

Real and virtual forest exposure differ in their physiological, but not psychological, effects

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Abstract

As stress related to modern, urbanized lifestyles grows, interest in nature-based interventions for well-being and relaxation continues to increase. However, whether virtual nature can replicate the physiological benefits of exposure to real nature remains unclear. We compared real and virtual exposure to forest and city environments in 27 participants, measuring heart rate variability (a marker of stress and relaxation) and self-reported well-being before and after each condition. We also tested, for the first time under virtual nature exposure, the Physiological Adjustment Effect, which predicts that physiological change depends on a person's baseline level. Real forest exposure produced a more relaxed physiological profile than real city exposure across several heart rate variability markers, whereas virtual forest vs. virtual city exposure affected only one marker. When comparing real and virtual forests directly, only heart rate differed significantly. The Physiological Adjustment Effect was observed for more markers in the real condition, though this difference was not statistically confirmed. Well-being improved after both real and virtual forest exposure, with no significant difference between them. These results suggest that virtual nature exposure is not a full substitute for real nature, reproducing some, but not all, of its physiological benefits.

Introduction

Contact with nature is increasingly recognized as an important factor supporting both psychological health and physiological regulation [1]. Growing urbanization, reduced physical activity, and rising mental health problems have intensified scientific interest in the psychological and physiological effects of contact with nature [2]. There is growing evidence that natural environments can promote relaxation, reduce stress, and support overall well-being [3-9]. Exposure to natural settings also provides measurable health benefits, including pain relief [10], quicker recovery from surgery [11], and increased natural killer cell activity along with higher levels of anti-cancer proteins [12].

However, the mechanisms underlying these beneficial effects are varied and not yet fully understood [13]. Early theoretical frameworks, such as *Stress Reduction Theory*, suggested that nature reduces stress by triggering a rapid, biologically inherited emotional and physiological calming response that operates below conscious awareness [11,14]. Alternatively, *Attention Restoration Theory* [15,16] proposed that viewing or experiencing nature helps restore depleted attentional and cognitive resources, thereby enhancing concentration, memory, and the effectiveness of problem-solving. More recently, affect regulation theories, grounded in modern affective neuroscience, have been proposed, treating nature exposure as **an emotion-regulation strategy** [17,18]. Field studies in Japan on *Shinrin-yoku* (forest bathing) have revealed significant physiological and emotional changes following brief exposure to forests, including lower cortisol concentrations, reduced heart rate and blood pressure, immune enhancement, and increased parasympathetic activity, compared with urban settings [19-23].

Autonomic changes of this kind are commonly assessed through heart rate variability (HRV), a measure of the variation in time intervals between successive heartbeats [24]. HRV is widely used as an index of autonomic regulation, reflecting interactions between the sympathetic and parasympathetic branches of the autonomic nervous system [25]. In HRV analysis, a variety of indices are used, typically divided into time-domain and frequency-domain measures. Frequency-domain HRV indices, particularly the high-frequency

(HF) component, reflecting parasympathetic (vagal) activity, and the low-frequency to high-frequency (LF/HF) ratio, commonly used as an index of sympathetic activity, are commonly used for quantifying physiological relaxation in nature-exposure research [21]. Increases in HF and decreases in LF/HF following nature exposure are typically interpreted as markers of a shift toward parasympathetic dominance and reduced physiological stress [26]. However, findings across studies have been inconsistent, as some find no significant HRV change following nature exposure [27,28] or report changes in the opposite direction [29].

Recently, it has been shown that the physiological effects of nature-based interventions follow the principles of the Physiological Adjustment Effect. Rooted in Wilder's Law of Initial Value [30], which states that "The change of any function of an organism due to a stimulus depends, to a large degree, on the pre-stimulus level of that function," this framework suggests that physiological measures tend to move from an individual's baseline level toward an "optimal" set point. Higher initial values tend to decrease, while lower initial values tend to increase, based on the pre-intervention baseline [31,32]. Evidence for the Physiological Adjustment Effect in the context of nature exposure was first reported for cardiovascular responses during forest walking, where changes in blood pressure and pulse rate depended on participants' initial values [32]. Similar patterns were later observed for HRV indices of sympathetic activity during exposure to natural stimuli, including visual stimulation with fresh roses and natural environment images [31,33].

Stimulation of different senses appears to be essential for these nature-related benefits. Evidence from single-sense laboratory studies suggests that the strongest effects are linked to vision and olfaction, while auditory and tactile effects are supported by a smaller but consistent body of literature [23]. However, the real-world effect likely results from multisensory nature exposure [34]. This raises an important question: is there a connection between methods of nature exposure and the outcome? Accordingly, the use of digitally mediated natural environments as a potential alternative to direct contact with nature has become an active area of research. These studies generally suggest that real environments elicit the most powerful psychological and physiological responses, followed by immersive virtual reality (VR), with screen-based images or videos eliciting the weakest responses [35-40]. Some exceptions to this order have also been reported. It was found that both 6-minute outdoor nature exposure and VR nature videos, filmed at the same location, increased physiological arousal and provided restorative benefits compared to indoor settings. However, real outdoor exposure increased positive mood, whereas virtual reality nature exposure did not [41]. Similarly, exposure to a forest environment, via VR or photo slideshows, resulted in a reduction in mood disturbance, but photo slideshows were more effective than VR videos at lowering arousal, suggesting that higher immersion does not necessarily enhance the restorative effect [42]. Additionally, not all studies confirmed that technologically mediated natural environments offer smaller, yet measurable, physiological benefits compared to direct nature exposure. In a study of heart rate recovery from low-level stress, participants viewed nature through a glass window, a plasma TV display, or a blank wall. The real nature scene was restorative, but the plasma window had no greater effect than a blank wall [43]. This indicates that the effects of technologically mediated nature remain incompletely understood.

Notably, VR nature exposure has never been tested for the Physiological Adjustment Effect. Accordingly, the present study has two aims. First, to compare the effects of real versus virtual (VR) nature exposure on self-reported well-being and HRV-based autonomic indices, relative to a matched urban/control condition.

Second, to determine whether the Physiological Adjustment Effect is present in both the real and virtual nature conditions, and whether its strength differs between the two modalities. Answering these questions would bring together two previously separate lines of research: Wilder's Law of Initial Value, which predicts a baseline-dependent shift toward an 'optimal' autonomic state, and the comparison of real vs. VR-mediated nature effects. Beyond its theoretical contribution, the study's findings may have practical significance for populations who cannot access natural outdoor environments, due to hospitalization, imprisonment, or mobility limitations, as well as for the design of VR-based therapeutic interventions for clinical populations with autonomic dysfunction.

Results

Physiological changes

To track autonomic changes in response to natural and urban environments, across real and virtual exposure methods, we measured the time intervals between consecutive normal sinus heartbeats, called normal-to-normal (NN) intervals. From these intervals, we calculated heart rate (HR) and a set of time-domain and frequency-domain HRV indices. Time-domain indices included the root mean square of successive differences (RMSSD), the standard deviation of NN intervals (SDNN), and the percentage of adjacent NN intervals differing by more than 50 ms (pNN50). Frequency-domain indices included the low-frequency (LF) and high-frequency (HF) components, and the LF/HF ratio. Some indices were log-transformed to satisfy the normality assumptions required by the parametric tests. To complement the statistical analyses, we plotted the mean values of each index over time, averaged across participants, across the 13-min analyzed segment of each 15-min exposure, in each experimental condition. For statistical evaluation, we used a two-way repeated-measures ANOVA to evaluate the effects of Place (forest vs. city), Exposure (real vs. virtual), and their interaction on HR and HRV indices. It was followed by post hoc comparisons to identify which group means differed.

ANOVA results

The ANOVA results are presented in Table 1. Significant main effects of Place were found for HR, $F(1, 26) = 7.01, p = 0.014, \eta^2 = 0.023$, log-transformed HF, $F(1, 26) = 14.89, p < 0.001, \eta^2 = 0.042$, log-transformed LF/HF ratio, $F(1, 26) = 24.55, p < 0.001, \eta^2 = 0.129$, RMSSD, $F(1, 26) = 5.99, p = 0.021, \eta^2 = 0.014$, and pNN50, $F(1, 26) = 6.50, p = 0.017, \eta^2 = 0.016$. A significant main effect of Exposure was observed only for HR, $F(1, 26) = 15.29, p < 0.001, \eta^2 = 0.082$. Significant Place $\times$ Exposure interactions were found for log-transformed HF, $F(1, 26) = 6.52, p = 0.017, \eta^2 = 0.014$, and SDNN, $F(1, 26) = 7.80, p = 0.010, \eta^2 = 0.017$. No significant effects were found for log-transformed LF.

Indicator	Place			Exposure			Interaction		
	<i>F</i>	<i>p</i>	ηG^2	<i>F</i>	<i>p</i>	ηG^2	<i>F</i>	<i>p</i>	ηG^2
HR	7.01	0.014*	0.023	15.29	<0.001***	0.082	0.05	0.818	<0.001
HF (log-transformed)	14.89	<0.001***	0.042	0.46	0.505	0.001	6.52	0.017*	0.014
LF (log-transformed)	1.70	0.203	0.004	1.48	0.235	0.003	2.64	0.116	0.006
LF/HF ratio (log-transformed)	24.55	<0.001***	0.129	4.15	0.052	0.013	2.71	0.112	0.008
RMSSD	5.99	0.021*	0.014	2.82	0.105	0.012	2.38	0.135	0.005
SDNN	0.76	0.391	0.002	0.12	0.729	<0.001	7.80	0.010*	0.017
pNN50	6.50	0.017*	0.016	2.56	0.122	0.011	1.13	0.297	0.003

Table 1. Results of the two-way repeated-measures ANOVA for HR and HRV indices. HR, heart rate; HRV, heart rate variability; HF, high-frequency power; LF, low-frequency power; RMSSD, root mean square of successive differences; SDNN, standard deviation of NN intervals; pNN50, percentage of NN intervals differing by >50 ms. Statistical significance is indicated by asterisks: * $p < 0.05$, *** $p < 0.001$.

Real forest vs real city

All post hoc comparison results are presented in Supplementary Table 1. Post hoc comparisons between the real forest and real city conditions showed significantly higher log-transformed HF, $t(26) = 4.77$, $p < 0.001$, $g = 0.646$, pNN50, $t(26) = 2.90$, $p = 0.015$, $g = 0.385$, RMSSD, $t(26) = 3.37$, $p = 0.005$, $g = 0.405$, and SDNN, $t(26) = 2.76$, $p = 0.021$, $g = 0.378$, in the real forest condition relative to the real city condition. In contrast, the log-transformed LF/HF ratio was significantly lower in the real forest condition than in the real city condition, $t(26) = -4.80$, $p < 0.001$, $g = -0.978$. No significant differences were observed for HR and log-transformed LF. These results suggest increased parasympathetic activation and decreased sympathetic activation in the real forest condition. The time course of various indices is shown in Fig. 1. It can be seen that HF decreases during the first two minutes of exposure and remains stable thereafter. Time-based HRV indices generally decrease during the first four minutes of exposure and stabilize afterward.

Virtual forest vs virtual city

Post hoc comparisons between the virtual forest and virtual city conditions showed a significantly lower log-transformed LF/HF ratio in the virtual forest condition, $t(26) = -3.32$, $p = 0.003$, $g = -0.540$. No significant differences were observed for the remaining indicators. These results suggest decreased sympathetic activation in the virtual forest condition, with no change in parasympathetic activation. The time course of HR and the log-transformed LF/HF ratio is shown in Fig. 2. Both indices remain lower in the virtual forest condition compared to the virtual city, although HR did not reach statistical significance.

Real vs virtual forest

Post hoc comparisons between the real forest and virtual forest conditions showed significantly higher HR in the real forest condition, $t(26) = 2.77, p = 0.010, g = 0.588$. The time course of HR and, for comparison, SDNN is shown in Fig. 3. HR decreases within the first minutes and levels off afterward, remaining higher in the real forest condition. Overall, SDNN remains higher in the real forest compared to virtual forest conditions, but in both scenarios, it steadily decreases during the first 6-7 minutes before leveling off, indicating that settling into a more regular rhythm is not unique to exposure to real nature.

Real vs virtual city

Post hoc comparisons between the real city and virtual city conditions showed significantly higher HR in the real city condition, $t(26) = 3.91, p = 0.001, g = 0.572$. In addition, the real city condition showed a significantly higher log-transformed LF/HF ratio, $t(26) = 2.96, p = 0.013, g = 0.411$, and significantly lower pNN50, $t(26) = -2.47, p = 0.040, g = -0.330$, and RMSSD, $t(26) = -2.82, p = 0.018, g = -0.358$, compared with the virtual city condition. The time course of various indices is shown in Fig. 4. It is evident that RMSSD and pNN50 decline during the first 6-7 minutes before reaching a plateau, indicating a gradual decrease in parasympathetic activation. In contrast, HR and the LF/HF ratio suggest more sustained sympathetic involvement. Taken together, these results suggest a shift toward greater sympathetic and reduced parasympathetic activation during real city exposure. Compared with real vs virtual forest exposure, **HR is higher in the real condition in both environments, but the city comparison additionally shows significant differences in the frequency- and time-domain indices (LF/HF, RMSSD, pNN50), while the forest comparison does not.**

Physiological adjustment

To examine the association between baseline City values and the magnitude of the Nature–City change in HRV indices, we conducted Pearson correlation analyses. In the real condition, significant negative correlations were observed for HR, $r = -0.438, p = 0.044$, SDNN, $r = -0.609, p = 0.003$, log-transformed HF, $r = -0.663, p = 0.002$, log-transformed LF, $r = -0.459, p = 0.038$, log-transformed LF/HF ratio, $r = -0.519, p = 0.015$, and pNN50, $r = -0.629, p = 0.003$. No significant association was found for RMSSD, $r = -0.331, p = 0.122$. In the virtual condition, significant negative correlations were observed only for HR, $r = -0.562, p = 0.008$, and SDNN, $r = -0.427, p = 0.046$, whereas the remaining indicators were not significantly correlated with the Nature–City change scores. A summary of the physiological adjustment results is provided in Supplementary Table 2. Selected results for two HRV indices, pNN50 and log-transformed HF, which show Physiological Adjustment Effects in the real but not in the virtual environments, are shown in Fig. 5.

Self-reported well-being

To assess the effect of nature on subjective well-being, we used the Polish version of the Psychological Well-Being Scales (PWBS) [44,45] before and after exposure. PWBS scores increased significantly after both real-forest and virtual-forest exposure (Fig. 6). In the real-forest condition, well-being increased from pre-exposure ($M = 4.59, SD = 0.53$) to post-exposure ($M = 4.69, SD = 0.55$), $t(26) = -2.74, p = 0.011, d = -0.53$, 95% CI [-0.93, -0.12]. In the virtual-forest condition, PWBS scores also increased significantly, as indicated by the Wilcoxon signed-rank test, $Z = 2.58, p = 0.010$.

A paired-samples t-test was used to compare change scores between exposure types. The mean increase following virtual-forest exposure ($M = 0.11$, $SD = 0.21$) did not differ significantly from the mean increase following real-forest exposure ($M = 0.09$, $SD = 0.18$), $t(26) = 0.43$, $p = 0.671$.

We also performed Pearson correlation analyses to examine the relationship between post-minus-pre PWBS scores and HRV indices. In both real and virtual forest conditions, there was generally no correlation between changes in psychological well-being and HRV indices.

Discussion

The aim of this study was twofold: first, to compare how real and virtual nature exposures affect HRV-based autonomic measures compared to urban (control) conditions and how they influence self-reported well-being; and second, to evaluate whether the Physiological Adjustment Effect occurs in both real and virtual nature environments, and whether its magnitude differs between these two modalities.

Regarding the first goal, the most notable finding was that exposure to the real forest environment led to significantly greater physiological relaxation than exposure to the real urban environment. This was demonstrated by five HRV indices: RMSSD, SDNN, and pNN50, along with log-transformed HF values, which were higher in the forest condition, while the log-transformed LF/HF ratio was lower. This suggests increased parasympathetic activity and reduced sympathetic arousal during forest exposure. These findings align with a broad body of literature indicating the beneficial physiological effects of natural environments [46], including *Shinrin-yoku* (forest bathing) therapy [21, 47].

Results from the real conditions were only partially reproduced in the virtual conditions. Virtual forest exposure elicited a significantly lower log-transformed LF/HF ratio than virtual city exposure, but no significant differences were observed for any of the remaining indices. These results suggest that virtual nature exposure was sufficient to reduce sympathetic activation but not to elicit a corresponding increase in parasympathetic activity. This contrasts with real forest exposure, which affected both parts of the autonomic nervous system.

Post hoc comparisons between the real and virtual forest conditions showed significantly higher HR in the real forest condition. No other HRV indices showed significant differences between the two conditions, and the corresponding effect sizes were consistently small ($g = 0.05-0.31$), suggesting that indeed virtual forest exposure was largely successful at reproducing the autonomic balance elicited by real forest exposure. However, this interpretation needs confirmation with a larger sample. Other studies have also not found a significant physiological difference between real and simulated nature when using cortisol as a biomarker [37]. Furthermore, the same study found that, in a self-report mood inventory, subjects experienced greater subjective energy in the real than in the simulated condition. This pattern is also consistent with findings from a 5-day nature immersion trip, during which HR significantly increased and respiratory sinus arrhythmia (RSA), a parasympathetic HRV marker, significantly decreased compared with the periods before and after the trip [48]. The authors interpreted these results as reflecting increased involuntary attention to environmental stimuli [48]. This interpretation is consistent with earlier work showing that HR increased during nature-video viewing relative to urban-video viewing, an effect attributed to increased autonomic

attention [49]. Accordingly, the elevated HR observed in the real forest condition relative to VR in our study (Fig. 3a) may reflect a distinct aspect of the physiological response, such as heightened sensory engagement or alertness caused by the richer multisensory stimulation of a real natural environment, rather than a broader shift in autonomic balance.

Post hoc comparisons between the real city and virtual city conditions showed significantly higher HR in the real city condition. In addition, the real city condition showed a significantly higher log-transformed LF/HF ratio and significantly lower pNN50 and RMSSD than the virtual city condition. Taken together, these results suggest a coherent pattern of greater sympathetic and reduced parasympathetic activation during real city exposure. It is worth noting that HR is consistently higher in real than in virtual exposure across both forest and city environments. This suggests that HR may also be sensitive to real-world exposure itself, rather than solely to emotional content, such as a calming forest versus a stimulating city. Increased HR might result from general alertness to being in a physical space or from richer sensory stimulation [48, 49].

Another important finding is related to the Physiological Adjustment Effect. In the real condition, the effect was observed across six of the seven physiological indices examined, i.e., HR, SDNN, HF, LF, LF/HF ratio and pNN50. It is consistent with prior demonstrations of this effect using real forest exposure and visual stimulation with fresh roses and static natural images [31–33]. In contrast, in the virtual condition, this effect was limited to HR and SDNN, with no significant correlations for the other indices. These results imply that the real forest engages widespread autonomic regulation, whereas the effects of virtual forest exposure appear limited to overall HR-related measures and do not affect the frequency-domain indices most closely associated with parasympathetic and sympathetic activity. In terms of Wilder's Law of Initial Value, these results suggest that direct contact with nature engages an initial-value-dependent physiological regulatory response that virtual exposure does not fully replicate.

However, when the real- and virtual-condition correlation coefficients were directly compared using Steiger's Z test (*cocor* function in R statistical package), no significant differences were found for any HRV index. This indicates that although fewer correlations were statistically significant in the virtual condition, correlation strengths did not differ significantly across conditions. This null result, however, should not be considered confirmatory evidence that the two conditions are equivalent. Given the moderate sample size ($n = 27$), this result more likely reflects limited power to detect more subtle differences, if they exist.

Both real and virtual forests enhanced subjective well-being. The absence of differences between these forms of exposure suggests that a virtual presentation of natural visual features, combined with natural pine scent and bird sounds, may be sufficient to improve subjective states. However, correlations between HRV and psychological well-being were not significant. This suggests that physiological and subjective indicators may capture different aspects of the relaxation response and are influenced by additional individual or contextual factors. This aligns with a broader pattern in the nature exposure literature, where subjective and physiological measures of relaxation do not always converge [50, 51]. Yet direct correlational tests between the two, as conducted in our study, have been rare, indicating a potential research gap.

Returning to the two aims that motivated this study, our findings offer a coherent picture. First, real and virtual nature exposure both produced measurable physiological and psychological benefits relative to the

urban control condition. During real forest exposure compared with city exposure, nearly all HRV indices indicated greater parasympathetic and reduced sympathetic activity. A direct comparison between real and virtual forest exposure showed that VR conditions reproduced most of these HRV changes, except for HR. Real and VR-mediated nature produced significant improvements in subjective well-being, and a direct comparison of the pre-post change scores between the two conditions revealed no significant difference.

Second, the Physiological Adjustment Effect was observed in both real and virtual conditions, but was significant across a broader set of indices in the real condition. A direct statistical comparison, however, did not confirm that its magnitude differed significantly between the two modalities. Together, these findings indicate that virtual nature exposure can approximate many, though evidently not all, of the physiological benefits of real nature exposure.

Several methodological limitations of the study should be considered when interpreting the findings. The sample consisted of young, healthy adults, limiting the generalizability of the results to broader populations. The sample size was modest ($n = 27$), limiting statistical power. Some of the non-significant results reported here, e.g., comparisons of correlation coefficients between real and virtual conditions using Steiger's Z test or pre-post well-being change scores, should not be interpreted as evidence of equivalence between real and virtual exposure, but rather as an absence of detected difference that might be due to limited power. Future studies with larger samples would allow more definitive conclusions regarding whether real and virtual nature exposure produce genuinely comparable effects.

The virtual forest did not fully replicate the characteristics of the real forest, and the virtual city scene depicted a much busier environment than the actual urban location. Real-world lighting, temperature, and weather variability were absent in VR, while the pine scent in the VR forest was stronger than in the real forest. These differences demonstrate the need for VR environments that more closely resemble real locations and incorporate multisensory stimulation to increase ecological validity.

Although the shortened Polish version of the Psychological Well-Being Scales (PWBS) is a validated instrument, it was not specifically designed to detect momentary, state-level changes in well-being and may therefore be less sensitive to subtle changes in subjective experience. Future studies could benefit from scales explicitly designed for repeated, momentary assessment.

Additional physiological indicators, such as EEG, skin conductance, or respiratory variability, may further clarify the mechanisms underlying responses to natural and virtual environments. These considerations point to several directions for future experimental work, including broader demographic sampling, improved VR fidelity, multisensory stimulation, and the use of scales designed for momentary assessments. Such approaches may help determine which components of natural and virtual environments are most relevant for inducing physiological and psychological relaxation.

Methods

Subjects and data collection

The study was approved by the University of Warsaw Rector's Committee for the Ethics of Research Involving Human Participants (opinion no. 404/2025, 19 May 2025). All procedures were performed in accordance with relevant guidelines and regulations. Written informed consent was obtained from all participants prior to participation. Twenty-seven university students (15 females, 12 males; mean age = 21.3 ± 1.3 years) participated in the experiment. To control for physiological variability, participants were asked to refrain from eating [52], drinking coffee or energy drinks [53] for two hours before testing, and to avoid alcohol [54] and intense exercise [55] for 24 hours. They were instructed to maintain a normal sleep routine [56] and wear comfortable clothing.

Stimuli and procedure

The study took place in Warsaw. Each participant completed two experimental sessions: a real-world session and a laboratory (VR) session. The order of the real and virtual sessions was randomized across participants. Within each session, participants completed both environmental conditions, forest and city, on the same day, with the order of these two conditions also randomized. Thus, both real-world conditions were completed on one day and both virtual conditions on another day. The total participation time was about 90 minutes. Representative photographs of the environments used during the experimental sessions are shown in Fig. 7.

Real conditions

The forest condition took place in a forest area dominated by oaks and pines. Weather data (temperature, wind, cloud cover, air quality) were recorded for each session; the mean temperature was 20.3°C ($SD = 3.6$). Sessions were postponed during heavy rain or excessive heat. Environmental disturbances, such as noise or other visitors, were noted. Each participant wore a Polar H10 chest strap [57] connected to the Elite HRV app [58] for continuous heart-rate recording. Participants sat quietly for 15 minutes without speaking or using a phone. They completed the short form of the Polish version of Psychological Well-Being Scales (PWBS) [44, 45] before and after exposure. The city condition followed the same protocol at a nearby city location characterized by typical urban stimuli such as traffic noise and pedestrian movement. Continuous HRV data were collected with the same equipment and procedure.

Virtual conditions

Laboratory sessions were conducted using Meta Quest 3 VR headsets. After completing the PWBS, participants received safety instructions. In the forest VR condition, a realistic pine-forest environment was presented, accompanied by natural bird sounds and the scent of scots pine essential oil. In the urban VR condition, participants viewed a 15-minute 360° recording of a busy city scene with traffic and pedestrians. Throughout both virtual exposures, HRV was continuously recorded using the Polar H10 sensor and Elite HRV application. After each session, participants completed questionnaires assessing well-being, subjective impressions, and any adverse effects.

Heart rate and HRV

Heart rate (HR) is the number of heartbeats per unit of time, typically expressed in beats per minute [59]. Its regulation is governed by the autonomic nervous system (ANS), composed of the sympathetic nervous

system (SNS) and the parasympathetic nervous system (PNS) [25]. Heart rate variability (HRV) refers to fluctuations in the time intervals between consecutive heartbeats [24]. It is a widely used marker of autonomic regulation, reflecting dynamic interactions between the heart, the central nervous system, and peripheral physiological processes [59, 60]. In HRV analysis, a variety of indices are used, typically divided into time-domain and frequency-domain measures.

Time-domain

SDNN (standard deviation of NN intervals) reflects the overall level of heart rate variability. It represents the standard deviation of the time intervals between consecutive normal-to-normal (NN) heartbeats. In short-term recordings, SDNN is shaped mainly by parasympathetic activity, particularly by the rhythmic coupling between respiration and cardiac function [61]. SDNN is strongly associated with total HRV power and with power within the low-frequency band [62, 63] and is commonly interpreted as a measure of overall HRV and global autonomic regulation [61, 64].

RMSSD (root mean square of successive differences) is the square root of the mean of the squared differences between successive NN intervals [24]. As an index of dynamic cardiac regulation in response to respiratory-driven changes, RMSSD is considered one of the most sensitive and reliable markers of parasympathetic activity under resting conditions.

PNN50 (the percentage of adjacent NN intervals that differ from each other by more than 50 ms) represents the proportion of successive NN intervals that differ by more than 50 ms and is commonly used to evaluate parasympathetic influence [61]. A high pNN50 value indicates high heart rate variability and strong vagal modulation, reflecting dynamic short-term parasympathetic control of cardiac function [62].

Frequency-domain

Frequency-domain measures are based on the analysis of the HRV signal's power spectrum [24]. The LF component (low frequency, 0.04–0.15 Hz) reflects the power of HRV within the range of slow oscillations in heart rate. LF band power is affected by both the parasympathetic and sympathetic branches of the autonomic nervous system, as well as baroreflex activity, but under resting conditions, parasympathetic activity and baroreflex modulation usually dominate [62]. During slow breathing, vagal activity can generate rhythmic oscillations within the LF band, thereby increasing LF power. For this reason, elevated LF values do not necessarily indicate sympathetic dominance [65].

The HF band (high frequency, 0.15–0.40 Hz) is generally interpreted as an index of parasympathetically mediated, respiration-related modulation of heart rate [61]. Increases in HF power are observed during states of relaxation and physiological recovery, whereas decreases accompany stress and reduced flexibility of regulatory systems [61, 62].

The LF/HF ratio, defined as the ratio of power in the LF band to that in the HF band, was originally intended to serve as a simplified measure of sympathovagal balance [24]. Its interpretive value has since been questioned due to the complexity of autonomic interactions and the influence of factors such as heart rate, body posture, and breathing frequency [62, 64]. Nevertheless, a high LF/HF ratio may indicate a predominance of sympathetic activation characteristic of stress responses [61, 66].

Data analysis

To derive heart rate variability (HRV) indices, raw RR data (the time intervals between consecutive heartbeats) were obtained from the Elite HRV application and processed using a custom Python script. For each participant and experimental condition, each recording was trimmed to a maximum duration of 13 minutes to ensure comparable signal length across sessions. Artifact correction was applied by removing RR intervals shorter than 300 ms, longer than 2000 ms or differing from the preceding interval by more than 20% [67]. The remaining intervals were treated as NN (normal-to-normal) intervals. On the cleaned NN series, time-domain HRV indices were calculated, including RMSSD, SDNN, and pNN50. For frequency-domain analysis, the signal was interpolated and resampled at 4 Hz, and power spectral density was computed to derive LF (0.04–0.15 Hz), HF (0.15–0.4 Hz), and the LF/HF ratio. Mean heart rate was derived from NN interval durations.

Statistical analysis

Normality was assessed for each HRV indicator before inferential analysis using the Shapiro–Wilk test. RMSSD, SDNN, pNN50, and HR met the assumption of normality in their original form and were therefore analyzed with repeated-measures ANOVA (*rm_anova* in the Pingouin statistical package in Python) involving two within-subjects factors. LF, HF, and the LF/HF ratio initially showed non-normal distributions, but after log-transformation, their distributions met the normality assumption. These variables were also analyzed using a repeated-measures ANOVA with two factors Place (forest and city), Exposure (real and virtual). All tests were two-sided, and statistical significance was set at $p < 0.05$. All analyses were conducted on $n = 27$ participants. We report results with F -statistic, both degrees of freedom, exact p value and generalized eta-square effect size (η^2).

Comparing real and virtual exposure within each environment (forest and city) was one of our main study aims, so we compared real and virtual conditions separately within each environment for every HRV index, regardless of whether the Place $\times$ Exposure interaction was significant. These comparisons were planned before the analysis to directly answer our research questions, rather than being follow-up tests run only because the interaction was significant. For post hoc pairwise comparisons, we used the *pairwise_tests* function in the Pingouin statistical package with the Benjamini-Hochberg False Discovery Rate (FDR) correction. We report results with t -statistic, degrees of freedom, corrected p value, and Hedges' g effect size.

To examine the Physiological Adjustment Effect, we tested the association between baseline values (measured during the City condition) and the magnitude of the change in HRV indices between the Nature and City conditions. This follows the approach used in previous studies [31, 33]. For each HRV index, we calculated a Pearson correlation between the baseline City value and the Nature–City change score, separately for the real and virtual conditions. Benjamini-Hochberg FDR correction was applied jointly across all 14 correlations.

We also tested whether this association differed in strength between the real and virtual conditions. To do this, we compared the correlation coefficients directly using Steiger's Z test for dependent, non-overlapping

correlations, implemented in the *cocor.dep.groups.nonoverlap* function in the R statistical package. It accounts for the fact that the real- and virtual-condition correlations were calculated from the same participants rather than from independent samples. We again applied Benjamini-Hochberg FDR correction across the seven comparisons.

PWBS scores were tested for normality using the Shapiro–Wilk test. Depending on the data distribution, pre–post comparisons were conducted using either the paired t-test or the Wilcoxon signed-rank test. Parametric methods were applied where normality assumptions were satisfied, whereas the virtual-forest pre vs. post comparison was analyzed using a non-parametric approach. Statistical significance was set at $p < 0.05$, two-sided.

Declarations

Additional Information

The authors declare no competing interests.

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Author Contribution

H.K and P.S. conceived and designed the experiments. H.K. performed the experiment. H.K. performed the analysis of the dataset and prepared the figures. H.K. and P.S. wrote the manuscript.

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Data Availability

The data that support the findings of this research are available from the corresponding author upon reasonable request.

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Figures

Real forest vs Real city

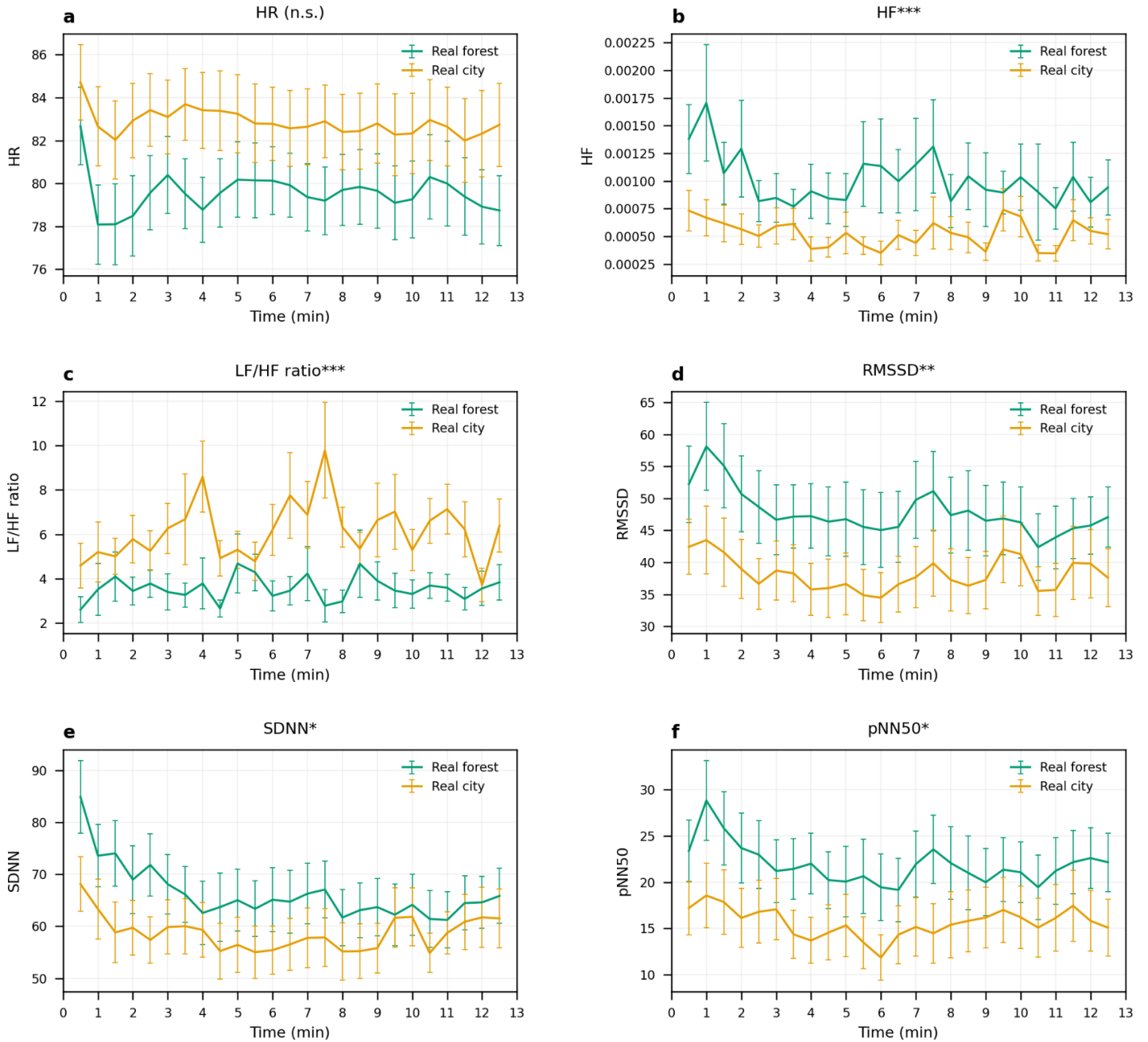


Figure 1

Time-course of heart rate (HR), high-frequency power (HF), the low-frequency to high-frequency ratio (LF/HF), root mean square of successive differences (RMSSD), standard deviation of NN intervals (SDNN), and the percentage of NN intervals differing by more than 50 ms (pNN50) during exposure to the real forest and real city conditions. Values are shown as mean $\pm$ s.e.m. across participants. Data were calculated using overlapping 1-min windows advanced in 30-s steps across the 13-min analysis period. Asterisks indicate statistically significant differences between conditions based on corrected p values from post hoc tests. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; n.s. - not significant.

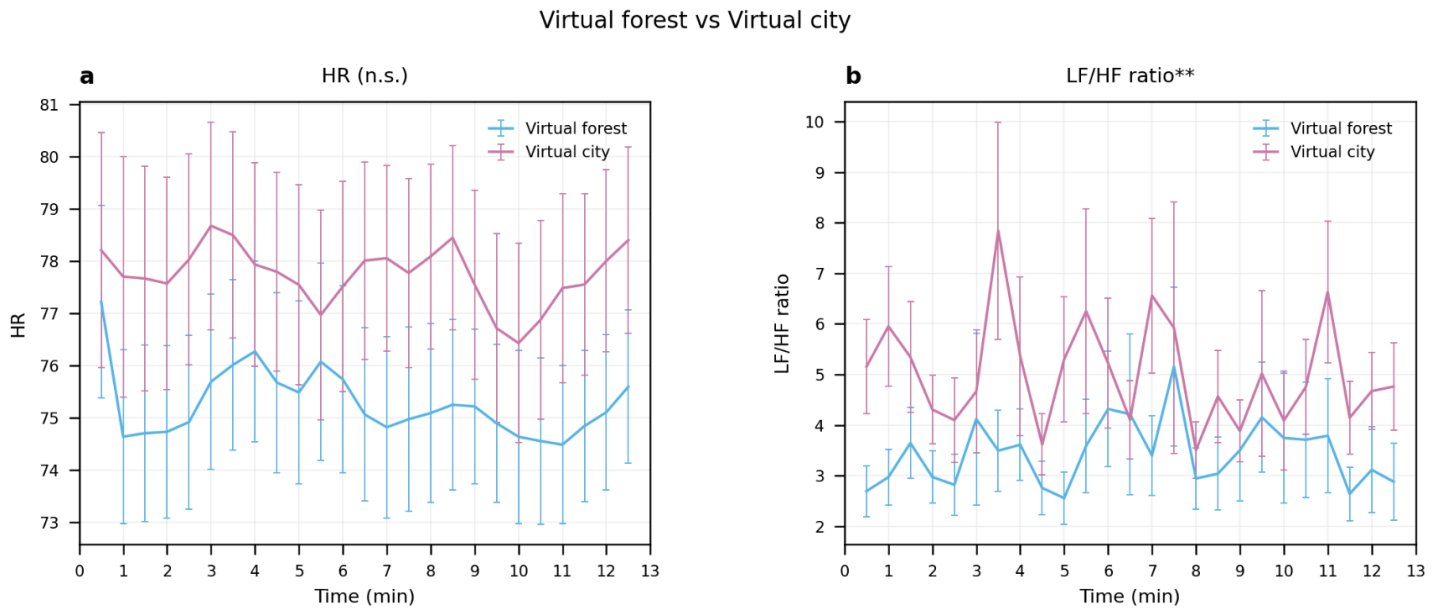


Figure 2

Time-course of heart rate (HR) and the log-transformed low-frequency to high-frequency ratio (LF/HF) during exposure to the virtual forest and virtual city conditions. Values are shown as mean $\pm$ s.e.m. across participants. Data were calculated using overlapping 1-min windows advanced in 30-s steps across the 13-min analysis period. Asterisks indicate statistically significant differences between conditions based on corrected p values from post hoc tests. ** $p < 0.01$; n.s. - not significant.

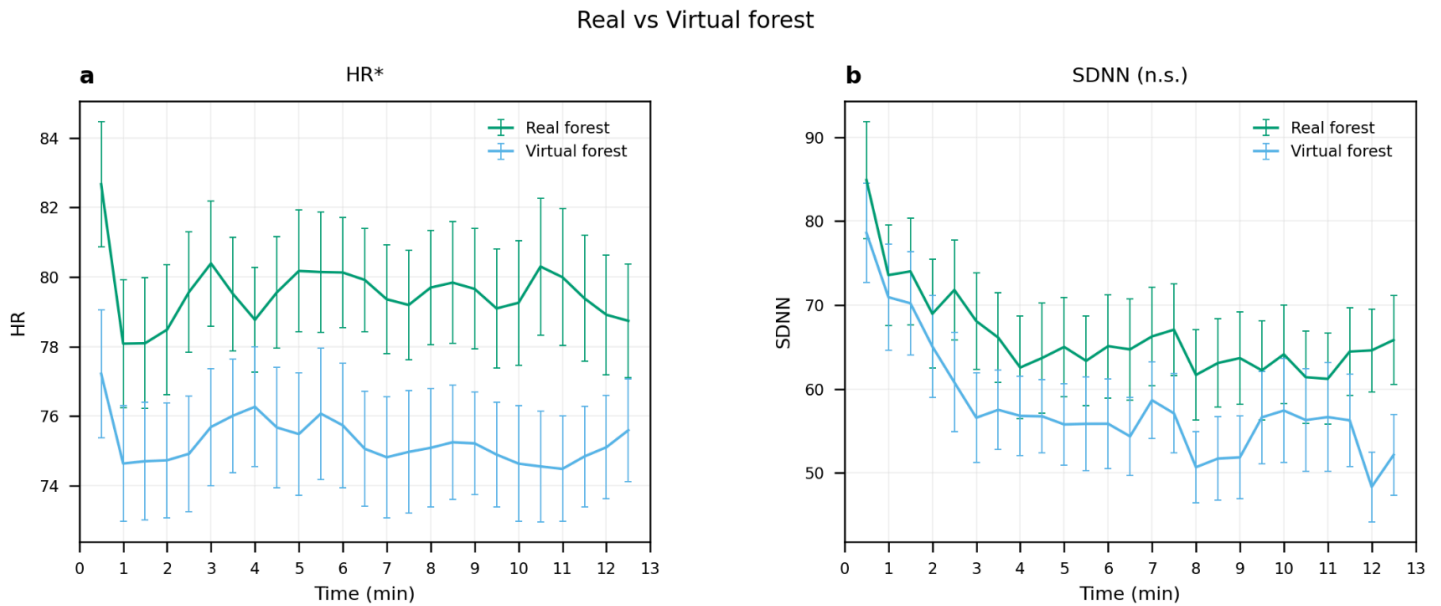


Figure 3

Time-course of heart rate (HR) and standard deviation of NN intervals (SDNN) comparing the real forest and virtual forest conditions. Values are shown as mean $\pm$ s.e.m. across participants. Data were calculated using overlapping 1-min windows advanced in 30-s steps across the 13-min analysis period. Asterisks indicate statistically significant differences between conditions based on corrected p values from post hoc tests. $*p < 0.05$; n.s. - not significant.

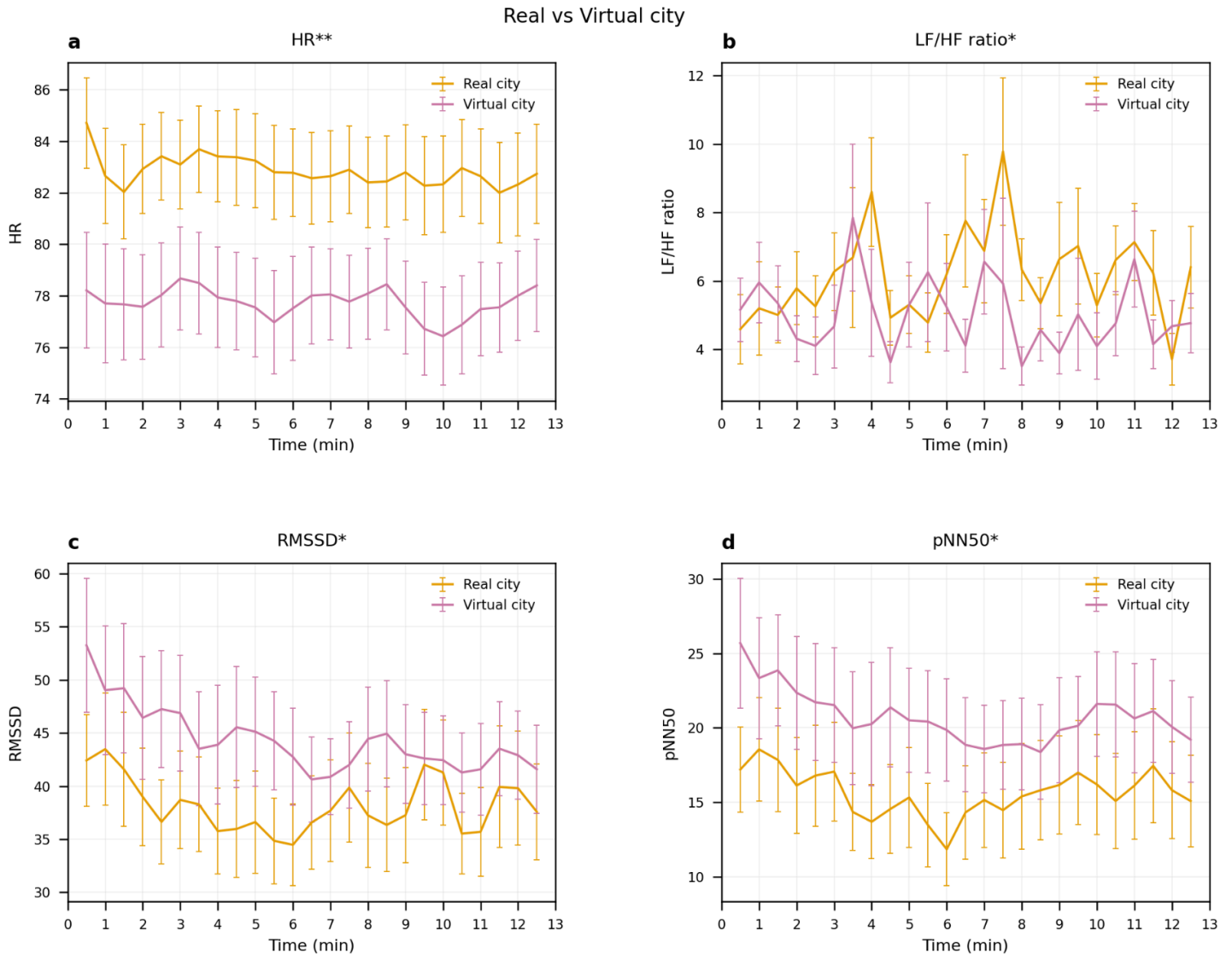


Figure 4

Time-course of heart rate (HR), log-transformed low-frequency to high-frequency ratio (LF/HF), root mean square of successive differences (RMSSD) and the percentage of NN intervals differing by more than 50 ms (pNN50) comparing the real city and virtual city conditions. Values are shown as mean $\pm$ s.e.m. across participants. Data were calculated using overlapping 1-min windows advanced in 30-s steps across the 13-min analysis period. Asterisks indicate statistically significant differences between conditions based on corrected p values from post hoc tests. $*p < 0.05$, $**p < 0.01$.

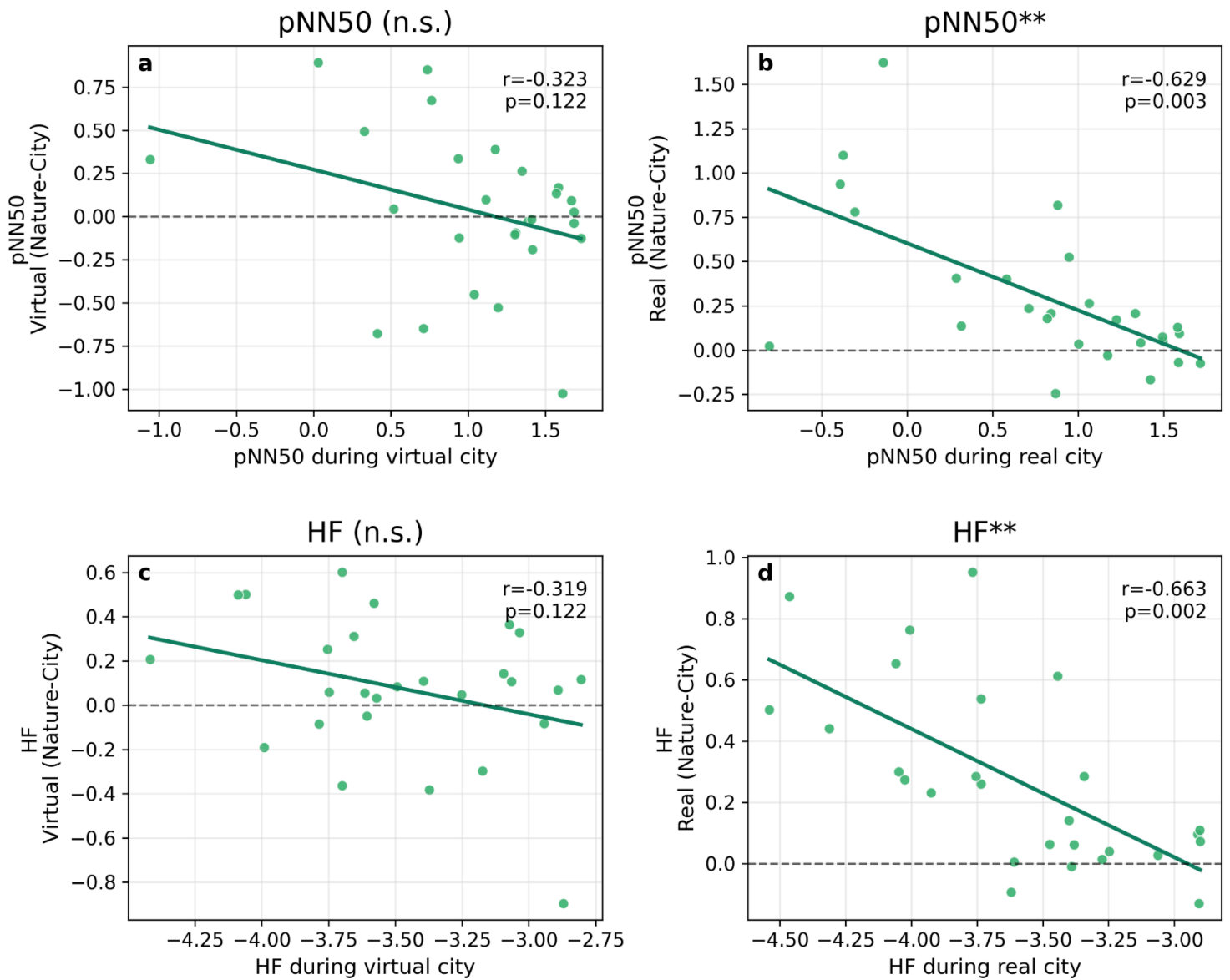


Figure 5

Relationship between baseline city values and forest-induced changes in the percentage of NN intervals differing by more than 50 ms (pNN50) and log transformed high-frequency power (HF) in the virtual and real conditions. Panels **a** and **c** show the virtual condition, and panels **b** and **d** the real condition. The horizontal axis shows the baseline city value, and the vertical axis shows the Nature-City change score. Corrected p values are shown in each panel. Significant negative correlations were observed for pNN50 and HF in the real condition, whereas the corresponding associations in the virtual condition were not significant. ** $p < 0.01$; n.s., not significant.

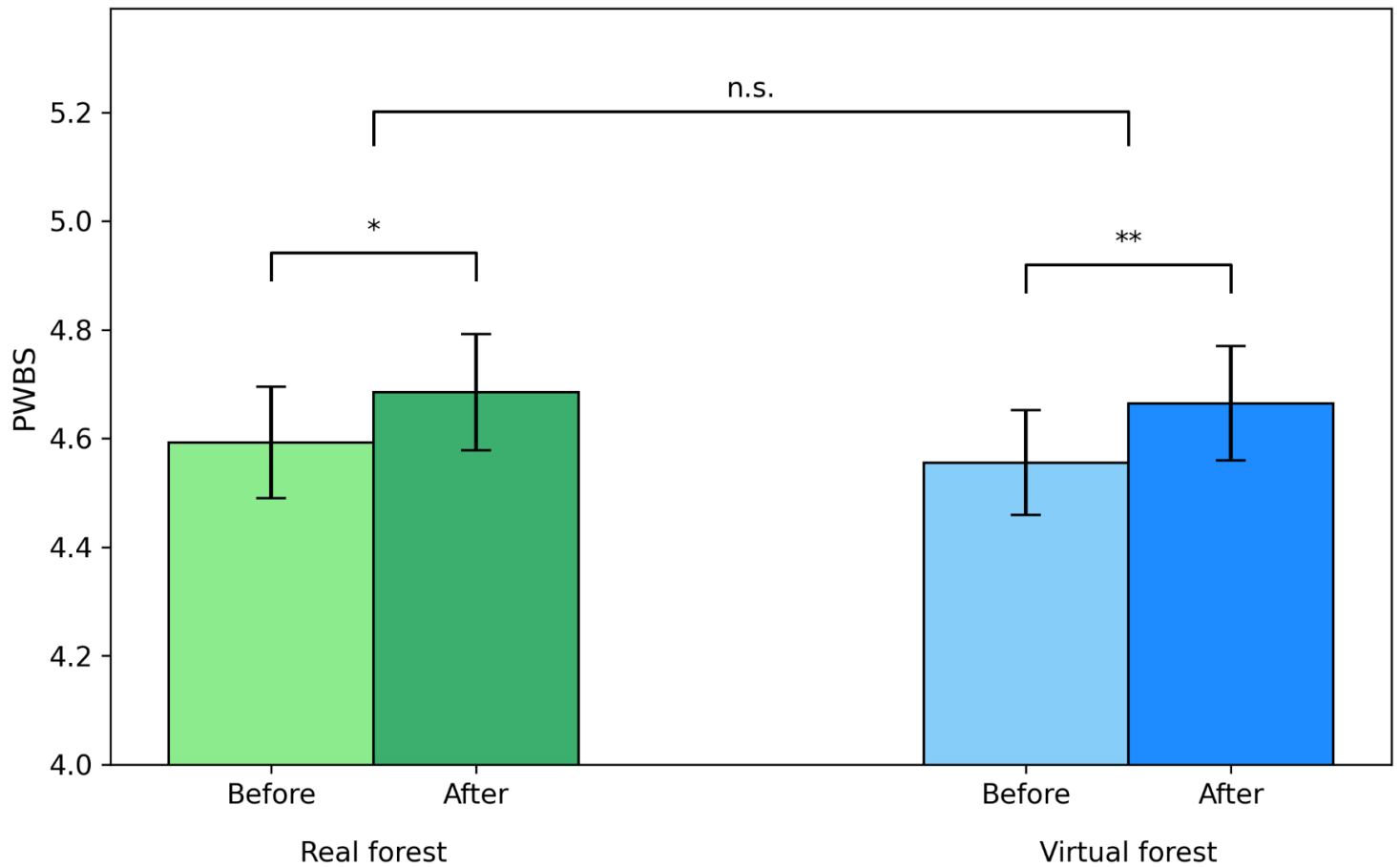


Figure 6

Psychological well-being before and after exposure to the real and virtual forest conditions. Psychological Well-Being Scales (PWBS) scores increased significantly following both real-forest and virtual-forest exposure. The pre–post increase was assessed using a paired-samples *t*-test for the real-forest condition and a Wilcoxon signed-rank test for the virtual-forest condition. The upper bracket indicates the comparison of pre–post change scores between the real and virtual forest conditions, which was not statistically significant. Asterisks indicate significant pre–post differences. **p* < 0.05, ** *p* < 0.01; n.s., not significant.

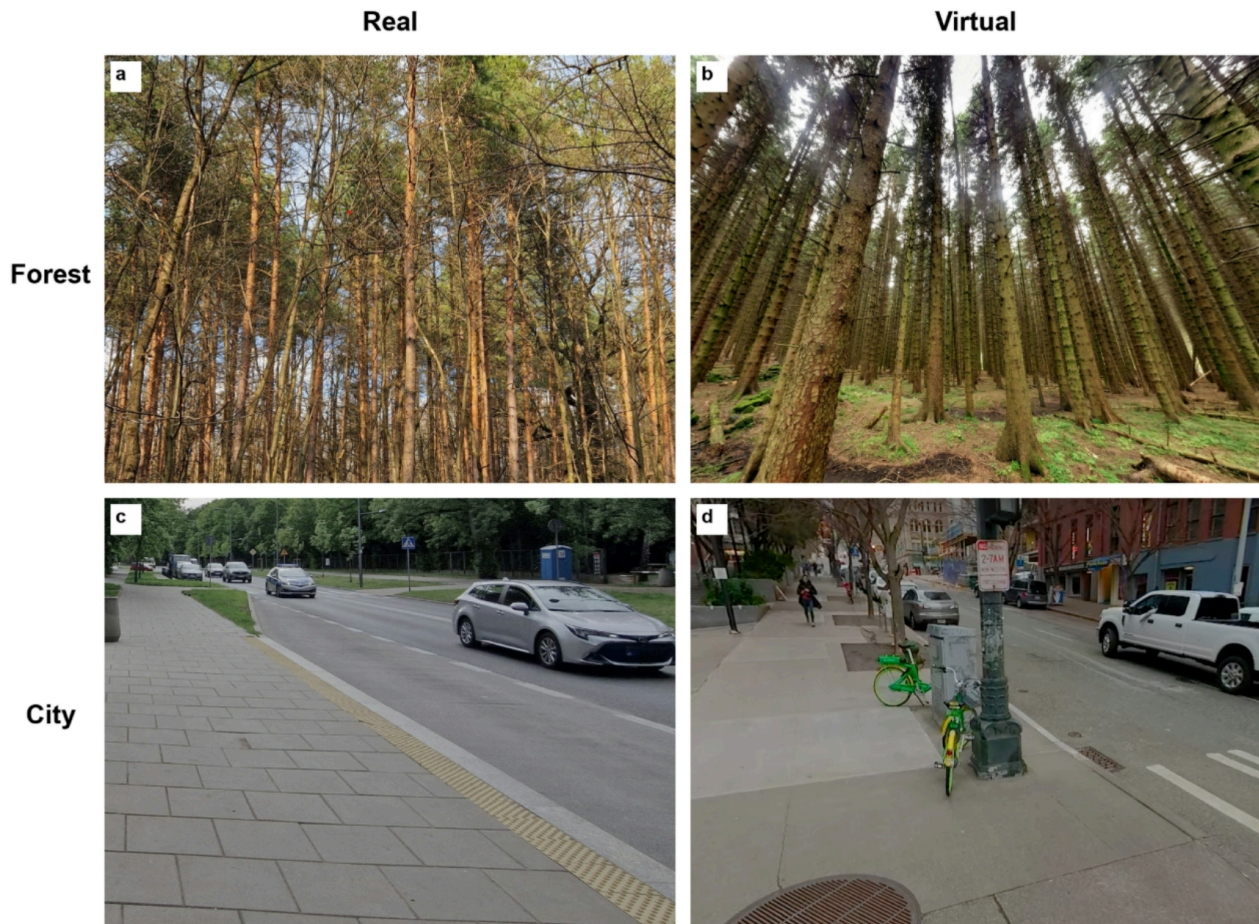


Figure 7

Overview of the experimental conditions. Representative photographs show **(a)** real forest, **(b)** virtual forest, **(c)** real city, and **(d)** virtual city environments used during the experimental sessions.

Supplementary Files

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