Physiological and Cognitive Responses to Walking in Natural and Built Urban Environments

Bhargavi Mahesh[1], Jauwairia Nasir[1], Stina Klein[1], Tobias Hallmen[1], Yekta Can[1], Jonathan Simon[2], Christoph Beck[2], Joachim Rathmann[3], Max Stocker[2], Lisa-Marie Falkenrodt[2], Elisabeth André[1]

[1]Chair for Human-Centered Artificial Intelligence, University of Augsburg, Germany
[2]Institute of Geography, Physical Geography and Climate Science, University of Augsburg, Germany
[3]Institute of Geography and Geology, University of Würzburg, Germany

***Abstract*—Walking in natural environments is widely recognized as an effective stress reduction strategy, often offering greater benefits than walking in built environments. We examined the physiological and cognitive responses to walking in urban forest versus urban built environments in summer and in winter. This study utilized continuous heart rate monitoring with a wearable chest sensor and 2-back cognitive tests. Higher increases in heart rate during the walk and slower post-walk recovery were observed for walks in built environments compared to those in the forest, in both seasons. However, the magnitudes varied between the seasons, emphasizing the contextual nature of restorative benefits. Improvements in the accuracy of the cognitive tests were observed during the forest walks in summer, but the results were less conclusive in winter. Despite these differences, walking in built environments still conferred well-being benefits, supporting stress reduction regardless of the environment or season.**

***Index Terms*—physiological stress, walking intervention, urban nature, wearables, heart rate recovery, cognitive restoration.**

I. Introduction

As cities grow and climate variability increases, understanding how different urban environments, such as natural, green areas versus built residential areas, affect human well-being becomes increasingly important [1]. While walking itself is beneficial, natural settings may offer added physiological and psychological benefits [2]. These benefits, however, may be shaped by context, such as seasonal variation. This study utilizes wearable sensors and standard cognitive tasks to investigate how environmental and seasonal factors impact heart rate and cognitive restoration during real-world walks. Findings have the potential to optimize nature-based therapeutic interventions, as well as identify patterns that can guide urban planning and public health initiatives.

II. Background and Related Work

Two prominent theories, namely Stress Reduction Theory (SRT) by Ulrich [3] and Attention Restoration Theory (ART) by Kaplan [4], propose distinct perspectives on how natural environments contribute to human well-being. SRT, from a psycho-evolutionary perspective, suggests that nature facilitates physiological stress reduction through autonomic nervous system (ANS) regulation [3], [5], with studies demonstrating reduction in heart rate (HR) and blood pressure [3], [6], cortisol and neural activity in stress-related brain regions upon nature exposure. The ANS modulates HR via sympathetic (excitatory) and parasympathetic (inhibitory) pathways [7]. During walking, HR increases in response to elevated metabolic demands, individual and environmental factors. Typically, it decreases by 12-20 beats per minute (bpm) within the first minute after the walk ends [8]. This drop is partly attributed to the reactivation of the parasympathetic nervous system [9], [10]. ART proposes that natural environments can restore depleted cognitive function and attention through gentle, involuntary engagement with nature [4]. Studies have shown improvements in attention, memory, and executive function following exposure to green environments [11]–[13]. Only a limited number of studies have simultaneously examined physiological and psychological restoration, with a particular focus on cognitive outcomes. Hartig et al. [14] reported reductions in blood pressure and modest improvements in attention after nature walks, while Laumann et al. [15] observed lower heart rates during nature video viewing, although the attention effects were less conclusive. Meta-analyses by Bowler et al. [2] and Ohly et al. [16] highlight common gaps and limitations, including reliance on passive exposure (e.g., images or videos), limiting ecological validity. Most existing research is biased toward spring or summer. Nevertheless, seasonal variation influences physiological responses [17], affecting environmental aesthetics [18] and perceived restorativeness [19]. To capture the full scope of restorative effects, real-world multimodal approaches have been recommended [12]. Advances in wearable sensors make such approaches increasingly feasible, enabling ecologically valid studies through continuous physiological monitoring in outdoor settings, in underrepresented seasons.

III. Methods

Building upon SRT and ART, and using a similar experiment setup across summer and winter, we attempted to address three key research questions (RQ):

RQ1 *Do individuals walking in an urban forest environment, compared to an urban built environment, exhibit (a) reduced stress-inducing effect (smaller increases in heart rate) during walking, and (b) enhanced stress recovery effect (greater heart rate recovery) following the walk, regardless of season?*

RQ2 *Do individuals walking in an urban forest environment, compared to an urban built environment, exhibit greater*

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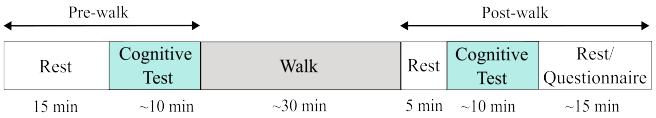

Fig. 1. Experiment protocol

improvements in cognitive test performance, regardless of the season?

A. Data Collection

Two walking routes were selected: a forest route through mixed urban forest with meadows and waterways (GA) and a city route through built, residential area alongside a major four-lane road (AV). Both were comparable in design: flat, about 2.2 km in length, and requiring about 30 minutes. Data were collected in summer (July 2023) and winter (Feb-Mar 2024) with 63 participants (summer: n=33, m/f=22/11; winter: n=30, m/f=10/20; mean age: 29.48±10.89 years). Participants were recruited via flyers and email and assigned to two walking sessions on different days for the two routes. Within each season, temperature ranges on the assigned days did not differ significantly (22-26° for summer and 7-13° for winter). On the day of the experiment, participants first rested briefly before being fitted with Polar H10 heart rate sensors. They followed a standardized protocol consisting of a pre-walk 2-back test, the walk, a post-walk 2-back test, and the completion of questionnaires (Fig. 1). Each participant's session lasted approximately 1.5 hours. Walk start and end times were logged. Micrometeorological data (temperature, heat index, humidity, and wind chill) confirmed significant seasonal differences between the seasons.

B. Physiological Data Annotation and Measures (RQ1)

To examine whether walking in an urban forest leads to (a) smaller heart rate increases and (b) greater heart rate recovery compared to a built-up area, HR data from chest-worn ECG sensors was utilized. The Nova tool [20] (see Fig. 2) was used to annotate the *pre-walk*, *walk*, and *post-walk* phases based on recorded timestamps. Recordings that were started late or stopped abruptly during the walk were excluded. Only participants with valid data from both walking routes were included (n=17, 11 in summer, 6 in winter; Age: 26.4±4.69). Two key HR metrics [8] were analyzed:

- Heart rate increase (HRI): difference between peak HR and baseline HR. Peak HR was calculated as the 85th percentile of HR values during the *walk* phase, while baseline HR was calculated as the 10th percentile of the *pre-walk* resting phase. These percentiles were selected to mitigate the influence of noise during movement.
- Heart rate recovery (HRR): *post-walk* HR decline (bpm/min). The HR data were smoothed using a 10-second moving average to remove motion artifacts. The recovery duration varied across participants; some returned to resting levels within 20 seconds, while others took over a minute. A 120-second window was initially selected and gradually shortened from the end until the most linear segment (with the highest coefficient of determination, R^2) was used to obtain the slope of decline, which was later used for the final HRR calculation.

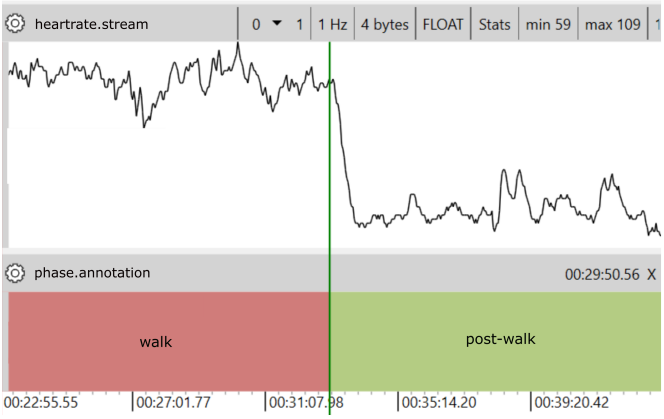

Fig. 2. Illustration of heart rate signal annotation on Nova for a participant.

C. Cognitive Task Design and Measures (RQ2)

To assess whether individuals walking in an urban forest environment exhibit greater improvements in cognitive performance compared to an urban built environment, regardless of season, the 2-back task, a commonly used measure associated with working memory and attention control [21], was administered using the PsyToolkit platform [22] before and after the walks. Participants viewed a sequence of letters and pressed the *Match* button whenever the current letter was identical to the one shown two steps earlier. The task began with a practice phase (10 trials, including guidance and two targets) followed by a main phase (30 trials, eight targets). Each letter was displayed for 1000 ms, with a 2000-ms response window. To ensure comparability, all participants received the same target/non-target sequence, while different letter sets were used before and after the walk to minimize practice effects. Any residual learning effects are expected to be consistent across participants, as analyses were based on within-subject pre- and post-walk comparisons. After each test session, participants rated perceived difficulty and their ability to follow the test using a 3-point Likert scale. Only participants who completed both routes and reported following the test instructions were included (n=30; 11 in summer, 19 in winter). Two task performance measures were obtained:

- Accuracy: calculated by subtracting false positives (non-target hits by the total number of non-targets) from true positives (number of target hits by the total number of targets) and dividing by the total number of targets,
- Response latency: calculated by averaging reaction times (in milliseconds) for correct target identifications.

D. Analysis Method

To address the research questions, we conducted within-subject comparisons between the two walking routes separately for each season. Due to non-equivalent participant groups for summer and winter, within-subject comparisons could not be extended for different seasons. Instead, we report

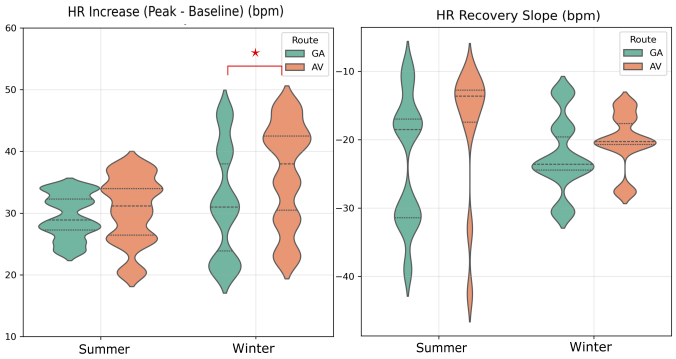

Fig. 3. Comparison of heart rate increase during the walks and heart rate recovery after the walks along the two routes for summer and winter.

descriptive observations from the route comparisons conducted separately in each season to assess consistency.

Statistical analyses were performed using two-sided Student's t-tests for group comparisons, following verification of parametric assumptions: normality (Shapiro-Wilk test) and homogeneity of variance (Levene's test), considering $\alpha = 0.05$. Paired t-tests were applied for within-season (within-subject) comparisons between the two routes. If parametric assumptions were violated, the Wilcoxon signed-rank test was used, with the rank-biserial correlation (r) used to calculate the effect size. Effect sizes and 95% confidence intervals (CI) were calculated using Hedge's g.

IV. Results

A. RQ1: Heart Rate Responses Across Walking Environments

To compare the physiological responses to walking in urban built-up (AV) and forest (GA) environments, we compared HR increase and recovery across two routes in each season.

Heart Rate Increase (HRI): As expected, greater heart rate increase was observed for AV in both seasons (Fig. 3-left). In winter, the difference between the HR increases in GA and AV was statistically significant, i.e., participants exhibited higher heart rate increases in AV (median HRI = 36.33 bpm) compared to GA (median HRI = 31.81 bpm), $t(10)$ = -3.57, p = 0.016, with a moderate effect size (Hedge's g = –0.44). However, the wide confidence interval (95% CI [-2.84, 1.96]) suggests limited statistical power, likely due to small sample size and considerable physiological variability across individuals. Violin plots in Fig. 3 provide further information, namely, wider distribution indicating greater individual variability, and multimodal distributions indicating the presence of subgroups.

Heart Rate Recovery (HRR): Following the expectation, median HRR was slightly greater in GA than AV in both seasons, although not significantly different (Fig. 3 (right)). For RQ1a, urban forest walks resulted in lower HRI than built-up area walks in winter, and a similar yet marginal trend was observed in summer. For RQ1b, although HRR was consistently faster after forest walks, the difference was not statistically significant in either season. These findings provide conditional support for RQ1: even in winter, urban forest walks appear to induce lower physiological stress and promote faster stress recovery compared to built environments.

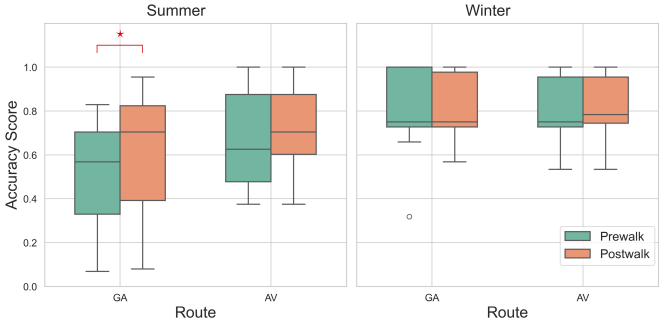

Fig. 4. Comparison of 2-back test accuracies in summer and winter.

B. RQ2: Cognitive Performance Across Walking Environments

To compare cognitive responses to walking in urban forest (GA) and urban built-up area (AV), we compared pre- to post-walk changes in 2-back task accuracy and response latency across two routes in each season.

Accuracy: In summer, participants walking in the urban forest (GA) showed a statistically significantly grater improvement in accuracy from pre-walk (median = 0.568) to post-walk (median = 0.704), as indicated by the Wilcoxon signed-rank test (W = 4.5, p = 0.031, r = 0.65, 95% CI [0.08, 0.90]), see Fig. 4. In the urban built-up area (AV), a similar trend was observed (pre-walk median = 0.625; post-walk median = 0.705), but the increase was not statistically significant (p = 0.263). In winter, no significant changes in accuracy were observed for either route. Participants began with higher baseline scores in the pre-walk condition, suggesting a potential ceiling effect limiting post-walk improvement.

Response Latency: Contradicting our expectation of post-walk performance to be associated with faster cognitive processing (i.e., lower response latency), response times tended to increase after the walk across both routes in summer and in winter (see Fig. 5), with a greater median increase after AV walks, although not statistically significantly different.

Furthermore, we compared the cognitive restoration potential of the two walking routes at the participant level, computing the difference between post- and pre-walk scores for each participant and comparing these difference scores across routes. In summer, GA walks were associated with greater accuracy improvements and smaller increases in response latency than AV walks, suggesting more substantial cognitive restoration effects in the urban forest environment. However, high variability was present across participants. In winter, this pattern in response latency persisted, but the accuracy differences between routes disappeared.

These findings partially support RQ2: urban forest walks appear to enhance cognitive performance in summer, particularly in terms of accuracy, consistent with attention restoration theory. However, this effect was not observed in winter.

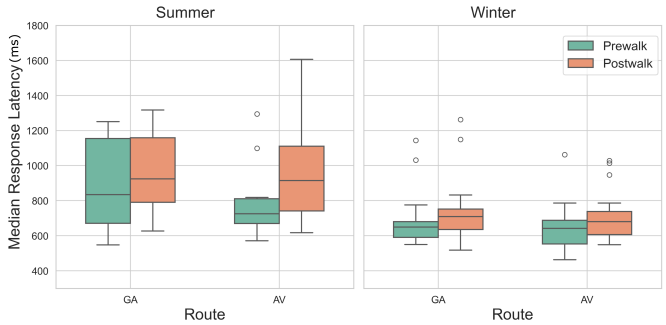

Fig. 5. Comparison of 2-back test mean response latencies in summer and winter.

V. Discussion

This study examined the impact of walking in urban forest (GA) versus built-up (AV) environments on cognitive and physiological responses during both summer and winter. Aligned with Attention Restoration Theory, participants showed improved 2-back accuracy after summer walks in GA, suggesting short-term cognitive benefits. This effect was not observed in winter, possibly due to ceiling effects from higher baseline scores or reduced sensory engagement (e.g., less greenery, sunlight). The increase in post-walk response latency may reflect separate cognitive mechanisms for speed and accuracy [15]. HR data showed consistent patterns for environment-related differences in both seasons. Specifically, HR increases were higher in AV than GA during winter, supporting Stress Reduction Theory. However, wide individual variability, especially in winter, suggests that cold adaptation may modulate these stress responses, which requires further investigation with a larger population. Several limitations should be noted. Despite an initially robust sample size, significant data loss due to incomplete physiological recordings and participants not walking both routes reduced statistical power, a common challenge in field studies. Nevertheless, a within-participant design for each season allowed for comparison, despite inter-individual variability, especially in heart rate responses. The winter participants had higher pre-walk accuracy, which may have masked restoration effects. Additionally, the ambulatory study design, although ecologically valid, introduced uncontrolled variables such as walking pace, limited interaction with the environment, variable clothing insulation, and the absence of an objective measure of thermal comfort. These findings carry implications for digital health technologies - continuous heart rate measurements demonstrated sensitivity to environmental context, suggesting potential for real-time stress tracking and intervention in daily life.

VI. Conclusion

This study investigated how walking in urban forest versus urban built-up environments influences cognitive and physiological responses across summer and winter. Results highlight conditional support for the additional restorative benefits of natural urban environments compared to built environments, and the extent of these benefits depends on contextual factors, including seasons. Forest walks in summer improved cognitive accuracy, while built-up area routes in winter elicited stronger stress-related heart rate responses and slower heart rate recovery. Future research should validate these patterns using larger samples and longitudinal designs to capture within-person changes across seasons.

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