Received: 29 March 2023 | Revised: 14 August 2023 | Accepted: 15 September 2023

DOI: 10.1111/sms.14505

ORIGINAL ARTICLE

WILEY

Physical activity, residential greenness, and cardiac autonomic function

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Funding information
European Regional Development Fund, Grant/Award Number: 539/2010 A31592; Opetus-ja Kulttuuriministeriö; Oulun Yliopistollinen Sairaala; Strategic Research Council, Grant/Award Number: 345222 and 345220; University of Oulu, Grant/Award Number: 24000692; Oulu University Hospital, Grant/Award Number: 24301140; Ministry of Education and Culture, Grant/Award Number: OKM/28/626/2023, OKM/76/626/2022, OKM/20/626/2022, OKM/1096/626/2020, OKM/85/626/2019 and OKM/54/626/2019

Abstract

Purpose: This population-based study examines the associations between physical activity (PA), residential environmental greenness, and cardiac health measured by resting short-term heart rate variability (HRV).

Methods: Residential greenness of a birth cohort sample ($n = 5433$) at 46 years was measured with normalized difference vegetation index (NDVI) by fixing a 1 km buffer around each participant's home. Daily light PA (LPA), moderate PA (MPA), vigorous PA (VPA), and the combination of both (MVPA) were measured using a wrist-worn accelerometer for 14 days. Resting HRV was measured with a heart rate monitor, and generalized additive modeling (GAM) was used to examine the association between PA, NDVI, and resting HRV.

Results: In nongreen areas, men had less PA at all intensity levels compared to men in green areas. Women had more LPA and total PA and less MPA, MVPA, and VPA in green residential areas compared to nongreen areas. In green residential areas, men had more MPA, MVPA, and VPA than women, whereas women had more LPA than men. GAM showed positive linear associations between LPA, MVPA and HRV in all models.

Conclusions: Higher LPA and MVPA were significantly associated with increased HRV, irrespective of residential greenness. Greenness was positively associated with PA at all intensity levels in men, whereas in women, a positive association was found for LPA and total PA. A positive relationship of PA with resting HRV and greenness with PA was found. Residential greenness for promoting PA and heart health in adults should be considered in city planning.

KEYWORDS

cardiovascular health, generalized additive model, geographic information system, physical activity, residential greenness

1 | INTRODUCTION

In recent years, there has been an increasing interest in the health benefits of residential greenness and the possible health benefits of green spaces for cardiac health. Residential greenness and engaging in physical activity (PA) in green areas have been suggested to be associated with improved cardiac autonomic function (i.e., increased values on resting vagal-related HRV parameters).[1] Heart rate variability (HRV) is a reliable indicator of parasympathetic regulation.[2] Decreased continuous resting HRV may reflect the future risk of cardiac events, such as sudden cardiac-related death, atherosclerosis, coronary heart disease, stroke, and myocardial infarction.[3] Field experiments have demonstrated that short walks in green environments are associated with short-term improvements in cardiovascular physiology and HRV.[4,5] Lunchtime walks in natural environments have been suggested to provide a greater restorative effect measured by HRV than inbuilt environments.[6] Residential greenness has also been shown to increase the amount of PA and lower the risk of obesity in women.[7] Among 31 European countries, it was estimated that a large number of premature deaths in European cities could be prevented by increasing patients' exposure to green spaces.[8] Apart from increasing the amount of PA, interaction with nature has been suggested to be associated with multiple other health outcomes.[9] According to a systematic review, nature exposure is positively associated with reduced perceived and measured physiological stress as well as with parasympathetic regulation and improved short-term HRV.[10,11] Green environments are associated with stress reduction, psychological well-being, and positive social outcomes.[12] Even 30-min visits to urban nature have been reported to reduce both mental and physiological stress.[13]

Residential greenness can be measured with the normalized difference vegetation index (NDVI), which refers to satellite imaging-based greenness measurement.[14] Using NDVI to measure residential greenness in epidemiological studies has gained popularity in recent years. The existing body of research on NDVI and PA suggests that distance to green spaces and surrounding green areas is associated with decreased possibility of being overweight and engaging in self-reported outdoor MVPA.[15] For example, in a national survey in Canada, NDVI-measured urban greenness was positively associated with higher levels of PA.[16]

The relationship between PA and cardiac health is well established. Regular PA, especially moderate-to-vigorous-intensity PA (MVPA), is associated with a lower risk of cardiovascular diseases and metabolic syndromes.[17] Empirical evidence demonstrates the importance of PA for improving autonomic regulation.[18] For example, MVPA improves resting HRV and the vagal activity, and even a slight increase in PA is shown to be beneficial for cardiac autonomic function in young men.[19] A higher level of MVPA is associated with an increase in cardiorespiratory fitness (CRF), including lower resting heart rate (HR) and improved heart rate recovery (HRR) after exercise.[20] Recent studies have also highlighted the importance of light physical activity (LPA), which is recommended for people with sedentary lifestyles. Light physical activity is associated with a lower risk of obesity, better glucose metabolism, and lower all-cause mortality risk.[21] Cardiovascular disease risk between both sexes is well established,[22] whereas there are fewer studies investigating gender differences related to the effect of environmental characteristics associated with PA. According to a systematic review, activity-friendly built environments in general have a positive effect on both sexes, but the impacts of separate environmental characteristics can vary between males and females.[23] According to another systematic review, urban greenness has been generally found to be protective against cardiovascular risk factors and diseases, but the exact risk factors and diseases may differ between sexes.[24]

The objective of this study is to reveal the associations between PA at different intensity levels and resting HRV, considering exposure to residential greenness measured with NDVI, among a large population-based sample of Finnish middle-aged adults. The hypothesis was that residential greenness is positively associated with improved resting HRV and the amount of PA at all intensity levels.

2 | MATERIALS AND METHODS

2.1 | Study population

The Northern Finland Birth Cohort includes all study participants whose expected birth dates fell in 1966 ($n=12\,058$). The data for this cross-sectional study were from the most recent data collection at 46 years of age for all study participants ($n=10\,321$). The data were collected from April 2012 to April 2014 through questionnaires ($n=6384$) and clinical examinations ($n=5852$). The data collection in the 46-year follow-up further included completion of postal questionnaires, a clinical examination for collection of fasting blood samples and anthropometric measurements, and on a separate day and oral glucose tolerance test. HRV was measured on the clinical examination day. Physical activity was measured with a Polar Active (Polar Electro) accelerometer-based activity monitor for 14 days ($n=5481$). The final study population included all those whose residential environmental greenness was measured objectively using a satellite imaging-based NDVI in a geographic information system (GIS) ($n=5433$).

The study was approved by the ethical committee of the Northern Ostrobothnia Hospital district in Oulu, Finland (94/2011), and it was performed in accordance with the Declaration of Helsinki. Written consent for the study was given by the subjects, and personal identity information was encrypted and replaced with identification codes to provide pseudonymized data for the research.

2.2 | Measurements

2.2.1 | Cardiac autonomic function measurement

One of the most often used methods to measure HRV are time-domain methods that measure the intervals in the QRS complex (a combination of the Q wave, R wave, and S wave) between successive normal-to-normal (NN) beats. Time domain variables are then calculated from the NN interval. Generally used variables are the standard deviation (SD) of the NN intervals (SDNN) and the mean square root of the successive NN differences (rMSSD). Among the existing variables, rMSSD is the most commonly used metric for assessing HRV.[19]

The description of the HRV measurement has been published previously.[25] In short, the study participants sat in a chair while the study protocol was described to them and the instrumentation for the measurement was attached. A heart rate monitor (RS800CX) was used to record the R-R intervals (RRi). A 1-min resting period was given to stabilize the HR. Resting short-term HRV was recorded in seated position, from which 150 s were analyzed. Artifacts and ectopic beats were removed and replaced by the local average (Hearts 1.2, University of Oulu, Oulu, Finland), and sequences with ≥10 consecutive beats of noise or ectopic beats were deleted. The RRi series with ≥80% accepted data was included in the analysis. A total of 5679 participants took part in the cardiac autonomic function measurement, and 5473 had eligible HRV data. For interpretation, the vagal activity root mean square of successive differences (rMSSD) was analyzed from the measurements taken in the seated position.

2.2.2 | Accelerometer-measured physical activity

Physical activity was measured with a wrist-worn Polar Active accelerometer without feedback sent to the user ($n=5481$). The participants wore activity monitors for 14 days (24 h/day) on the wrists of their nondominant hands. Polar Active provides metabolic equivalent of task (MET) values every 30 s, and it has been shown to correlate ($R^2=0.74$) with the double labeled water technique in assessing energy expenditure while training and during daily living ($R^2=0.77$).[26] Polar Active uses the height, weight, sex, and age of the user as predefined inputs. Furthermore, the daily durations of different activity levels were calculated based on the intensity levels provided by the device manufacturer (very light: 1–1.99 MET; light: 2–3.49 MET; moderate: 3.5–4.99 MET; vigorous: 5–7.99 MET; and very vigorous ≥8 MET).[27] The MVPA intensity threshold was set to all activities with an intensity of at least 3.5 METs. The average volume of each activity level (MET min/day) was calculated by multiplying each MET value by its duration. The participants who provided at least four valid days, defined as 600 min/day of monitor wearing time during their waking hours, were included in the analysis.

2.2.3 | Residential greenness

Geographic information system was used to assess the quantitative features of the participants' residential environment. This information was based on the exact geographical coordinates of their home addresses in 2014. The inclusion criteria for the study were that the participants had lived in their residential area and at the same address for at least 3 months. A circular buffer with a 1 km radius was fixed around each participant's home to represent their living environment. Residential greenness in a living environment was measured using NDVI based on satellite imaging (with a resolution of 30×30m), defined as NDVI = $(NIR-R)/(NIR+R)$ in which NIR represents near infrared and R represents the red values from the spectrum. NDVI has been shown to be a reliable method for analyzing overall residential greenness.[14] NDVI values range from −1 to +1. Areas with natural elements such as rock and water are valued closer to −1. Built areas and areas with sparse vegetation are typically valued closer to 0.2–0.3. Finally, areas with sparse vegetation, such as bushes, are valued at approximately 0.4. Substantially greener areas such as forests and fields have high NDVI values (>0.6).[28] The NDVI was calculated from the Landsat 8 (L8) satellite images provided by the United States Geological Survey (USGS). Images were selected by cloud coverage (<10%) and the time of the year (June 2013–July 2016), since they are the greenest months during the growing season in Finland.

2.2.4 | Confounders

Participants were asked about their education, which was categorized as either high or low. Alcohol consumption was estimated by the question, "How much alcoholic beverages do you normally drink?" This was accompanied by portion examples that were converted to grams per day. Further, sleep duration was assessed by the question, "How many hours do you sleep on average per day?" The responses were changed to minutes per day, and the variables were categorized to avert multicollinearity.

The weight and height of the participants were measured at the clinical examination, and their body mass index (BMI) was calculated as weight (kg) divided by height square (m^2). Cardiorespiratory fitness was measured by a submaximal 4-min single-step test with continuous heart rate measurement (RS800CX, Polar Electro) and expressed as the peak heart rate. In essence, the peak heart rate in a submaximal step test is an acceptable surrogate for estimating CRF in the general adult population.[29] Sedentary activity was obtained from accelerometry data. The total amount of sedentary time was measured as very light activity (min/day) to represent the participants' sedentary behavior.

2.3 | Statistical analyses

The distribution of the variables was determined by analyzing skewness with histograms. The descriptive statistics were calculated with Pearson's correlation test, and the means and SDs for the continuous variables were calculated with normal distributions. Spearman's rank correlation coefficient was used for continuous variables with skewed distributions, and frequencies and percentages were used for categorical variables. An independent samples T test was used to analyze the statistical significance of the difference of means between grouping variables (at each intensity level of PA for men and women, including the amount of residential greenness [NDVI was either <0.5 or >0.5]). For skewed variables, Mann–Whitney U test was performed. Moreover, explanatory variables were tested for multicollinearity, and the highest correlation allowed between variables was 0.6. The data were analyzed using SPSS version 28.0.1.0 (IBM). The limit for statistical difference was set at $p<0.05$ in all analyses.

Generalized additive modeling (GAM) was used to study the association between resting HRV, LPA, and MVPA. It is reported to be applicable when the data are not linear, as GAM is flexible and allows nonlinear shapes, providing the potential for there being better matches to the data.[30] Using the mcgv package, natural cubic splines with four degrees of freedom were fitted using the ns function in the R software, version 4.01 (R Core Team). The normality of the residuals was checked, and the restricted maximum likelihood (REML) was used in the GAM. The nonlinear associations were characterized by fitted smoothing curves in the GAM. In addition, the GAM was characterized in univariate and multivariable models. The univariate models included HRV, LPA, and MVPA. Multivariable GAM was adjusted with the possible confounders BMI (kg/m^2), daily alcohol consumption (g), higher education (yes/no), sleep duration, CRF, and sedentary time. In addition, as rMSSD and HR are strongly associated with each other,[31] the GAM models were characterized with HR as covariate (Figure S1).

Then, a sensitivity analysis was performed by excluding participants with self-reported elevated blood pressure, congenital heart disease, heart failure, coronary artery disease, diabetes (types 1 and 2), or transient ischemic attack ($n=3817$) (Table S1 and Figures S1, S2 and S3).

3 | RESULTS

A total of 5433 participants had valid coordinate-based data on residential greenness and HRV. The mean age of the participants was 46.6 (0.5) years, and 56% ($n=3043$) were women and 44% ($n=2390$) were men. In green environments (NDVI > 0.5), 55.1% of the participants were women, and in nongreen environments (NDVI < 0.5), 56.4% of the participants were women. Participants living in green environments were engaged in more physical activity at all intensity levels ($p<0.001$). On average, the factors associated with participants' health-related quality of life were better in nongreen environments. Nongreen environments were related to lower BMI ($p<0.001$) and higher education ($p<0.001$). However, daily alcohol intake (g) and current smoking (%) were higher in nongreen environments

($p < 0.001$). Regarding factors associated with cardiac function, participants in green environment (NDVI > 0.5) had a better CRF ($p < 0.001$). Participants living in green environment (NDVI > 0.5) had higher amount of PA at all intensity levels (LPA; $p < 0.001$, MPA; $p < 0.001$; MVPA: $p < 0.001$; VPA: $p < 0.001$; Total PA: $p < 0.001$) and had less sedentary time than participants living in nongreen environment (NDVI < 0.5) ($p < 0.001$). The full characteristics of the study population are presented in Table 1.

The amount of PA at different intensity levels in green and nongreen areas in men and women is presented in Table 2. Men had approximately 60 MET min more (mean difference 56.0, 95% CI; 39.6 to 72.4) of daily LPA in green areas compared to men living in nongreen areas. In green residential areas, men also had more MPA (mean difference 18.8, 95% CI; 10.4 to 27.3), MVPA (mean difference 27.1, 95% CI; 5.2 to 49.0), VPA (mean difference 8.2, 95% CI; −6.7 to 23.3), and total PA (mean difference 83.2, 95% CI; 50.7 to 115.6) compared with men in nongreen areas.

Women had approximately 40 MET min more LPA (mean difference 38.7, 95% CI; 23.8 to 53.6) and 26 MET min more total amount of PA (mean difference 26.6, 95% CI; 3.3 to 49.8) in green areas. In the nongreen areas, women had more MPA (mean difference −6.9, 95% CI; −11.4 to −2.4), MVPA (mean difference −12.1, 95% CI; −25.8 to 1.4), and VPA (mean difference 5.1, 95% CI; −16.5 to 6.1), but only MPA was statistically significant.

When comparing the amount of PA in green and nongreen areas in men and women, women had about 28 MET min more LPA in green areas than men. In all other intensity levels of PA (MPA, MVPA, VPA, and total PA), men were more active in green areas than women.

3.1 | Univariate generalized additive modeling-based associations between PA and HRV

GAM-based associations between LPA, MVPA, and the cardiac autonomic function measured as resting rMSSD are presented in Figures 1–4. Figure 1A,B present univariate associations between LPA, MVPA, and rMSSD

TABLE 1 Characteristics of the study population in green (NDVI > 0.5; $n = 1690$) and nongreen (NDVI < 0.5; $n = 3743$) environments.

Variable	Full sample ($n = 5433$)	NDVI > 0.5 (green environment; $n = 1690$)	NDVI < 0.5 (nongreen environment; $n = 3743$)
Demographics			
Age (year)	46.6 (0.5)	46.6 (0.5)	46.6 (0.5)
Men	2390 (44%)	759 (44.9%)	1631 (43.6%)
Women	3043 (56%)	931 (55.1%)	2112 (56.4%)
Lifestyle factors and health-related quality of life			
Weight (kg)	78.5 (16.6)	78.8 (16.8)	78.4 (16.5)**
Height (cm)	170.8 (9.1)	170.6 (9.1)	170.9 (9.1)**
BMI (kg/m^2)	26.8 (4.8)	26.9 (4.9)	26.7 (4.8)**
Daily alcohol intake (g)	10.4 (16.9)	9.8 (16.4)	10.7 (17.1)**
Current smoking (*n*, %)	1168 (21.4)	369 (21.8)	799 (21.3)
Highly educated (*n*, %)	1443 (26.3)	324 (19.1)	1119 (29.9)**
Cardiac function			
HR (bpm)	72.0 (11.3)	71.5 (11.1)	72.0 (11.3)
rMSSD (ms, median/range)	22.1 (134.6)	22.1 (134.2)	22.1 (123.6)
Cardiorespiratory fitness (peak HR)	147.5 (15.4)	146.3 (15.5)	148.0 (15.3)**
Physical activity			
LPA (MET min/day)	719.4 (193.8)	751.1 (197.4)	705.1 (190.5)**
MPA (MET min/day)	144.2 (87.6)	148.0 (97.9)	142.5 (82.6)**
MVPA (MET min/day)	370.0 (208.9)	374.5 (235.3)	367.9 (195.7)**
VPA (MET min/day)	225.7 (160.1)	226.4 (177.5)	225.4 (151.7)**
Total PA	1089.4 (326.7)	1125.6 (358.2)	1073.1 (310.2)**
Sedentary behavior (very light activity) (min/day)	631.2 (91.6)	619.9 (91.7)	636.4 (91.5)**

Note: Values are mean (SD) or count (%) if not otherwise stated. *$p < 0.05$, **$p < 0.001$, *p*-values indicate statistical difference between groups (total study population in green environments and nongreen environments).

Abbreviations: HR, heart rate; LPA, light physical activity; MPA, moderate physical activity; MVPA, moderate to vigorous physical activity; rMSSD, root mean square of successive differences in R-R intervals; Total PA, all at least 2 METs metmin/day from those with valid PA data; VPA, vigorous physical activity.

TABLE 2 Physical activity intensity levels in green (NDVI > 0.5) and nongreen (NDVI < 0.5) environments in men and women.

Variable	Men in green environments NDVI > 0.5 (n = 759)	Men in nongreen environments NDVI < 0.5 (n = 1631)	Women in green environments NDVI > 0.5 (n = 931)	Women in nongreen environments NDVI < 0.5 (n = 2112)
LPA (MET min/day)	735.8 (197.8)	679.8 (185.9)**	763.5 (196.2)	724.7 (191.7)**
MPA (MET min/day)	201.0 (109.3)	182.1 (92.3)**	104.9 (59.3)	111.9 (57.9)**
MVPA (MET min/day)	440.9 (271.3)	413.8 (213.1)*	320.4 (184.5)	332.5 (173.2)
VPA (MET min/day)	239.9 (202.0)	231.6 (160.6)	215.5 (153.9)	220.6 (144.2)
Total PA	1176.8 (396.7)	1093.6 (328.8)**	1083.9 (317.5)	1057.3 (294.1)*

Note: Values are means (SD) if not stated otherwise. *$p < 0.05$, **$p < 0.001$, p-values indicate statistical difference between groups (men in green and nongreen areas, and women in green and nongreen areas).

Abbreviations: NDVI, Normalized difference vegetation index; LPA, light physical activity; MPA, moderate physical activity; MVPA, moderate to vigorous physical activity; Total PA, all at least 2 METs metmin/day from those with valid PA data; VPA, vigorous physical activity.

(Model I). There was a significant and positive association between higher LPA and rMSSD (Figure 1A), which leveled off after 400–500 MET min of daily LPA. Higher MVPA and rMSSD were also nonlinearly associated, and the point after which PA had a positive association with resting HRV was about 500 MET min of daily LPA and 500–600 MET min of daily MVPA.

3.2 | Multivariable generalized additive modeling-based associations between PA and HRV

Figure 2A,B show the plots for the associations between PA and rMSSD after the adjustment with BMI, daily alcohol consumption, higher education, sleep duration, CRF, and sedentary time (Model II). There was a relationship between higher LPA and increased rMSSD (Figure 2A), leveling off after a threshold value of 500 MET min daily. There was an even stronger linear response curve for the association between high levels of MVPA and increased rMSSD. However, the precision was reduced, and the confidence intervals grew wider after 500 MET min (Figure 2B).

Figure 3A,B present the GAM after the adjustment with Model II confounders and NDVI (Model III). Model III for rMSSD and LPA (Figure 3A) and rMSSD and MVPA (Figure 3B) had a positive linear relationship, which became less precise after 500 MET min. Therefore, Models II and III yielded similar results, indicating that PA was associated with rMSSD, irrespective of NDVI.

The differences in the multivariable GAM (Model IV) between men and women are presented in Figure 4A–D. For rMSSD and LPA (Figure 4A), in men, there was a positive association similar to the previous multivariable Model II. Higher MVPA was strongly and linearly associated with increased rMSSD in men (Figure 4B). In the multivariable GAM for women, the response curve for LPA and rMSSD (Figure 4C) was almost even with a nearly negative effect, indicating a weaker association. Higher MVPA and increased rMSSD were linearly associated in women (Figure 4D).

Performing the sensitivity analysis with the exclusion of participants with elevated blood pressure, congenital heart disease, heart failure, coronary artery disease, diabetes (types 1 and 2), or transient ischemic attack (n = 3817) changed the shape of the GAM association only slightly and did not change the interpretation of the main results (Table S1 and Figures S1, S2 and S3). In univariate LPA and rMSSD, the sensitivity analysis of the association was similar to Model I. In univariate analysis of MVPA and rMSSD, the association was more linear than in the univariate Model I without the sensitivity analysis. In multivariable sensitivity analyses, the association between LPA and rMSSD was more strongly inverse, whereas the association between MVPA and rMSSD was more strongly positive, and the estimate was more precise than in Model III without the sensitivity analysis.

4 | DISCUSSION

We found a significant positive association with LPA, MVPA, and resting short-term HRV, as well as with residential greenness and PA at all intensity levels. However, in contrast to our hypothesis, residential greenness did not have an impact on the association between PA intensity levels and resting HRV. There were differences in the amount of PA in men and women in green and nongreen areas. Women had more LPA in green residential areas than men; however, men had more PA at all other intensity levels in green residential areas compared to women.

In this study, PA was associated with resting HRV, irrespective of residential greenness. These results differ from those of recent small-scale studies that have suggested that walking in a green environment or forest seems to benefit

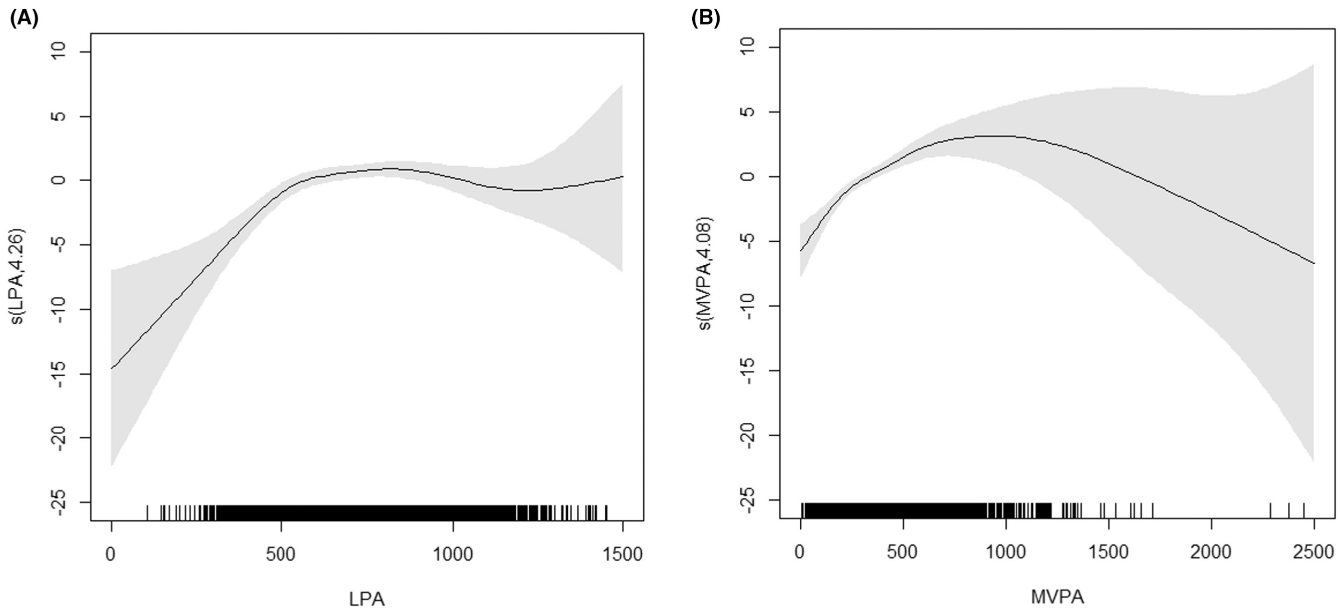

FIGURE 1 Model I. Univariate Generalized Additive Modeling-based Response Curves for the Association between (A) LPA and (B) MVPA and rMSSD ($n = 5433$). The explanatory variables were fitted to rMSSD using a smoothing spline. x-axes represent the observed values of LPA/MVPA, and y-axes represent the fitted function with estimated degrees of freedom. LPA, light physical activity; MVPA, moderate to vigorous physical activity; rMSSD, root mean square of successive differences in R-R intervals.

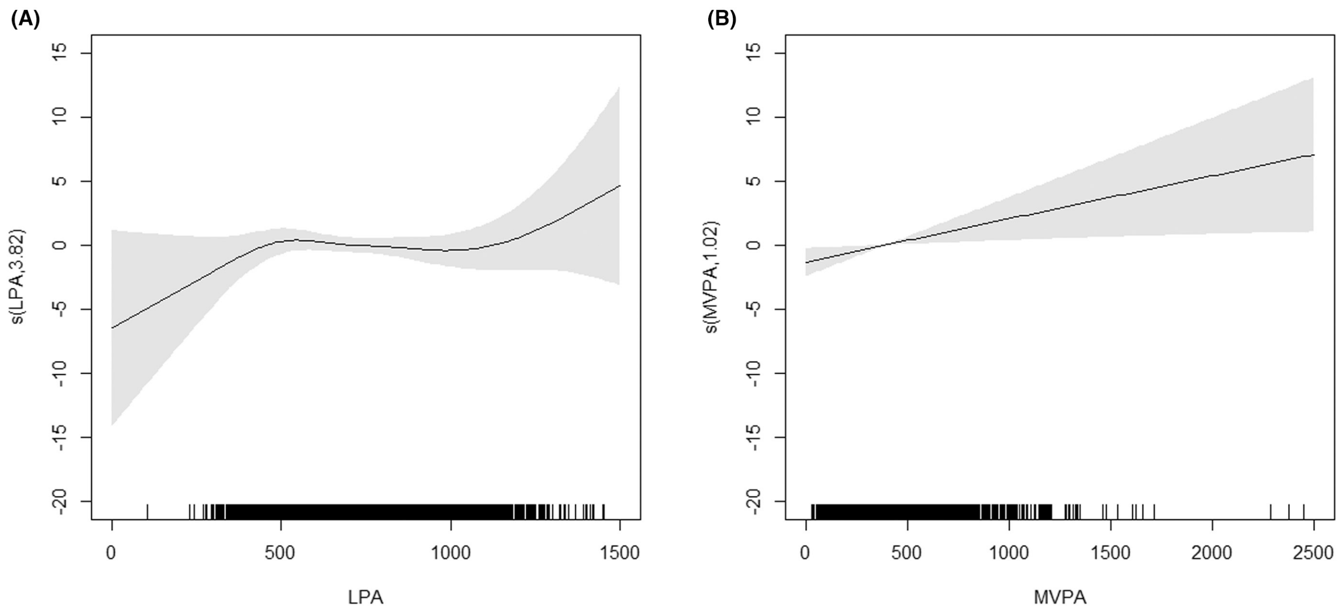

FIGURE 2 Model II. Multivariable Generalized Additive Modeling-based Response Curves for the Association between LPA, MVPA, and rMSSD ($n = 5433$). The explanatory variables were fitted to rMSSD using a smoothing spline. Adjusted with BMI, alcohol consumption, gender, higher education, sleep duration, CRF and sedentary time. (A) Adjusted rMSSD and LPA. (B) Adjusted rMSSD and MVPA. x-axes represent the observed values of LPA/MVPA, and y-axes represent the fitted function with estimated degrees of freedom. BMI, body mass index; CRF, cardiorespiratory fitness; LPA, light physical activity; MVPA, moderate to vigorous physical activity; rMSSD, root mean square of successive differences in R-R intervals.

HRV responses compared to an urban environment.[4,5] Green environments have been suggested to improve HRV through stress reduction, as natural environments have been shown to exhibit restorative effects.[32] This is consistent with a recent study that found that exposure to natural environment was associated with stress reduction and decrease in HRV.[10] Even 30-min visits to urban nature have also been shown to reduce psychological stress in a field experiment.[13] Contrary to expectations and the previous literature, in this study, we did not find a significant

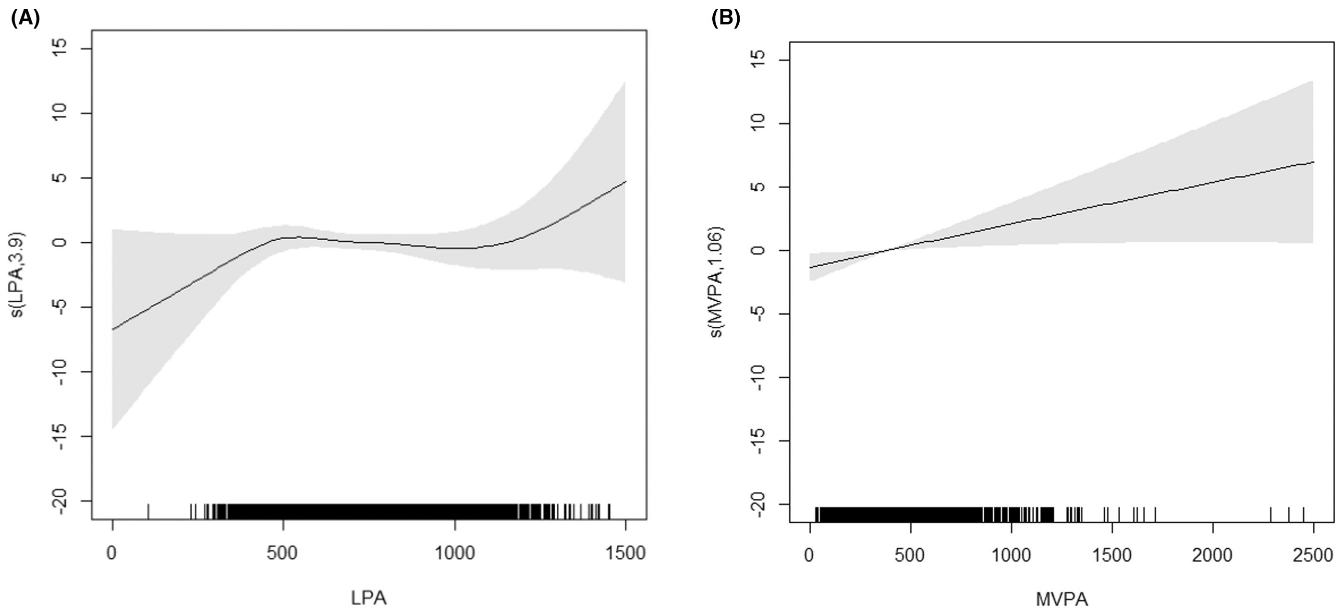

FIGURE 3 Model III. Multivariable Generalized Additive Modeling-based Response Curves for the Association between LPA, MVPA, and rMSSD ($n = 5433$). The explanatory variables were fitted to rMSSD using a smoothing spline. Adjusted with BMI, alcohol consumption, gender, higher education, sleep duration, CRF, sedentary time, and NDVI. (A) Adjusted rMSSD and LPA. (B) Adjusted rMSSD and MVPA. x-axes represent the observed values of LPA/MVPA, and y-axes represent the fitted function with estimated degrees of freedom. BMI, body mass index; CRF, cardiorespiratory fitness; LPA, light physical activity; MVPA, moderate to vigorous physical activity; NDVI, normalized difference vegetation index; rMSSD, root mean square of successive differences in R-R intervals.

association between PA, HRV, and residential greenness. A possible explanation for these contradictory findings may be differences in the study sampling and settings. Findings in previous, somewhat smaller-scale studies conducted among smaller or younger populations may not represent the effects of longer-term living in green residential areas.[33]

We found that both LPA and MVPA were positively associated with resting HRV with a minimum needed amount of 500 MET min for LPA intensity and 500–600 MET min for MVPA intensity, irrespective of residential greenness. Our results specifically indicated a linear association between high levels of LPA and MVPA and resting HRV. However, the association leveled off after 500 MET min. The possible reason for this is that the response curves in the GAM level off after the number of participants decreases. The results are in line with the existing literature suggesting that the total PA volume needs to be several times higher than the recommended minimum level of 600 MET min/week for larger reductions in the risk of heart disease.[34]

Based on our results, residential greenness is associated with the amount of PA. This is consistent with the previous literature. Recently, there has been emerging evidence on the health benefits of residential greenness towards promoting PA and improving overall cardiac health by decreasing cardiovascular disease risk and mortality.[35] Previous studies have shown that access to green areas can increase the amount of PA. For example, a self-reported distance to green spaces has been associated with leisure time MVPA.[36] Green residential areas may also offer a suitable environment for LPA, such as walking, cycling, or gardening.[37] The benefits of LPA are its relatively easy incorporation into daily life and activities. In more urban areas, green spaces are associated with more frequent PA in association with commuting. This highlights the importance of urban infrastructure for recreational and commuting opportunities that promote PA in green environments.[38]

There is some evidence suggesting that residential greenness has no association with PA. In a cross-sectional study with middle-aged adults, there were no population-level associations between recreational PA and access to green spaces.[39] Furthermore, in another cohort study, there was no association between health and the percentage of greenness in residential spaces.[40]

This study indicated that a high amount of greenness in residential areas was associated with a higher amount of accelerometry-measured PA at all different intensities. The amount of PA at all measured intensities, except for LPA, was higher among men living in green environments compared to women, supporting a few previous studies suggesting that men may be more engaged in PA in green environments. For example, it was shown among older adults that men spent more minutes in MVPA and sedentary time compared with women.[41]

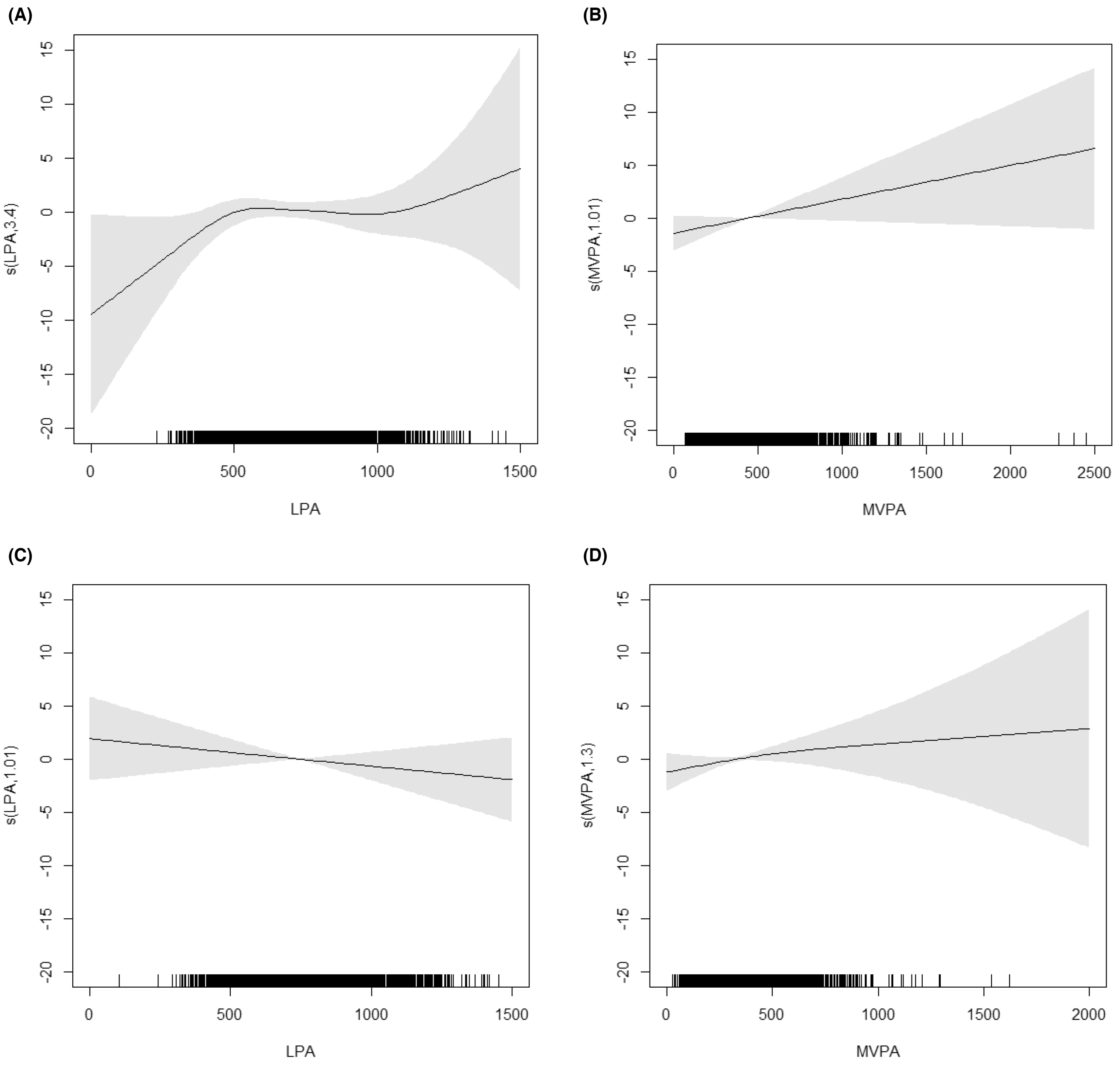

FIGURE 4 Model IV. Multivariable Generalized Additive Modeling-based Response Curves for the Association between LPA and MVPA with rMSSD stratified by men (A and B) ($n = 2390$) and women (C and D) ($n = 3043$). All the models were adjusted for BMI, alcohol consumption, higher education, sleep duration, CRF, sedentary time, and NDVI. x-axes represent the observed values of LPA/MVPA, and y-axes represent the fitted function with estimated degrees of freedom. LPA, light physical activity; MVPA, moderate to vigorous physical activity; rMSSD, root mean square of successive differences in R-R intervals; BMI, body mass index; CRF, cardiorespiratory fitness; NDVI, normalized difference vegetation index.

In another study conducted for older men, the amount of PA was higher in green neighborhoods.[42] However, in this study, women living in green areas had more LPA compared to men. Urban green open spaces play an important role in promoting PA, especially among women and the old.[43] Previously, it was shown that there is an association between greenness and the measures of PA in young women.[16] One reason women may engage in more LPA in green residential areas is that women may complete lighter household chores, walk more, or garden more than men.[44]

The strengths of this study are its large population-based cohort sample of Finnish adults and the accelerometer-based measurement of PA. GIS was used to measure the amount of greenness. Thus far, this is the first population-based study to use the GAM to model the association between PA, HRV, and residential greenness. Another strength of this study compared to field experiments is that the participants of the NFBC1966 have lived in their residential area or coordinate location for at least 3 months. This provides a more reliable way of interpreting the association of residential greenness with PA and HRV.

However, the methodological limitations of this study should be acknowledged. Interpreting the association between PA, HRV, and residential greenness is complicated. Overall, the response of HRV to residential greenness is not yet fully understood. Socioeconomic statuses and strenuous work, for example, may have mediating effects. Furthermore, with a lack of information about where the study participants' PA occurred, the results have some uncertainty. Based on a self-selection bias, we cannot determine whether green residential environments made the participants more physically active or if they are naturally more physically active individuals. Moreover, we cannot know for certain whether PA occurred in green environments or not. Also, in future research, it could be beneficial to conduct the analyses for MPA and VPA separately along with MVPA to interpret the associations between residential greenness, PA, and HRV. In addition, a variety of time- and frequency-domain metrics have also been proposed for assessing HRV.[11] In future, considering a variety of time- and frequency-domain HRV measurements could be beneficial for understanding the associations between PA, HRV, and residential greenness. Nevertheless, existing studies have commonly used rMSSD for assessing HRV.

Measuring residential greenness with NDVI has its limitations. Some studies have pointed out that NDVI, as an objective measure of residential greenness, cannot provide qualitative information about participants' access to green spaces or the usability of such areas. This is because NDVI measures only the amount of vegetation.[7] While NDVI is a useful method for measuring greenness based on satellite imaging, there is a need to estimate the quality and usage of greenness in future studies.

Overall, NDVI has been shown to be a reliable method for analyzing residential greenness.[14] Other limitations include the cross-sectional study design and the inability to determine causality. For example, seeing the long-term effects of living in green residential areas on HRV and parasympathetic regulation cannot be determined from this study setting. Our findings highlight the need to understand the complicated association of PA, HRV, and residential greenness as well as the need for future work in other population-based studies to validate our findings. Longitudinal data are especially needed to validate our findings and attain a better understanding of the possible effects experienced by participants on their heart health while living in green areas.

This population-based birth cohort study evaluated the associations between PA, residential greenness, and cardiac autonomic function at a population level for the first time. Contrary to our expectations, this study showed that being engaged in both LPA and MVPA was associated with improved cardiac autonomic function, irrespective of residential greenness. A second finding was that green residential areas were associated with the amount of accelerometry-measured PA at different intensities. The results of this study may indicate that promoting green exercise and taking residential greenness into consideration in urban planning could be beneficial for cardiac autonomic regulation and for promoting PA. However, further research needs to be conducted to establish this possible association.

5 | PERSPECTIVE

This population-based study of middle-aged adults showed that residential greenness was significantly and positively associated with the amount of PA at different intensities. A positive relationship of both PA with HRV and greenness with PA was found. Our results suggest that higher PA levels are associated with cardiac health, as represented by resting HRV. As PA was associated with HRV irrespective of residential greenness, this study shows that people should be engaging in PA no matter where they live to improve their cardiac health. However, including green residential areas in urban planning could be one possibility to engage people in PA and improve their cardiac health.

ACKNOWLEDGEMENTS

We thank the participants of NFBC1966 in the 46-year study and the Northern Finland Birth Cohort (NFBC) project centre. Further, this project is funded by the Strategic Research Council (SRC) established within the Academy of Finland (grant numbers 345220 and 345222). NFBC1966 received financial support from the University of Oulu (grant number 24000692), Oulu University Hospital (grant number 24301140), and the European Regional Development Fund (ERDF; grant number 539/2010 A31592). This study was supported by the Ministry of Education and Culture (grant numbers OKM/54/626/2019, OKM/85/626/2019, OKM/1096/626/2020, OKM/20/626/2022, OKM/76/626/2022, and OKM/28/626/2023). The funders of the study did not have any role in its design, data collection, analysis, interpretation, or in writing the manuscript.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available at the NFBC for researchers who meet the criteria for accessing confidential data. Please contact the NFBC project centre (nfbcprojectcenter@oulu.fi) and visit the cohort website for more information.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Korpisaari M, Puhakka S, Farrahi V, et al. Physical activity, residential greenness, and cardiac autonomic function. *Scand J Med Sci Sports*. 2023;00:1-12. doi:10.1111/sms.14505