Y.; Wang, Y.; Jiang, W.; Zhang, J.; Zhong, H.; Chen, X.; Luo, W.; et al. Electroencephalography (EEG)-based neural emotional response to the vegetation density and integrated sound environment in a green space. *Forests* **2021**, *12*, 1380. [CrossRef]
50. Bai, Z.; Zhang, S. Effects of different natural soundscapes on human psychophysiology in national forest park. *Sci. Rep.* **2024**, *14*, 17462. [CrossRef]
51. Gould van Praag, C.D.; Garfinkel, S.N.; Sparasci, O.; Mees, A.; Philippides, A.O.; Ware, M.; Ottaviani, C.; Critchley, H.D. Mind-wandering and alterations to default mode network connectivity when listening to naturalistic versus artificial sounds. *Sci. Rep.* **2017**, *7*, 45273. [CrossRef]
52. Li, H.; Xie, H.; Woodward, G. Soundscape components, perceptions, and EEG reactions in typical mountainous urban parks. *Urban For. Urban Green.* **2021**, *64*, 127269. [CrossRef]
53. Frescura, A.; Lee, P.J.; Jeong, J.H.; Soeta, Y. EEG alpha wave responses to sounds from neighbours in high-rise wood residential buildings. *Build. Environ.* **2023**, *242*, 110560. [CrossRef]
54. Zhang, X.; Shu, R.; Dong, J.; Hu, S.; Tong, Z.; Zhang, X.; Guan, H. Effects of nature sounds at different sound levels on the recovery from noise-induced stress. *Build. Environ.* **2025**, *285*, 113573. [CrossRef]
55. Dai, X.J.; Liao, J.H.; Jia, Y.; Cao, R.; Zhou, M.N. Noise Exposure Promotes Alzheimer's Disease–Like Lesions and DNA Damage. *Noise Health* **2024**, *26*, 287–293. [CrossRef]
56. Kirste, I.; Nicola, Z.; Kronenberg, G.; Walker, T.L.; Liu, R.C.; Kempermann, G. Is silence golden? Effects of auditory stimuli and their absence on adult hippocampal neurogenesis. *Brain Struct. Funct.* **2015**, *220*, 1221–1228.
57. Kraus, K.S.; Mitra, S.; Jimenez, Z.; Hinduja, S.; Ding, D.; Jiang, H.; Gray, L.; Lobarinas, E.; Sun, W.; Salvi, R. Noise trauma impairs neurogenesis in the rat hippocampus. *Neuroscience* **2010**, *167*, 1216–1226. [CrossRef]
58. Liu, L.; Shen, P.; He, T.; Chang, Y.; Shi, L.; Tao, S.; Li, X.; Xun, Q.; Guo, X.; Yu, Z.; et al. Noise induced hearing loss impairs spatial learning/memory and hippocampal neurogenesis in mice. *Sci. Rep.* **2016**, *6*, 20374. [CrossRef]
59. Kurioka, T.; Mogi, S.; Yamashita, T. Decreasing auditory input induces neurogenesis impairment in the hippocampus. *Sci. Rep.* **2021**, *11*, 423. [CrossRef] [PubMed]
60. Rusznák, Z.; Sengul, G.; Paxinos, G.; Kim, W.S.; Fu, Y. Odor enrichment increases hippocampal neuron numbers in mouse. *Exp. Neurobiol.* **2018**, *27*, 94. [CrossRef] [PubMed]
61. Veyrac, A.; Sacquet, J.; Nguyen, V.; Marien, M.; Jourdan, F.; Didier, A. Novelty determines the effects of olfactory enrichment on memory and neurogenesis through noradrenergic mechanisms. *Neuropsychopharmacology* **2009**, *34*, 786–795. [CrossRef]
62. Woo, C.C.; Miranda, B.; Sathishkumar, M.; Dehkordi-Vakil, F.; Yassa, M.A.; Leon, M. Overnight olfactory enrichment using an odorant diffuser improves memory and modifies the uncinate fasciculus in older adults. *Front. Neurosci.* **2023**, *17*, 1200448. [CrossRef]
63. Tong, Z.; Liu, X.; Song, Y.; Guan, H.; Wen, X.; Hu, S.; Lu, M. The influence of odors on cognitive performance based on different olfactory preferences. *Build. Environ.* **2025**, *271*, 112603. [CrossRef]
64. Sayorwan, W.; Siripornpanich, V.; Piriyapunyaporn, T.; Hongratanaworakit, T.; Kotchabhakdi, N.; Ruangrungsi, N. The effects of lavender oil inhalation on emotional states, autonomic nervous system, and brain electrical activity. *J. Med. Assoc. Thai* **2012**, *95*, 598–606.
65. Zhang, X.; Guo, J.; Zhang, X.; Zhang, Q. Physiological effects of a garden plant smellscape from the perspective of perceptual interaction. *Int. J. Environ. Res. Public Health* **2023**, *20*, 5004. [CrossRef] [PubMed]
66. Rhee, J.H.; Schermer, B.; Han, G.; Park, S.Y.; Lee, K.H. Effects of nature on restorative and cognitive benefits in indoor environment. *Sci. Rep.* **2023**, *13*, 13199. [CrossRef] [PubMed]
67. Rhee, J.H.; Schermer, B.; Cha, S.H. Effects of indoor vegetation density on human well-being for a healthy built environment. *Dev. Built Environ.* **2023**, *14*, 100172. [CrossRef]
68. Hassan, A.; Chen, Q.B.; Liu, Y.G.; Jiang, T.; Guo, L.; Mingyan, J.; Li, N.; Ly, B.-Y.; Liu, S.L. Do plants affect brainwaves? Effect of indoor plants in work environment on mental stress. *Eur. J. Hortic. Sci.* **2020**, *85*, 279–283. [CrossRef]
69. Soreanu, G.; Dixon, M.; Darlington, A. Botanical biofiltration of indoor gaseous pollutants–A mini-review. *Chem. Eng. J.* **2013**, *229*, 585–594. [CrossRef]
70. Mannan, M.; Al-Ghamdi, S.G. Active botanical biofiltration in built environment to maintain indoor air quality. *Front. Built Environ.* **2021**, *7*, 672102. [CrossRef]

71. Kim, S. Cognitive efficiency in VR simulated natural indoor environments examined through EEG and affective responses. *Sci. Rep.* **2025**, *15*, 33398. [CrossRef]
72. Binarti, F.; Sekarlangi, N.; Brilianto, M.K.V.; Hakim, B.R. EEG-Based Neurophysiological Responses to Classroom Window Views in Green Campus Settings. *J. Daylighting* **2025**, *12*, 359–374. [CrossRef]
73. Jing, X.; Liu, C.; Li, J.; Gao, W.; Fukuda, H. Effects of window green view index on stress recovery of college students from psychological and physiological aspects. *Buildings* **2024**, *14*, 3316. [CrossRef]
74. Wang, Y.; Wang, D.; Zhang, X. Higher greenery visibility is not necessarily better: A quantitative approach to evaluating window view quality in residential buildings. *Build. Environ.* **2025**, *285*, 113563. [CrossRef]
75. Kim, S.; Park, H.; Choo, S. Effects of changes to architectural elements on human relaxation-arousal responses: Based on VR and EEG. *Int. J. Environ. Res. Public Health* **2021**, *18*, 4305. [CrossRef] [PubMed]
76. Zhang, Z.; Li, Z.; Xu, J. Study on window size and indoor color of typical residential units based on EEG measurement and semantic differential method coupling analysis. *Energy Build.* **2025**, *342*, 115855. [CrossRef]
77. Wang, Z.; Yang, Y.; Liu, C.; Zhou, F.; Hao, H. Human thermal comfort model and evaluation on building thermal environment. *Energy Build.* **2024**, *323*, 114796. [CrossRef]
78. Kirby, N.V.; Meade, R.D.; Mccormick, J.J.; King, K.E.; Notley, S.R.; Kenny, G.P. Brain-derived neurotrophic factor in older adults exposed to simulated indoor overheating. *Eur. J. Appl. Physiol.* **2025**, *125*, 769–780.
79. Goulet, N.; McCormick, J.J.; King, K.E.; Notley, S.R.; Goldfield, G.S.; Fujii, N.; Amano, T.; Kenny, G.P. Elevations in serum brain-derived neurotrophic factor following occupational heat stress are not influenced by age or common chronic disease. *Temperature* **2023**, *10*, 454–464. [CrossRef] [PubMed]
80. Hossain, E.; Matsuzaki, K.; Katakura, M.; Sugimoto, N.; Al Mamun, A.; Islam, R.; Hashimoto, M.; Shido, O. Direct exposure to mild heat promotes proliferation and neuronal differentiation of neural stem/progenitor cells in vitro. *PLoS ONE* **2017**, *12*, e0190356.
81. Choi, Y.; Kim, M.; Chun, C. Measurement of occupants' stress based on electroencephalograms (EEG) in twelve combined environments. *Build. Environ.* **2015**, *88*, 65–72. [CrossRef]
82. Huo, J.; Qin, H.; Hong, D.; Niu, J.; Wu, H.; Wei, X.; Han, G.; Yan, J.; Liu, Z. The physiological restorative effects in changing air temperature among various landscape composition of green spaces during summer: Empirical evidence from Chongqing, China. *Ecol. Indic.* **2025**, *175*, 113537. [CrossRef]
83. Kojima, D.; Nakamura, T.; Banno, M.; Umemoto, Y.; Kinoshita, T.; Ishida, Y.; Tajima, F. Head-out immersion in hot water increases serum BDNF in healthy males. *Int. J. Hyperth.* **2018**, *34*, 834–839.
84. Kirby, N.V.; Meade, R.D.; McCormick, J.J.; King, K.E.; Kenny, G.P. Brain-derived neurotrophic factor response to daylong exposure to extreme heat in young and older adults: A secondary analysis. *Appl. Physiol. Nutr. Metab.* **2025**, *50*, 1–9. [CrossRef]
85. Chauhan, N.R.; Kumar, R.; Gupta, A.; Meena, R.C.; Nanda, S.; Mishra, K.P.; Singh, S.B. Heat stress induced oxidative damage and perturbation in BDNF/ERK1/2/CREB axis in hippocampus impairs spatial memory. *Behav. Brain Res.* **2021**, *396*, 112895.
86. Piil, J.F.; Christiansen, L.; Morris, N.B.; Mikkelsen, C.J.; Ioannou, L.G.; Flouris, A.D.; Lundbye-Jensen, J.; Nybo, L. Direct exposure of the head to solar heat radiation impairs motor-cognitive performance. *Sci. Rep.* **2020**, *10*, 7812. [CrossRef] [PubMed]
87. Bos, I.; Jacobs, L.; Nawrot, T.S.; De Geus, B.; Torfs, R.; Panis, L.I.; Degraeuwe, B.; Meeusen, R. No exercise-induced increase in serum BDNF after cycling near a major traffic road. *Neurosci. Lett.* **2011**, *500*, 129–132. [CrossRef]
88. Cassilhas, R.C.; De Sousa, R.A.L.; Caxa, L.; Viana, V.; Meeusen, R.; Goncalves, F.L.; e Magalhães, C.O.D.; Tufik, S.; Peixoto, M.F.D.; Junior, R.S.M.; et al. Indoor aerobic exercise reduces exposure to pollution, improves cognitive function, and enhances BDNF levels in the elderly. *Air Qual. Atmos. Health* **2022**, *15*, 35–45. [CrossRef]
89. Ogbodo, J.O.; Arazu, A.V.; Iguh, T.C.; Onwodi, N.J.; Ezike, T.C. Volatile organic compounds: A proinflammatory activator in autoimmune diseases. *Front. Immunol.* **2022**, *13*, 928379. [CrossRef]
90. Paciência, I.; Madureira, J.; Rufo, J.; Moreira, A.; Fernandes, E.D.O. A systematic review of evidence and implications of spatial and seasonal variations of volatile organic compounds (VOC) in indoor human environments. *J. Toxicol. Environ. Health Part B* **2016**, *19*, 47–64.
91. Gholampour, M.; Taghipour, M.; Tahavvor, A.; Jafari, S. Statistical analysis of natural and mechanical ventilation performance in improving indoor air quality, thermal comfort, and perceived air quality in a healthcare facility. *Int. J. Vent.* **2025**, *24*, 166–187.
92. Park, S.; Kagi, N.; Umishio, W.; Shinohara, N.; Kim, H. Influence of mechanical ventilation systems on indoor VOC concentrations in residential buildings. *J. Asian Archit. Build. Eng.* **2025**, 1–21. [CrossRef]
93. Li, W.; Peng, P.; Wang, T.; Gong, G. Effects of indoor environment on EEG and thermal comfort under the ceiling-fan-integrated air conditioning system. *Build. Environ.* **2024**, *257*, 111547.
94. Maruyama, Y.; Nakamura, R.; Tsuji, S.; Xuan, Y.; Mizutani, K.; Okaze, T.; Yoshimura, N. Classification of pleasantness of wind by electroencephalography. *PLoS ONE* **2024**, *19*, e0299036. [CrossRef]
95. Ikei, H.; Song, C.; Miyazaki, Y. Physiological effects of touching wood. *Int. J. Environ. Res. Public Health* **2017**, *14*, 801. [PubMed]

96. Wan, Q.; Li, X.; Zhang, Y.; Song, S.; Ke, Q. Visual perception of different wood surfaces: An event-related potentials study. *Ann. For. Sci.* **2021**, *78*, 25. [CrossRef]
97. Sun, J.; Zhou, X.; Xiao, C.; Li, Z.; Xu, C.; Qin, X.; Lu, J.; Wu, Y.; Cheng, J.; Chen, S.; et al. Prenatal exposure to indoor VOCs impairs synaptic plasticity and cognitive function in mouse offspring via retinol metabolism disorder. *J. Hazard. Mater.* **2025**, *501*, 140688. [CrossRef]
98. Madaniyazi, L.; Jung, C.R.; Ng, C.F.S.; Seposo, X.; Hashizume, M.; Nakayama, S.F. Early life exposure to indoor air pollutants and the risk of neurodevelopmental delays: The Japan Environment and Children's Study. *Environ. Int.* **2022**, *158*, 107004. [CrossRef]
99. Park, S.A.; Lee, A.Y.; Park, H.G.; Lee, W.L. Benefits of gardening activities for cognitive function according to measurement of brain nerve growth factor levels. *Int. J. Environ. Res. Public Health* **2019**, *16*, 760. [CrossRef]
100. Khalil, M.H.; Steemers, K. Brain Booster Buildings: Modelling Stair Use as a Daily Booster of Brain-Derived Neurotrophic Factor. *Buildings* **2025**, *15*, 3730. [CrossRef]
101. Kim, S.; Finlay, J.B.; Ko, T.; Goldstein, B.J. Long-term olfactory loss post-COVID-19: Pathobiology and potential therapeutic strategies. *World J. Otorhinolaryngol.-Head Neck Surg.* **2024**, *10*, 148–155. [CrossRef]
102. Dumas, L.E.; Vandersteen, C.; Metelkina-Fernandez, V.; Gros, A.; Auby, P.; Askenazy-Gittard, F. Impact of post-COVID-19 olfactory disorders on quality of life, hedonic experiences and psychiatric dimensions in general population. *BMC Psychiatry* **2024**, *24*, 111. [CrossRef]
103. Stigliano, E.; Tocci, A.; Florio, R.; Arena, V.; Amadoro, G. Olfactory Dysfunction and Cognitive Deterioration in Long COVID: Pathomechanisms and Clinical Implications in Development of Alzheimer's Disease. *Cells* **2026**, *15*, 176. [CrossRef] [PubMed]
104. Nik Ramli, N.N.; Kamarul Sahrin, N.A.; Nasarudin, S.N.A.Z.; Hashim, M.H.; Abdul Mutalib, M.; Mohamad Alwi, M.N.; Rashed, A.A.; Ramasamy, R. Restricted Daily Exposure of Environmental Enrichment: Bridging the Practical Gap from Animal Studies to Human Application. *Int. J. Environ. Res. Public Health* **2024**, *21*, 1584. [CrossRef]
105. Pu, F.; Chen, W.; Li, C.; Fu, J.; Gao, W.; Ma, C.; Cao, X.; Zhang, L.; Hao, M.; Zhou, J.; et al. Heterogeneous associations of multiplexed environmental factors and multidimensional aging metrics. *Nat. Commun.* **2024**, *15*, 4921. [CrossRef] [PubMed]
106. Harris, J.C.; Liuzzi, M.T.; Cardenas-Iniguez, C.; Larson, C.L.; Lisdahl, K.M. Gray space and default mode network-amygdala connectivity. *Front. Hum. Neurosci.* **2023**, *17*, 1167786. [CrossRef] [PubMed]
107. Khalil, M.H. Borderline in a linear city: Urban living brings borderline personality disorder to crisis through neuroplasticity—An urgent call to action. *Front. Psychiatry* **2025**, *15*, 1524531. [CrossRef]
108. Vrijen, C.; Schenk, H.M.; Hartman, C.A.; Oldehinkel, A.J. Measuring BDNF in saliva using commercial ELISA: Results from a small pilot study. *Psychiatry Res.* **2017**, *254*, 340–346. [CrossRef]
109. Mandel, A.L.; Ozdener, H.; Utermohlen, V. Brain-derived neurotrophic factor in human saliva: ELISA optimization and biological correlates. *J. Immunoass. Immunochem.* **2011**, *32*, 18–30. [CrossRef] [PubMed]
110. Tirassa, P.; Iannitelli, A.; Sornelli, F.; Cirulli, F.; Mazza, M.; Calza, A.; Alleva, E.; Branchi, I.; Aloe, L.; Bersani, G.; et al. Daily serum and salivary BDNF levels correlate with morning-evening personality type in women and are affected by light therapy. *Riv. Psichiatr.* **2012**, *47*, 527–534. [CrossRef]
111. Evelis, K.; Kolesovs, A.; Rostoka, E.; Plakane, L. Acute high-intensity interval training, but not reduced-exertion high-intensity interval training increase brain-derived neurotrophic factor in a block randomized controlled trial. *Sci. Rep.* **2025**, *15*, 38322. [CrossRef]
112. Khalil, M.H. The BDNF-interactive model for sustainable hippocampal neurogenesis in humans: Synergistic effects of environmentally-mediated physical activity, cognitive stimulation, and mindfulness. *Int. J. Mol. Sci.* **2024**, *25*, 12924. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.