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The relation between proximity to and characteristics of green spaces to physical activity and health: A multi-dimensional sensitivity analysis in four European cities

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ABSTRACT

Introduction: Non-communicable diseases are the global disease burden of our time, with physical inactivity identified as one major risk factor. Green spaces are associated with increased physical activity of nearby residents. But there are still gaps in understanding which proximity and what characteristics of green spaces can trigger physical activity. This study aims to unveil these differences with a rigorous sensitivity analysis.

Methods: We gathered data on self-reported health and physical activity from 1365 participants in selected neighbourhoods in Porto, Nantes, Sofia, and Høje-Taastrup. Spatial data were retrieved from OpenStreetMap. We followed the PRIGSHARE guidelines to control for bias. Around the residential addresses, we generated seven different green space indicators for 15 distances (100–1500 m) using the AID-PRIGSHARE tool. We then analysed each of these 105 green space indicators together with physical activity and health in 105 adjusted structural equation models.

Results: Green space accessibility and green space uses indicators showed a pattern of significant positive associations to physical activity and indirect to health at distances of 1100 m or less, with a peak at 600 m for most indicators. Greenness in close proximity (100 m) had significant positive effects on physical activity and indirect effects on health. Surrounding greenness showed positive direct effects on health at 500–1100 m and so do green corridors in 800 m network distance. In contrast, a high quantity of green space uses, and surrounding greenness measured in a larger radius (1100–1500 m) showed a negative relationship with physical activity and indirect health effects.

Conclusions: Our results provide insight into how green space characteristics can influence health at different scales, with important implications for urban planners on how to integrate accessible green spaces into urban structures and public health decision-makers on the ability of green spaces to combat physical inactivity.

1. Introduction

Non-communicable diseases (NCDs) are the global disease burden of our time and were associated with 74% of global all-cause deaths in 2019 (Bai et al., 2023). The main NCD clusters are cardiovascular diseases, diabetes, cancer, chronic respiratory diseases and mental health with physical inactivity as one of the main risk factors (UN General Assembly, 2018). It has been shown that inactivity is closely related to our daily living environment in general and to the modern and car-dependent lifestyle in particular (Carlin et al., 2017; Cerin et al., 2014; Sallis et al., 2016). Previous research has demonstrated that interventions in urban design and transport have the potential to provide large, long-lasting, and immediate benefits for health (de Sa et al., 2022) and that approximately 70% of studies found evidence that changes in the built environment can lead to changes in physical activity (McCormack et al., 2022). Especially green spaces are associated with an increase in physical activity levels, among a variety of other direct and indirect health benefits (WHO Regional Office for Europe, 2016). Because of this multitude of benefits, green spaces are given a major role in the necessary upcoming urban transformation of the 21st century (Giles-Corti et al., 2016).

If and how green space relates to health has been extensively studied

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in relation to public health in the past decades (Zhang et al., 2021). A growing body of evidence suggests three main pathways between green space and health by 1) surrounding vegetation that can reduce environmental pollution (Mitigation pathway) or induce environmental stressors like pollen (causing harm), 2) through direct contact with nature by reducing stress and increasing cognitive capacities (Restoration pathway) or contact with wildlife (causing harm), and 3) encouraging healthy behaviour (Instoration pathway), which could potentially also lead to more injuries (causing harm) (Cardinali et al., 2023a; Markevych et al., 2017; Marselle et al., 2021). Within the Instoration pathway, one of these health behaviours relates mainly to residents near green spaces being more physically active which then potentially cascades into a positive influence on a variety of mental and physical health outcomes, like reduced risk of cardiovascular diseases, diabetes, and obesity, as well as improved mental health and well-being (Yang et al., 2021).

Nevertheless, despite the growing evidence and policy attention, there is still a significant research gap in understanding how green spaces influence physical activity and health outcomes, particularly the proximity and characteristics of green spaces required to increase physical activity. In addition, the influence of specific features of green spaces like their connectivity and usability remain of research interest. For example, studies investigating the relationship between greenness and physical health have yielded mixed results, with only a third of the studies showing a significant positive relationship (Browning and Lee, 2017). Furthermore, only 50% of the studies that analysed an indirect effect via physical activity showed a significant indirect effect (Dzhambov et al., 2020) or they demonstrated significant relationships for one green space indicator, while another was insignificant (Browning et al., 2022; Luo et al., 2020). Additionally, depending on the study focus, different buffer sizes and types have been selected and rarely for a sequence of distances (Labib et al., 2020). Thus, it remains unclear which proximity to and what characteristics of green spaces are related to positive health outcomes. In particular for physical activity, it is unknown what kind of proximity is needed to encourage physical activity and in turn, if this link is strong enough to result in significant indirect health effects. More research and rigorous sensitivity analysis are warranted on the pathway between green space and health to understand the heterogeneity of existing literature (Cardinali et al., 2023b; Markevych et al., 2017). Up to now, this uncertainty limits our ability to optimally design effective interventions and policies that can promote healthy and sustainable urban environments.

This paper aims to address this gap by exploring and comparing the relation of different green space characteristics and their proximity to physical activity and health in a rigorous sensitivity analysis. We hypothesize differences in green space characteristics, e.g. a stronger relationship of physical activity to the green space characteristics of accessibility, connectivity and green space uses than to greenness (Cardinali et al., 2023b), and expect an indirect effect, especially in walkable distances based on previous research (Akpinar, 2016; McCormack et al., 2010; Sugiyama et al., 2010). Understanding the influence of specific green space characteristics and their relative proximity to residents should enable a better understanding of the heterogeneity of past results in the field and contributes important insights for urban planners and decision-makers on how to integrate green spaces in our cities for maximum effect on health in general and physical activity in particular.

2. Methods

2.1. Study design and sampling

We gathered data from 1365 participants in selected neighbourhoods in Porto (Portugal), Nantes (France), Sofia (Bulgaria) and Høje-Taastrup (Denmark) as part of the URBiNAT project. We collected data in Porto around September 2019, conducted the survey in Nantes and Sofia around December 2019, and obtained the sample from Høje-Taastrup in September 2021. Participants had to be 14 years or older to be included in the study and were selected at random. Local polling companies contracted by the municipality administered the questionnaires with guidance and protocols provided by the authors. The administration in Porto was done face-to-face. The administration in Nantes, Sofia and Høje-Taastrup was done via phone. When contacted, people were informed about the purpose of the project, the role of this questionnaire, and asked for informed consent. The questionnaire took about 20–25 min to complete and was approved by the ethics committee of the URBiNAT project. No incentives were offered.

The study areas have different urban characteristics of importance (see Fig. 1). Nantes Nord, a district with around 20,000 inhabitants, is located on the northern outskirts of the Nantes Metropole, but with a well-connected public transport. Porto Campanhã is a district of similar size but is located on hilly terrain and divided by car-centric infrastructure. Sofia Nadezhda, again a district of similar size, is well connected with public transport. In contrast to the other cities, flats in Sofia Nadezhda are mostly individual property instead of rented and plots are state-owned instead of owned by a residential company. Høje-Taastrup, is a satellite city of greater Copenhagen, which is more rural but well-connected via public transport. In addition, respondents from Høje-Taastrup were clustered in a much smaller geographical area.

2.2. Green space characteristics

We obtained the necessary spatial data for the four study areas from OpenStreetMap in January 2023 and manually corrected it to the timestamp of the survey conduction. To control for bias, we followed the PRIGSHARE Reporting Guidelines (Cardinali et al., 2023b). A table with the inclusion/exclusion criteria can be viewed in the appendix (S2). As a basis for greenness indicators, we calculated the Natural Difference Vegetation Index (NDVI) with sentinel 2 data in 10 × 10 m resolution from the EEA (European Space Agency, 2021) from cloud-free time points in the month of the survey conduction in the city (see Fig. 2 for exact dates). The NDVI is calculated through rasterised satellite images in near-infrared and red light (NDVI=(NIR-Red)/(NIR + Red)) (Tucker, 1979). Its values range from −1.0 to 1.0, where 0.2–0.5 usually indicate sparse vegetation like shrubs or grassland and values of 0.6 and higher indicate dense vegetation like trees. Sealed surfaces like streets or buildings usually range around 0.0–0.1 and negative values arise from water bodies and clouds. That is why we manually set larger water bodies like the rivers in Porto and Nantes to missing.

Based on this curated data, we constructed seven indicators on specific green space characteristics (see Fig. 3) in buffer distances from 100 to 1500 m, every 100 m, using the AID-PRIGSHARE tool (Cardinali et al., 2023b). Firstly, we assessed greenness with two indicators based on NDVI – one with Euclidean buffers (A), and one with a buffered service area (BSA) as a proxy for the network distance (B), representing

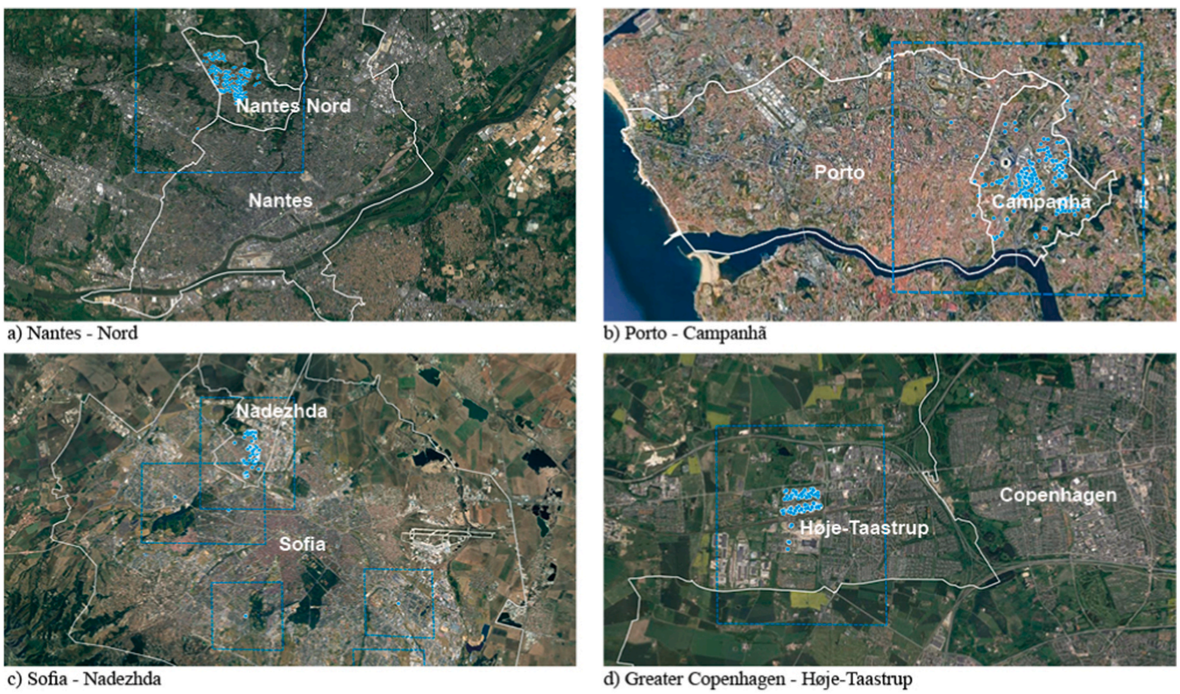

Fig. 1. Study areas overview: a) Nantes - Nord (France); b) Porto - Campanhã (Portugal), c) Sofia - Nadezhda (Bulgaria), d) Greater Copenhagen - *Høje-Taastrup (Denmark); white line indicates administrative borders; blue dotted line indicates the study area(s); blue points indicate the residential address of the study participants.*

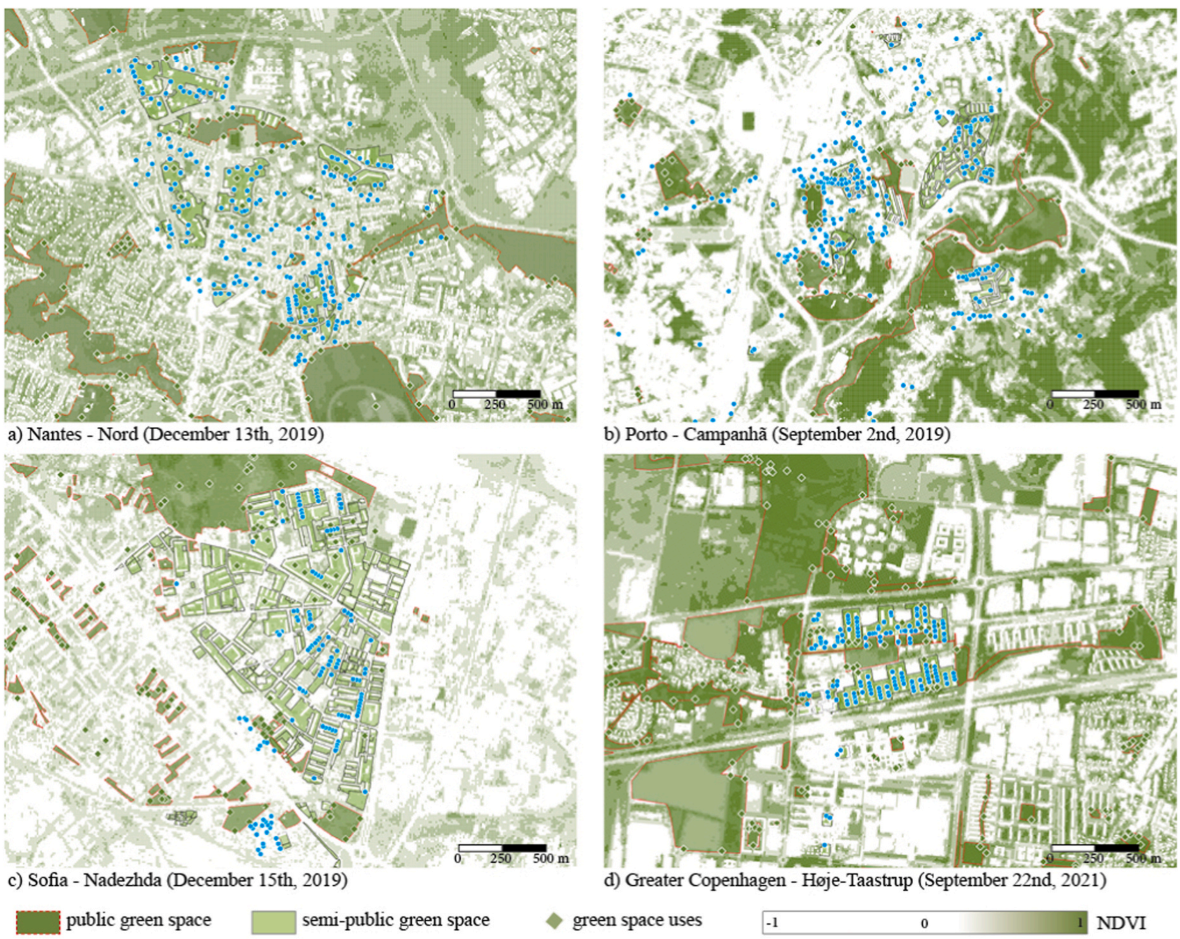

Fig. 2. Study areas green space: a) Nantes Nord (France); b) Porto Campanhã (Portugal), c) Sofia Nadezhda (Bulgaria), d) Greater Copenhagen *Høje-Taastrup (Denmark); blue points indicate the residential addresses of the study participants. For better readability only the study areas are covered (*e.g. *some respondents do not live in the main study area) and private green space is not shown.*

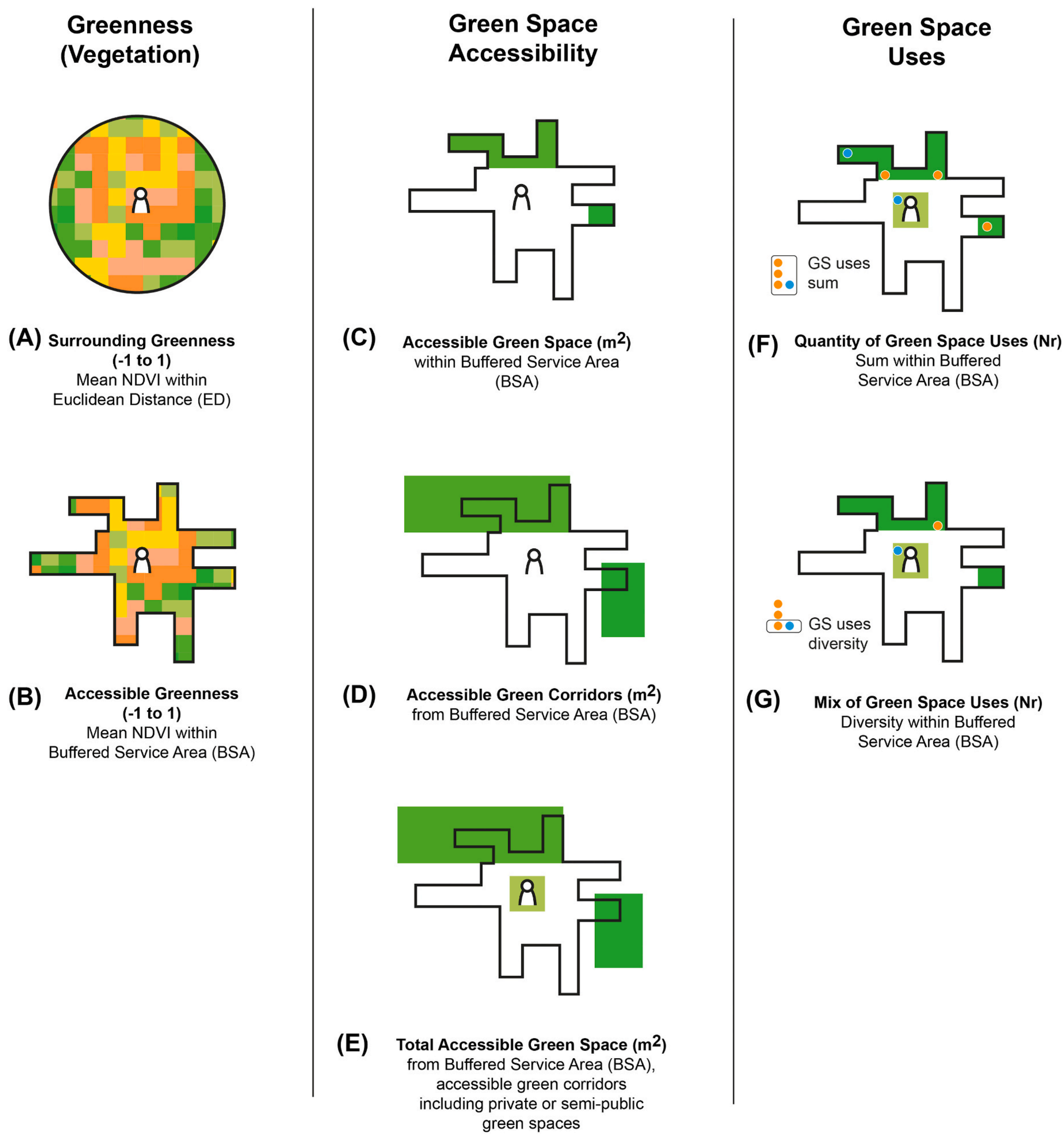

Fig. 3. Green space characteristics: Indicators used in the sensitivity analysis.

surrounding vegetation and accessible vegetation. Secondly, we assessed green space accessibility with three indicators: accessible green spaces in network distance (C), accessible green corridors (D), and total accessible green space, including individual private or semi-public green space of the individual plot (E). Thirdly, we assessed green space uses by counting points of green space uses (playgrounds, gardens, sports fields, social facilities, cultural facilities and walking entries to bigger green spaces) present in the accessible green spaces through open street map data, Google Street View and expert knowledge from local site visits. To represent the quantity of green space uses, we counted the total number of uses in green spaces within network distance (F). We counted the number of different uses (G) to capture the mix of uses.

2.3. Physical activity

We assessed participants' physical activity with the help of the International Physical Activity Questionnaire short form (IPAQ, 2002). The items asked about the vigorous, moderate, and walking activity during the last 7 days. The raw input was then truncated to a minimum of 1 and a maximum of 7 days of activity, and to a minimum of 0.2 h–8 h maximum to account for outliers in the raw data. We followed the guidance of IPAQ to convert the obtained results in minutes/week into metabolic time equivalent of task (MET) values according to their category. Total time spent per week on vigorous physical activity was multiplied by 8.0, moderate physical activity by 4.0, and walking by 3.3 to represent the MET equivalent (IPAQ, 2002). The disadvantage of the original IPAQ categorization of low, moderate and high categories is the significant loss in dimensionality of the data. In contrast, numerical variables of physical activity are heavily right skewed and can be categorised as a zero-inflated count variable, which can cause problems in structural equation modelling (Rosseel, 2023). We tested a cube-root transformation of the data to receive closer-to-normal distribution like other researchers (Dzhambov et al., 2018), but this didn't improve the model convergence and bootstrapping behaviour. For this reason, we decided to transform the numerical indicator of MET-Minutes/Week to an ordinal variable but still tried to maintain as much of the data dimensionality as possible by using 8 categories to reflect physical activity levels (very high: >12,000, high: 7500–12,000, high-moderate 5000–7,500, moderate: 3600–5,000, low moderate: 2400–3,600, low: 1600–2,400, very low: 400–1,600, no: 0–400). A sensitivity analysis for both categorial indicators confirmed the superior behaviour of the 8-category version of the physical activity variable (see S5 for a histogram).

2.4. Health

We assessed perceived general health by the 1-item questionnaire (World Health Organization, 1998). The question asked, "How is your health in general?". Answers were given on a 5-point Likert scale item from (5) very good to (1) very bad. The variable was included as an ordinal variable in the analysis.

2.5. Context variables

In line with the PRIGSHARE Reporting Guidelines (Cardinali et al., 2023b), we obtained data on potential confounders in personal, local, urbanicity, and global context. To assess the personal context, we gathered data on age, sex, disabilities (sensorial, motor, cognitive or organic), years lived in the neighbourhood, occupation, years of education, and monthly net income. To harmonize between cases across countries, monthly net income was centred around the mean minimum wage of the country and is shown in percentages of minimum wage. Local context was accounted for by using 5-point Likert scale items to measure perceived safety, satisfaction with shops, services, leisure facilities, and public transport as part of the environmental quality of life questionnaire (Fleury-Bahi et al., 2013). To account for the urbanicity context, we obtained 2018 population density data from Eurostat (2023). Furthermore, we controlled for the global and climate context by including the city samples as a dummy variable in the model. By doing this, we also controlled for differences in timing (pre- or post-pandemic) and differences in the season when the survey was conducted while maintaining the statistical power. The PRIGSHARE reporting guidelines also prescribe to assess modifying variables (Cardinali et al., 2023b). This assessment was out of scope for this study because of the number of structural equation models to perform and compare (see 2.6). This limitation will be debated in the discussion.

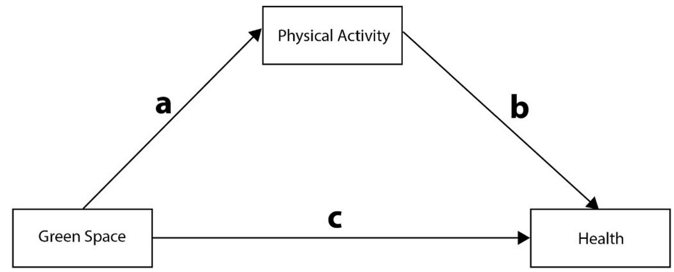

Fig. 4. Conceptual Model: Conceptual diagram showing theoretically indicated pathways linking green space to physical activity and health. The green space indicator was exchanged 105 times for each structural equation model.

2.6. Statistical analysis

Data handling and processing were done in Python. Missing data could be classified as missing at random (MAR) since missingness was associated with other observed variables. Thus, a multiple imputation technique is considered the most appropriate to handle the missing data (Mirzaei et al., 2022). We used multiple imputation software package of miceforest 5.6.3 in Python (Wilson, 2022), with 10 iterations to estimate the missing variables. The final step of data processing was to standardize the dataset by min-max scaling (0–1) since all our variables, except NDVI, can only be positive. This ensured that all variables were on the same scale, thus allowing for meaningful comparisons and accurate model estimation (Kline, 2015).

Structural equation modelling (SEM) was performed in R with the lavaan package (Rosseel, 2023) on a one-mediator model (see Fig. 4) using the diagonal weighted least squares estimator. The full model including all control variables can be found in the supplementary material (S3). Sensitivity analysis was done by exchanging the green space indicator 105 times (7 indicators, each for 15 distances). The rest of the model remained unchanged. An example of the summary statistics for one green space indicator can be found in the supplementary material (S4). By using a single mediator model, we avoid adding another level of complexity to the research framework through potential differences in the model fit of the 105 models, which would make this large-scale sensitivity analysis unfeasible and work against the main goal of this research to compare green space indicators and relative proximity of green spaces.

In the following results and discussion, we use the common phrases of partial effects (a or b), indirect effects (a*b), direct effects (c) and total effects (a*b + c) in SEM, but want to highlight that these are in fact associations, due to the cross-sectional study design. Since indirect effects and total effects are products and not linear, we used bootstrap-generated standard errors and confidence intervals for all regression paths (5000 samples for every structural equation model). The relationship was considered significant when the bootstrapped 95% confidence intervals did not include zero. To further examine the unique contribution of a green space characteristic, we compared the significant green space characteristics in a correlation matrix (see supplementary material S06). We used the cut-off points of Dancey and Reidy, with zero (0), weak (0.1–0.3), moderate (0.4–0.6), strong (0.7–0.9), and perfect correlation (1.0) (Dancey and Reidy, 2007).

3. Results

3.1. Characteristics of the sample

The participants lived on average between 14 and 29 years in their current neighbourhood (see Table 1). The global city sample includes 201 residents from Høje-Taastrup (Denmark), 293 residents from Nantes (France), 439 residents from Porto (Portugal), and 432 residents from Sofia (Bulgaria). The sample was composed of roughly 50% of men and women in Høje-Taastrup, Nantes, and Sofia. In Porto, the sample was composed of nearly 64% men and 36% women. The mean (SD) age of the participants was 53.66 (SD: 18.43) in Høje-Taastrup and 58.12 (18.20) years in Porto, and a considerably younger sample in Nantes 45.66 (17.59) and Sofia 45.47 (16.52). In total, the age ranged from 15

Table 1
Characteristics of the sample (unstandardized).

Context	Indicator	Høje-Taastrup	Nantes	Porto	Sofia	p
global	*city sample (n)*	201	293	439	432	
urbanicity	*population density (mean (SD))*	4028.65 (1336.94)	5616.27 (2353.62)	4829.28 (1632.50)	9021.14 (3689.54)	<0.001
local	*perceived safety, Likert 1–5 (mean (SD))*	3.59 (1.14)	2.75 (1.27)	3.65 (1.39)	2.80 (0.63)	<0.001
	satisfaction with shops, Likert 1–5 (mean (SD))	3.98 (1.08)	3.48 (1.07)	3.41 (1.39)	3.82 (0.86)	<0.001
	satisfaction with leisure facilities, Likert 1–5 (mean (SD))	3.78 (1.11)	2.85 (1.16)	3.34 (1.36)	3.28 (0.88)	<0.001
	satisfaction with public transport, Likert 1–5 (mean (SD))	4.45 (0.90)	4.43 (0.66)	3.59 (1.44)	3.85 (0.63)	<0.001
personal	***gender (%)***					<0.001
	male	52.2%	44.0%	36.2%	47.2%	
	female	47.8%	55.3%	63.8%	52.8%	
	diverse	0.0%	0.7%	0.0%	0.0%	
	age group (%)					<0.001
	15–24	6.5%	10.9%	4.1%	10.6%	
	25–44	28.4%	42.7%	21.4%	39.6%	
	45–64	32.8%	29.4%	33.5%	29.6%	
	over 65	32.3%	17.1%	41.0%	20.1%	
	mean years lived in neighbourhood (SD)	16.60 (13.76)	14.53 (15.03)	28.90 (20.08)	22.41 (12.34)	<0.001
	mean net income as % of minimum wage (SD)	141% (93%)	149% (63%)	40% (66%)	143% (73%)	<0.001
	mean years of education (SD)	12.40 (2.51)	12.46 (3.38)	7.03 (3.72)	13.16 (2.67)	<0.001
	Has disabilities (%)	10.0%	15.7%	39.6%	15.5%	<0.001
	employed (%)	57.2%	56.7%	28.7%	73.6%	<0.001
	physical activity (%)					<0.001
	very high activity	9.5%	5.5%	0.2%	0.7%	
	high activity	7.0%	2.4%	3.2%	2.5%	
	high-medium activity	12.4%	5.8%	2.7%	4.2%	
	medium activity	10.0%	8.2%	6.2%	6.9%	
	low -medium activity	10.4%	9.2%	9.8%	17.1%	
	low activity	12.9%	15.0%	4.8%	19.0%	
	very low activity	25.4%	40.3%	34.9%	30.3%	
	no activity	12.4%	13.7%	38.3%	19.2%	
	self-perceived health (%)					<0.001
	very good	24.9%	29.7%	8.9%	34.5%	
	good	36.8%	46.8%	38.0%	39.4%	
	fair	23.9%	17.4%	32.3%	19.9%	
	bad	11.4%	5.8%	13.7%	6.2%	
	very bad	3.0%	0.3%	7.1%	0.0%	
green space characteristics	*surrounding greenness in 500 m Euclidean distance (-1 to 1, mean (SD))*	0.46 (0.05)	0.42 (0.03)	0.37 (0.08)	0.23 (0.04)	<0.001
	accessible greenness in 500 m network distance (-1 to 1, mean (SD))	0.44 (0.04)	0.39 (0.03)	0.34 (0.06)	0.24 (0.04)	<0.001
	accessible green space in 500 m network distance (0 - 16.32 ha, mean (SD))	3.70 (1.45)	1.64 (1.56)	2.35 (2.11)	3.12 (3.68)	<0.001
	accessible green corridors in 500 m network distance (0 – 154.30 ha, mean (SD))	51.76 (17.59)	56.92 (66.64)	9.74 (9.81)	28.93 (37.99)	<0.001
	accessible total green space in 500 m network distance (0 – 158.66 ha, mean (SD))	56.77 (16.33)	60.18 (66.51)	12.16 (10.37)	32.99 (41.47)	<0.001
	quantity of green space uses in 500 m network distance (0–34, mean (SD))	21.17 (7.49)	6.13 (4.04)	5.15 (4.39)	10.17 (6.70)	<0.001
	mix of green space uses in 500 m network distance (0–5, mean (SD))	3.75 (0.65)	2.10 (0.82)	1.83 (1.01)	2.36 (1.13)	<0.001

to 99 years. The samples also differed significantly in the number of people with disabilities, ranging from 10.0% in Høje-Taastrup to 39.6% in Porto. The mean years of education were around 12 years in Høje-Taastrup, Nantes and Sofia, but only seven in Porto. In terms of occupation, the majority of the participants were employed, with significant differences between cities. The mean (SD) income was 141% (93%) of the minimum wage in Høje-Taastrup, 149 % (63%) in Nantes, 40% (66%) in Porto, and 143% (73%) in Sofia. The overall perceived safety, as well as the neighbourhood characteristics of shops, leisure facilities, and public transport, were also significantly different among the cities. In addition, the sample differed significantly in terms of population density, with Sofia having the highest mean population density and Høje-Taastrup having the lowest. Self-rated physical activity was the highest in Høje-Taastrup with 37.8% reporting very low or no activity, followed by Sofia (50.1%), Nantes (54.0%), and Porto (73.2%). Very good or good self-perceived health was the highest in Nantes (76.5%), followed by Sofia (73.9%), Høje-Taastrup (61.7%) and Porto (46.9%).

3.2. *Partial effects – how green space indicators are associated with physical activity*

We observed clear and distinct patterns in the associations between green space and physical activity (path a) in terms of proximity to green spaces and green space characteristics (Table 2). Surrounding greenness (Fig. 5A) showed a two-sided pattern starting with positive significance in the immediate surrounding of 100 m (ß: 0.542; CI: 0.048, 1.023) and turning negative in larger Euclidean distances of 900–1500 m with a peak at 1300 m, although not significant. Accessible greenness (Fig. 5B) showed a similar pattern and stronger relation to physical activity levels in the immediate surrounding of 100 m (ß: 0.753; CI: 0.221, 1.283) and no negative significant association in the higher buffers. Accessible green space (Fig. 5C) presented a significant positive association with physical activity at 500–600 m, with a peak at 500 m (ß: 0.401; CI: 0.087, 0.679). Access to green corridors (Fig. 5D) showed a clear pattern of significant positive associations with physical activity in distances of 200–800 m, with a peak at 600 m (ß: 0.657; CI: 0.150, 1.227). Accessible total green space (Fig. 5E) reacted similarly but more consistently and showed significant associations with physical activity up to 800 m, with a peak at 600 m (ß: 0.765; CI: 0.260, 1.355). The quantity of green space uses (Fig. 5F) showed positive significant associations with physical activity at 600–700 m, with a peak at 600 m (ß: 0.516; CI: 0.196, 0.840). In addition, the indicator turned to significant negative associations with physical activity at distances of 1100–1500 m, with a peak at 1100 m (ß: 1.068; CI: 1.667, −0.504). On the contrary, the mix of green space uses in network distance (Fig. 5G) again showed a clear positive plateau (200–1000 m) of significant associations with physical activity and

Table 2

Partial Effects (a). Green Space – Physical Activity Sensitivity Analysis. Standardized Estimated ß (95% CI) for partial effects (a) of green space indicators on physical activity in the 105 structural equation models each with 5000 bootstrap samples.

	Greenness		Green Space Accessibility			Green Space Uses	
Distance	**(A) Surrounding GN**	**(B) Accessible GN**	**(C) Accessible GS**	**(D) Accessible GC**	**(E) Accessible TGS**	**(F) Quantity of GSU**	**(G) Mix Of GSU**
100	0.546 (0.041, 1.026) *	0.416 (-0.087, 0.905)	0.318 (-0.253, 0.886)	0.178 (-0.229, 0.636)	0.166 (-0.250, 0.577)	**-0.544 (-1.009, -0.054)** *	-0.270 (-0.616, 0.087)
200	0.506 (-0.055, 1.030)	0.505 (-0.119, 1.115)	0.349 (-0.049, 0.728)	0.228 (-0.040, 0.512)	0.217 (-0.064, 0.492)	-0.021 (-0.374, 0.332)	-0.026 (-0.273, 0.233)
300	0.432 (-0.106, 0.967)	0.549 (-0.107, 1.193)	0.310 (-0.071, 0.702)	0.180 (-0.064, 0.442)	0.173 (-0.074, 0.423)	0.054 (-0.263, 0.370)	-0.060 (-0.287, 0.171)
400	0.440 (-0.053, 0.947)	0.355 (-0.317, 1.002)	0.176 (-0.203, 0.592)	0.154 (-0.085, 0.378)	0.152 (-0.075, 0.389)	0.050 (-0.300, 0.394)	-0.098 (-0.382, 0.189)
500	0.562 (0.078, 1.020) *	0.272 (-0.373, 0.921)	0.068 (-0.297, 0.425)	0.305 (0.083, 0.552) *	0.298 (0.052, 0.523) *	0.055 (-0.290, 0.404)	-0.179 (-0.441, 0.121)
600	0.615 (0.170, 1.059) *	0.352 (-0.320, 1.019)	0.038 (-0.258, 0.345)	0.417 (-0.056, 1.018)	0.410 (-0.067, 0.982)	0.073 (-0.259, 0.413)	-0.133 (-0.423, 0.152)
700	0.651 (0.222, 1.101) *	0.439 (-0.181, 1.062)	0.015 (-0.273, 0.313)	0.560 (0.078, 1.210) *	0.552 (0.052, 1.137) *	-0.013 (-0.350, 0.333)	-0.076 (-0.381, 0.237)
800	**0.649 (0.201, 1.122)** *	0.494 (-0.131, 1.119)	0.057 (-0.269, 0.394)	**0.701 (0.179, 1.359)** *	**0.696 (0.178, 1.322)** *	-0.057 (-0.462, 0.333)	-0.111 (-0.437, 0.205)
900	0.622 (0.132, 1.135) *	0.516 (-0.123, 1.134)	0.124 (-0.219, 0.473)	0.244 (-0.180, 0.713)	0.245 (-0.173, 0.693)	0.038 (-0.382, 0.490)	-0.190 (-0.545, 0.148)
1000	0.558 (0.039, 1.049) *	0.521 (-0.093, 1.156)	0.152 (-0.213, 0.502)	0.224 (-0.166, 0.681)	0.226 (-0.182, 0.705)	0.003 (-0.499, 0.507)	**-0.299 (-0.580, -0.003)** *
1100	0.502 (0.010, 1.000) *	0.455 (-0.064, 0.957)	0.161 (-0.284, 0.591)	0.206 (-0.179, 0.645)	0.208 (-0.206, 0.686)	-0.091 (-0.620, 0.426)	0.062 (-0.258, 0.374)
1200	0.457 (-0.083, 0.990)	0.625 (0.027, 1.280) *	0.174 (-0.227, 0.618)	0.060 (-0.345, 0.497)	0.061 (-0.327, 0.502)	-0.047 (-0.510, 0.434)	-0.178 (-0.458, 0.122)
1300	0.387 (-0.162, 0.915)	0.652 (-0.015, 1.327)	0.218 (-0.197, 0.630)	-0.044 (-0.448, 0.382)	-0.044 (-0.445, 0.409)	-0.055 (-0.517, 0.399)	-0.311 (-0.621, 0.008)
1400	0.394 (-0.167, 0.972)	**0.689 (0.019, 1.383)** *	0.200 (-0.204, 0.641)	-0.109 (-0.541, 0.331)	-0.110 (-0.561, 0.327)	-0.150 (-0.609, 0.335)	-0.244 (-0.579, 0.093)
1500	0.456 (-0.158, 1.077)	0.698 (-0.025, 1.414)	0.123 (-0.299, 0.558)	-0.194 (-0.637, 0.257)	-0.196 (-0.618, 0.282)	-0.159 (-0.615, 0.304)	-0.250 (-0.592, 0.069)

Notes: Adjusted for sex, age, disabilities, education, income, occupation, years lived in the neighbourhood, perceived neighbourhood safety, satisfaction with shops, leisure facilities, public transport, population density and city. **Abbreviations:** (A) Surrounding GN: Surrounding Greenness (measured as mean NDVI within Euclidean Distance), (B) Accessible GN: Accessible Greenness (measured as mean NDVI within network distance), (C) Accessible GS: Accessible Green spaces (measured as public green space within network distance), (D) Accessible GC: Accessible Green Corridors (measured as public green space accessible from network distance), (E) Accessible TGS: Accessible Total Green Space (measured like E, but with private or semi-public green spaces included), (F) Quantity of GSU: Quantity of Green Space Uses (measured as sum of points within network distance), (G) Mix of GSU: Mix of Green Space Uses (measured as sum of different uses within network distance) ; ***: Coefficient is statistically significant; bold estimates indicate highest significant positive and negative estimate within specific indicator.**

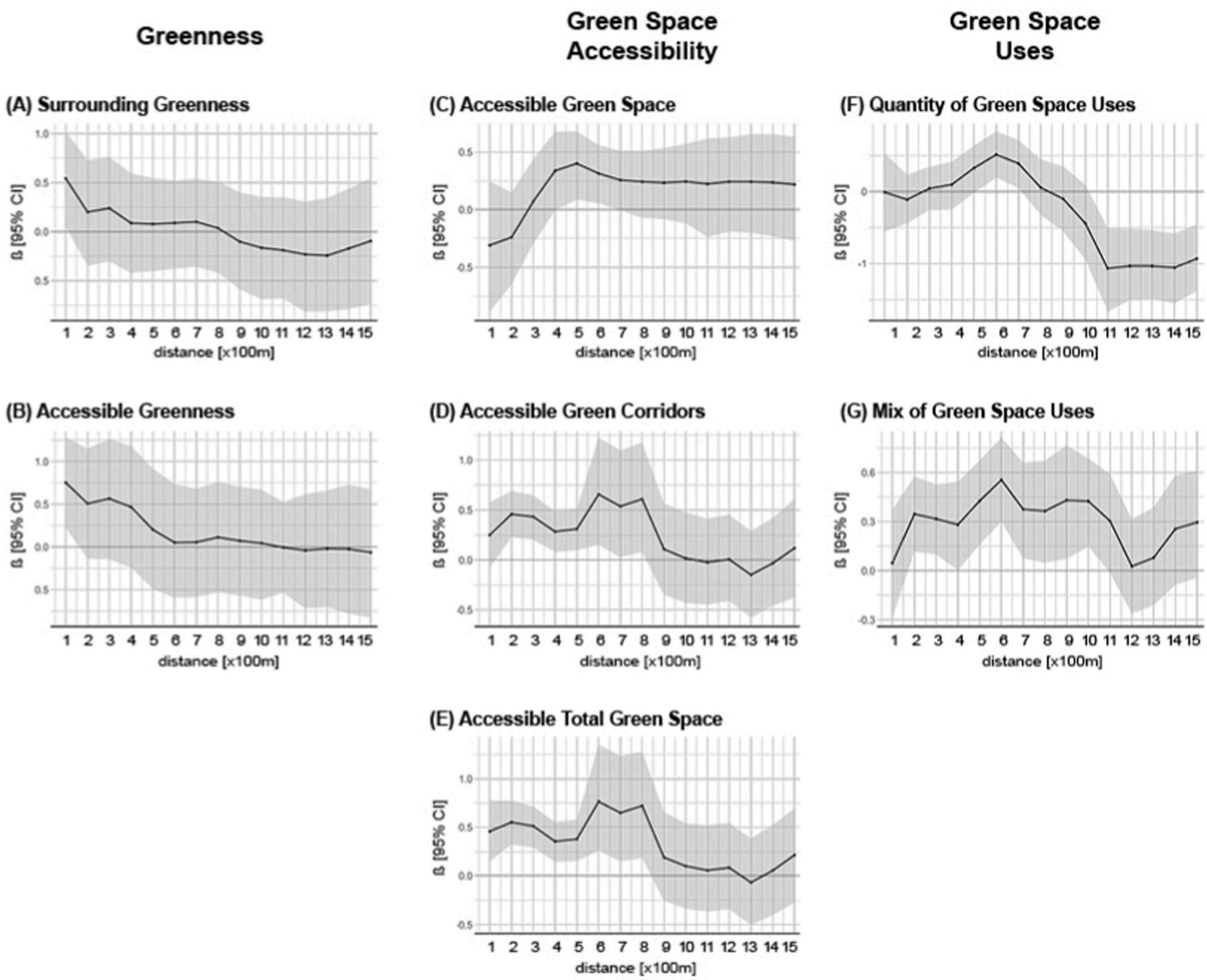

Fig. 5. Partial Effects (a). Green Space – Physical Activity Sensitivity Analysis. Standardized Estimated ß (95% CI) of the 105 structural equation models; adjusted for sex, age, disabilities, years of education, income, occupation, years lived in the neighbourhood, perceived neighbourhood safety, satisfaction with shops, leisure facilities, public transport, population density and city; 5000 Bootstrap Samples; shaded grey area show 95% confidence interval.

Table 3

Indirect Effects (a*b). Green Space – Physical Activity – Health Sensitivity Analysis. Standardized estimated ß (95% CI) for the indirect effect (a*b) of green space indicators, mediated by physical activity on self-perceived general health in the 105 structural equation models each with 5000 bootstrap samples.

	Greenness		Green Space Accessibility			Green Space Uses	
Distance	(A) Surrounding GN	(B) Accessible GN	(C) Accessible GS	(D) Accessible GC	(E) Accessible TGS	(F) Quantity of GSU	(G) Mix Of GSU
100	**0.085 (0.013, 0.188)** *	**0.118 (0.038, 0.243)** *	-0.050 (-0.158, 0.037)	0.040 (-0.008, 0.103)	0.073 (0.024, 0.143) *	-0.001 (-0.091, 0.092)	0.007 (-0.047, 0.064)
200	0.032 (-0.053, 0.129)	0.081 (-0.017, 0.210)	-0.039 (-0.116, 0.021)	0.072 (0.033, 0.127) *	0.086 (0.043, 0.145) *	-0.018 (-0.078, 0.037)	0.056 (0.019, 0.106) *
300	0.038 (-0.042, 0.135)	0.090 (-0.017, 0.229)	0.012 (-0.047, 0.074)	0.068 (0.030, 0.122) *	0.080 (0.039, 0.136) *	0.007 (-0.041, 0.059)	0.051 (0.017, 0.100) *
400	0.014 (-0.065, 0.102)	0.075 (-0.033, 0.213)	0.054 (0.002, 0.124) *	0.045 (0.014, 0.091) *	0.056 (0.021, 0.104) *	0.016 (-0.041, 0.071)	0.045 (0.003, 0.101) *
500	0.012 (-0.064, 0.094)	0.032 (-0.075, 0.165)	**0.064 (0.015, 0.126)** *	0.048 (0.015, 0.094) *	0.058 (0.023, 0.108) *	0.053 (0.001, 0.112) *	0.069 (0.026, 0.127) *
600	0.014 (-0.060, 0.093)	0.008 (-0.098, 0.127)	0.050 (0.010, 0.106) *	**0.104 (0.030, 0.224)** *	**0.120 (0.042, 0.243)** *	**0.082 (0.031, 0.154)** *	**0.090 (0.045, 0.155)** *
700	0.016 (-0.058, 0.096)	0.009 (-0.094, 0.118)	0.041 (0.002, 0.096) *	0.085 (0.010, 0.194) *	0.102 (0.027, 0.222) *	0.063 (0.013, 0.134) *	0.060 (0.016, 0.123) *
800	0.006 (-0.067, 0.088)	0.018 (-0.082, 0.131)	0.039 (-0.007, 0.094)	0.095 (0.018, 0.210) *	0.112 (0.033, 0.229) *	0.009 (-0.053, 0.077)	0.059 (0.011, 0.124) *
900	-0.017 (-0.099, 0.067)	0.012 (-0.092, 0.123)	0.037 (-0.009, 0.099)	0.017 (-0.054, 0.099)	0.030 (-0.039, 0.115)	-0.016 (-0.095, 0.057)	0.070 (0.016, 0.145) *
1000	-0.027 (-0.118, 0.056)	0.007 (-0.098, 0.117)	0.039 (-0.015, 0.103)	0.003 (-0.070, 0.078)	0.016 (-0.054, 0.097)	-0.071 (-0.175, 0.010)	0.070 (0.027, 0.133) *
1100	-0.031 (-0.115, 0.056)	-0.001 (-0.087, 0.090)	0.036 (-0.034, 0.111)	-0.004 (-0.074, 0.071)	0.009 (-0.062, 0.089)	**-0.171 (-0.317, -0.078)** *	0.048 (0.001, 0.109) *
1200	-0.037 (-0.140, 0.047)	-0.006 (-0.119, 0.104)	0.039 (-0.025, 0.114)	0.001 (-0.067, 0.077)	0.013 (-0.054, 0.094)	-0.166 (-0.290, -0.080) *	0.004 (-0.043, 0.053)
1300	-0.039 (-0.139, 0.050)	-0.003 (-0.114, 0.116)	0.039 (-0.028, 0.117)	-0.024 (-0.100, 0.044)	-0.011 (-0.086, 0.063)	-0.166 (-0.282, -0.078) *	0.013 (-0.035, 0.066)
1400	-0.028 (-0.130, 0.069)	-0.004 (-0.128, 0.123)	0.038 (-0.032, 0.119)	-0.005 (-0.077, 0.070)	0.009 (-0.065, 0.088)	-0.168 (-0.294, -0.083) *	0.041 (-0.011, 0.103)
1500	-0.015 (-0.121, 0.090)	-0.010 (-0.135, 0.114)	0.035 (-0.037, 0.111)	0.019 (-0.058, 0.107)	0.034 (-0.040, 0.125)	-0.148 (-0.266, -0.066) *	0.048 (-0.002, 0.113)

Notes: Adjusted for sex, age, disabilities, education, income, occupation, years lived in the neighbourhood, perceived neighbourhood safety, satisfaction with shops, leisure facilities, public transport, population density and city. **Abbreviations:** (A) Surrounding GN: Surrounding Greenness (measured as mean NDVI within Euclidean Distance), (B) Accessible GN: Accessible Greenness (measured as mean NDVI within network distance), (C) Accessible GS: Accessible Green spaces (measured as public green space within network distance), (D) Accessible GC: Accessible Green Corridors (measured as public green space accessible from network distance), (E) Accessible TGS: Accessible Total Green Space (measured like E, but with private or semi-public green spaces included), (F) Quantity of GSU: Quantity of Green Space Uses (measured as sum of points within network distance), (G) Mix of GSU: Mix of Green Space Uses (measured as sum of different uses within network distance) ; *: Coefficient is statistically significant; bold estimates indicate highest significant positive and negative estimate within specific indicator.

again a peak at 600 m (ß: 0.554; CI: 0.298, 0.814). The overall strongest positive association to physical activity was related to accessible total green space in 600 m network distance.

3.3. Indirect effects – how green space indicators are indirectly associated with health via physical activity

We observed clear patterns in the indirect effects (path a*b) in terms of proximity to green spaces and different green space characteristics (Table 3), which were very similar to the partial effects (a) due to the stable significant association (b) between physical activity and health (ß: 0.16; CI: 0.10, 0.21). Surrounding greenness (Fig. 6A) showed the same two-sided pattern starting with positive significance in the immediate surrounding of 100 m (ß: 0.085; CI: 0.013, 0.188) and turning negative in larger Euclidean distances of 800–1500 m with a peak at 1300 m, although not significant. Accessible greenness (Fig. 6B) reacted similarly but created stronger associations to indirect health effects in the immediate surrounding of 100 m (ß: 0.118; CI: 0.038, 0.243). Accessible green space within network distance (Fig. 6C) showed a significant positive indirect health relation at 400–700 m, with a peak at 500 m (ß: 0.064; CI: 0.015, 0.126). Access to green corridors (Fig. 6D) showed a clear plateau of positive indirect health associations in distances from 200 to 800 m, with a peak at 600 m (ß: 0.104; CI: 0.030, 0.224). Accessible total green space (Fig. 6E) reacted similarly from 100 to 800 m, with a peak at 600 m but with a higher estimate (ß: 0.120; CI: 0.042, 0.243). The quantity of green space uses (Fig. 6F) showed positive significant associations with physical activity at 500–700 m, with a peak at 600 m (ß: 0.082; CI: 0.031, 0.154). Similar to the partial effect, the indicator turned to significant negative associations with indirect health effects at distances of 1100–1500 m, with a peak at 1100 m (ß: 0.171; CI: 0.317, −0.078). On the contrary, the mix of green space uses in network distance (Fig. 6G) again showed a clear positive plateau (200–1000 m) of significant associations with indirect health effects and a peak at 600 m (ß: 0.090; CI: 0.045, 0.155). The overall strongest positive association of indirect health effects via physical activity was related to accessible total green space in 600 m network distance.

3.4. Direct effects – how green space indicators are associated with health

The direct effects, factually adjusted for physical activity (path c), showed clear patterns in terms of proximity to green spaces and differed by green space characteristics (Table 4). Surrounding greenness (Fig. 7A) showed a clear positive plateau for intermediate distances of 500–1100 m with a peak at 800 m (ß: 0.643; CI: 0.201, 1.106). Accessible greenness (Fig. 7B) showed an almost linear pattern, with a significant association at 1200 m and 1400 m (ß: 0.693; CI: 0.031, 1.271). Accessible green space (Fig. 7C) showed a peak in immediate proximity but was not significant. Access to green corridors (Fig. 7D) showed a one-clear peak at 800 m (ß: 0.606; CI: 0.093, 1.272), and was also significant at 500 m network distance. Accessible total green space (Fig. 7E) reacted similarly with a peak at 800 m, but this time with a slightly lower estimate and consistency in the pattern (ß: 0.584; CI: 0.065, 1.212). The quantity of green space uses in network distance (Fig. 7F) showed a significant negative direct association with health in the immediate surrounding of 100 m (ß: 0.543; CI: 1.003, −0.054). The diversity of green space uses in network distance (Fig. 7G) showed a stable negative pattern through all distances, but was only significant at 1000 m and 1300 m distance with a peak at 1000 m (ß: 0.369; CI: 0.656, −0.077). The overall strongest positive direct association with health was related to green corridors measured in 600 m network distance.

3.5. Total effects – how green space indicators, directly and indirectly, relate to health

The total effects (path a*b + c) in the structural equation model behaved similarly to the direct effects (Table 5), due to the differences in effect size between direct (path c, maximum ß 0.693) and indirect effects (path a*b, maximum ß 0.120), with the exception of surrounding greenness. Surrounding greenness (Fig. 8A) showed a double peak in the total effects, with a significant effect at 100 m and a significant pattern for intermediate distances of 600–1100 m with a peak at 800 m (ß: 0.649; CI: 0.201, 1.122). Accessible greenness showed an almost linear pattern, with significant associations at 1200 m and 1400 m (ß: 0.689;

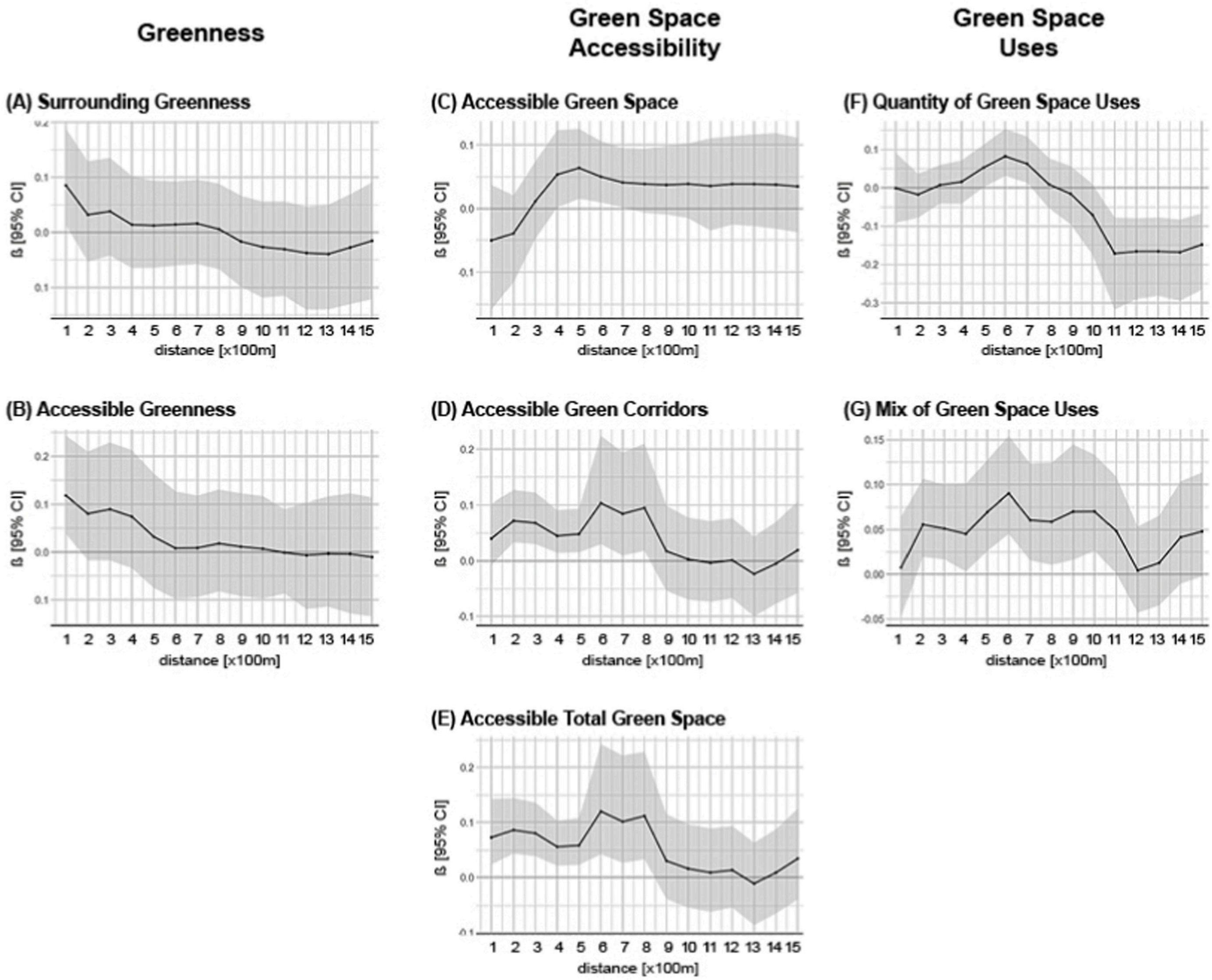

Fig. 6. Indirect Effects (a*b). Green Space – Physical Activity – Health Sensitivity Analysis. Standardized Estimated ß (95% CI) of the 105 structural equation models; adjusted for sex, age, disabilities, years of education, income, occupation, years lived in the neighbourhood, perceived neighbourhood safety, satisfaction with shops, leisure facilities, public transport, population density and city; 5000 Bootstrap Samples; shaded grey area show 95% confidence interval.

Table 4
Direct Effects (c). Green Space – Health Sensitivity Analysis. Standardized estimated ß (95% CI) for the direct effect (c) of green space indicators on self-perceived general health in the 105 structural equation models each with 5000 bootstrap samples.

	Greenness		Green Space Accessibility			Green Space Uses	
Distance	(A) Surrounding GN	(B) Accessible GN	(C) Accessible GS	(D) Accessible GC	(E) Accessible TGS	(F) Quantity of GSU	(G) Mix Of GSU
100	0.461 (-0.026, 0.941)	0.298 (-0.206, 0.793)	0.367 (-0.215, 0.942)	0.138 (-0.258, 0.584)	0.093 (-0.311, 0.512)	**-0.543 (-1.003, -0.054)** *	-0.277 (-0.612, 0.076)
200	0.474 (-0.067, 1.001)	0.425 (-0.186, 1.035)	0.388 (-0.011, 0.770)	0.156 (-0.102, 0.440)	0.131 (-0.140, 0.414)	-0.004 (-0.353, 0.346)	-0.082 (-0.324, 0.178)
300	0.394 (-0.140, 0.935)	0.459 (-0.189, 1.094)	0.298 (-0.080, 0.684)	0.112 (-0.132, 0.369)	0.093 (-0.155, 0.345)	0.047 (-0.273, 0.355)	-0.111 (-0.337, 0.119)
400	0.426 (-0.061, 0.912)	0.280 (-0.395, 0.927)	0.122 (-0.255, 0.530)	0.110 (-0.126, 0.334)	0.096 (-0.128, 0.342)	0.034 (-0.316, 0.376)	-0.143 (-0.425, 0.141)
500	0.550 (0.075, 0.996) *	0.240 (-0.395, 0.889)	0.004 (-0.350, 0.360)	0.256 (0.033, 0.501) *	0.239 (-0.009, 0.464)	0.002 (-0.336, 0.349)	-0.249 (-0.513, 0.049)
600	0.601 (0.159, 1.029) *	0.343 (-0.326, 0.997)	-0.012 (-0.304, 0.294)	0.313 (-0.146, 0.913)	0.290 (-0.187, 0.862)	-0.009 (-0.348, 0.331)	-0.224 (-0.516, 0.062)
700	0.635 (0.209, 1.075) *	0.430 (-0.179, 1.040)	-0.026 (-0.315, 0.270)	0.476 (-0.012, 1.127)	0.451 (-0.047, 1.038)	-0.076 (-0.415, 0.263)	-0.136 (-0.447, 0.174)
800	**0.643 (0.201, 1.106)** *	0.476 (-0.145, 1.102)	0.018 (-0.295, 0.361)	**0.606 (0.093, 1.272)** *	**0.584 (0.065, 1.212)** *	-0.066 (-0.461, 0.329)	-0.170 (-0.493, 0.150)
900	0.639 (0.149, 1.133) *	0.504 (-0.136, 1.115)	0.086 (-0.252, 0.438)	0.227 (-0.198, 0.705)	0.214 (-0.209, 0.669)	0.054 (-0.364, 0.504)	-0.260 (-0.616, 0.085)
1000	0.585 (0.075, 1.074) *	0.514 (-0.099, 1.143)	0.113 (-0.247, 0.469)	0.222 (-0.177, 0.685)	0.210 (-0.204, 0.689)	0.073 (-0.412, 0.572)	**-0.369 (-0.656, -0.077)** *
1100	0.533 (0.048, 1.027) *	0.456 (-0.044, 0.955)	0.125 (-0.303, 0.559)	0.210 (-0.192, 0.660)	0.199 (-0.217, 0.689)	0.080 (-0.441, 0.609)	0.014 (-0.312, 0.330)
1200	0.494 (-0.045, 1.011)	0.631 (0.031, 1.271) *	0.135 (-0.267, 0.582)	0.059 (-0.355, 0.503)	0.048 (-0.351, 0.490)	0.120 (-0.350, 0.607)	-0.183 (-0.464, 0.123)
1300	0.426 (-0.120, 0.948)	0.655 (-0.014, 1.322)	0.179 (-0.234, 0.601)	-0.020 (-0.428, 0.416)	-0.033 (-0.446, 0.419)	0.111 (-0.359, 0.564)	-0.324 (-0.636, -0.012) *
1400	0.422 (-0.133, 0.994)	**0.693 (0.028, 1.384)** *	0.163 (-0.243, 0.614)	-0.103 (-0.541, 0.350)	-0.118 (-0.578, 0.327)	0.018 (-0.455, 0.510)	-0.286 (-0.617, 0.052)
1500	0.471 (-0.148, 1.091)	0.708 (-0.024, 1.407)	0.088 (-0.326, 0.526)	-0.213 (-0.662, 0.260)	-0.230 (-0.667, 0.243)	-0.011 (-0.473, 0.449)	-0.298 (-0.637, 0.024)

Notes: Adjusted for sex, age, disabilities, education, income, occupation, years lived in the neighbourhood, perceived neighbourhood safety, satisfaction with shops, leisure facilities, public transport, population density and city. **Abbreviations:** (A) Surrounding GN: Surrounding Greenness (measured as mean NDVI within Euclidean Distance), (B) Accessible GN: Accessible Greenness (measured as mean NDVI within network distance), (C) Accessible GS: Accessible Green spaces (measured as public green space within network distance), (D) Accessible GC: Accessible Green Corridors (measured as public green space accessible from network distance), (E) Accessible TGS: Accessible Total Green Space (measured like E, but with private or semi-public green spaces included), (F) Quantity of GSU: Quantity of Green Space Uses (measured as sum of points within network distance), (G) Mix of GSU: Mix of Green Space Uses (measured as sum of different uses within network distance) ; *: Coefficient is statistically significant; bold estimates indicate highest significant positive and negative estimate within specific indicator.

CI: 0.019, 1.383). Accessible green space (Fig. 8C) showed a peak in immediate proximity but was not significant. Access to green corridors (Fig. 8D) and accessible total green space (Fig. 8E) showed significant associations in network distances of 500 m, 700 m, and 800 m, both with a peak at 800 m. The quantity of green space uses (Fig. 8F) showed a significant negative relation to health in the immediate proximity of 100 m (ß: 0.544; CI: 1.009; −0.054). The total effect of the mix of green space uses on health (Fig. 8G) reacted similarly to the direct effects, but only showed a significant negative association at 1000 m (ß: 0.299; CI: 0.580, −0.003). The overall strongest positive total association with health was related to accessible green corridors in 800 m network distance.

3.6. Collinearity between significant green space characteristics

To further examine if the measured associations stem from unique mechanisms or just act as an alternative measure of the same underlying construct, we examined the correlation matrix of the significant green space characteristics at their peak values for the partial (path a) and direct effects (path c) (S06).

As described in section 3.2, the peak associations for the partial effect (path a) were between physical activity and surrounding greenness in 100 m (A), accessible greenness in 100 m (B), accessible green space 500 m (C), accessible green corridors in 600 m (D), accessible total green spaces in 600 m (E), quantity of green space uses in 600 m was positive and 1100 m negative (F), an mix of green space uses in 600 m (G). The investigation of the correlation matrix indicated the expected strong collinearity between the nested green space characteristics when measured in similar distances (A & B; D & E; F & G). However, the correlation across the different sets of indicators (e.g. between A and D or between E and G), was weak for accessible greenness (−0.03-0.18), green space (0.03–0.25), green corridors (0.06–0.23), green space uses at 600 m (0.18–0.26), except for a strong correlation between accessible green spaces and green space uses (0.55–0.61). We found a weak to moderate correlation for the negative association of the quantity of green space uses at 1100 m to other green space characteristics (−0.03-0.25). This indicates partially unique mechanisms to physical activity from greenness, green space accessibility, green corridors and green space uses.

As described in section 3.4, the peak associations for the direct effect (path c) were between self-assessed health and surrounding greenness in 800 m (A), accessible greenness in 1400 m (B), accessible green corridors in 800 m (D), accessible total green space in 800 m (E), as well as negative associations for quantity of green space uses in 100 m (F), and mix of green space uses in 1000 m (G). Similar to the peak of the partial effects, the investigation of the correlation matrix showed the expected strong collinearity between nested green space characteristics (A & B, D & E), although surrounding and accessible greenness peaked at different distances. However, we found weak correlation to other green space characteristics for surrounding greenness (−0.32-0.17), green corridors (0.00–0.21), as well as the negative association with the quantity of green space uses (0.00–0.24), and mix of green space uses (−0.32-0.24), indicating partially unique mechanisms to health.

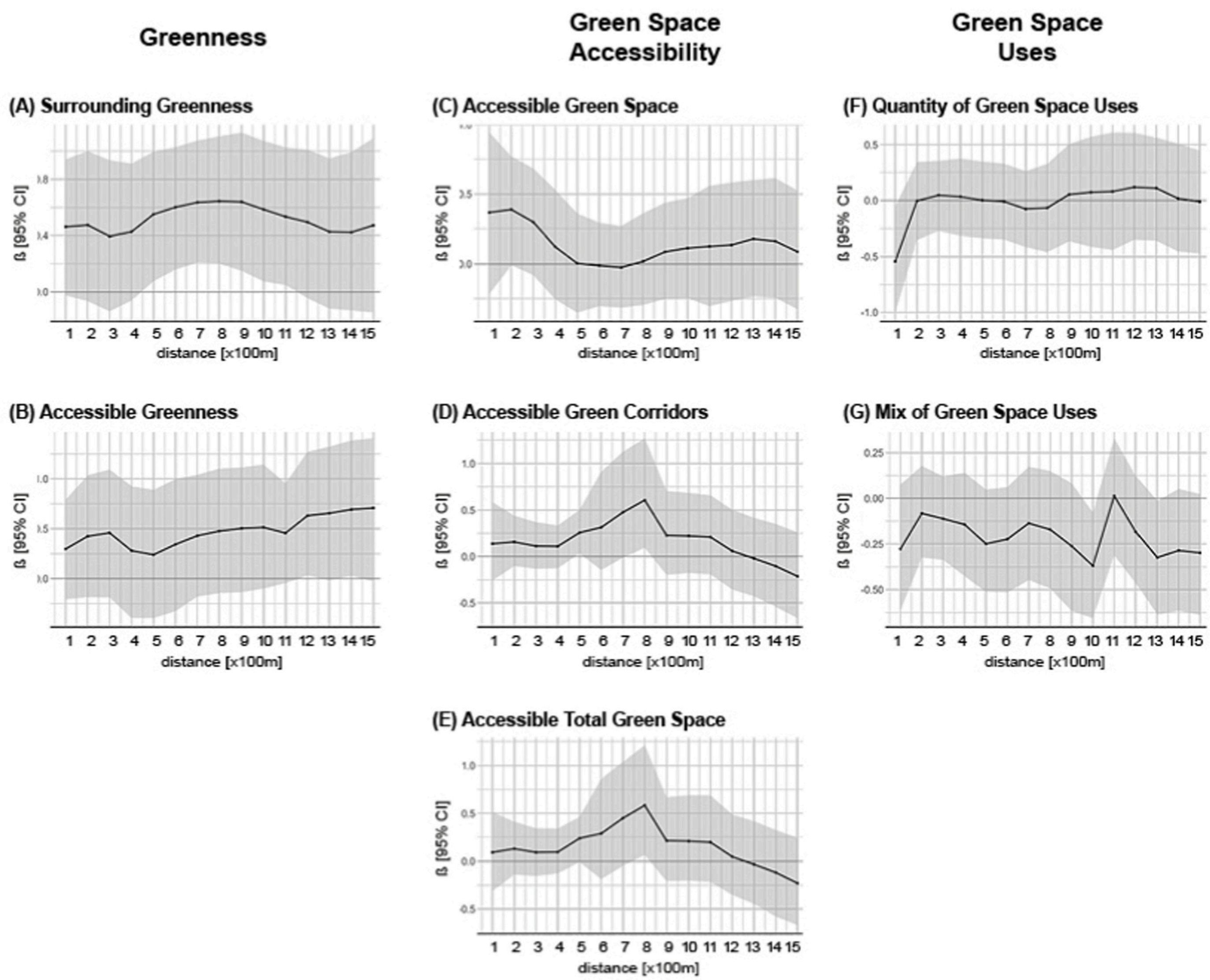

Fig. 7. Direct Effects (c). Green Space – Health Sensitivity Analysis. Standardized Estimated ß (95% CI) of the 105 structural equation models; adjusted for sex, age, disabilities, years of education, income, occupation, years lived in the neighbourhood, perceived neighbourhood safety, satisfaction with shops, leisure facilities, public transport, population density and city; 5000 Bootstrap Samples; shaded grey area show 95% confidence interval.

Table 5
Total Effects (a*b + c). Green Space – Physical Activity – Health Sensitivity Analysis. Standardized estimated ß (95% CI) for the total effect (a*b + c) of green space indicators, both indirectly via physical activity, and directly on self-perceived general health in the 105 structural equation models each with 5000 bootstrap samples.

	Greenness		**Green Space Accessibility**			**Green Space Uses**	
Distance	**(A) Surrounding GN**	**(B) Accessible GN**	**(C) Accessible GS**	**(D) Accessible GC**	**(E) Accessible TGS**	**(F) Quantity of GSU**	**(G) Mix Of GSU**
100	0.546 (0.041, 1.026) *	0.416 (-0.087, 0.905)	0.318 (-0.253, 0.886)	0.178 (-0.229, 0.636)	0.166 (-0.250, 0.577)	**-0.544 (-1.009, -0.054)** *	-0.270 (-0.616, 0.087)
200	0.506 (-0.055, 1.030)	0.505 (-0.119, 1.115)	0.349 (-0.049, 0.728)	0.228 (-0.040, 0.512)	0.217 (-0.064, 0.492)	-0.021 (-0.374, 0.332)	-0.026 (-0.273, 0.233)
300	0.432 (-0.106, 0.967)	0.549 (-0.107, 1.193)	0.310 (-0.071, 0.702)	0.180 (-0.064, 0.442)	0.173 (-0.074, 0.423)	0.054 (-0.263, 0.370)	-0.060 (-0.287, 0.171)
400	0.440 (-0.053, 0.947)	0.355 (-0.317, 1.002)	0.176 (-0.203, 0.592)	0.154 (-0.085, 0.378)	0.152 (-0.075, 0.389)	0.050 (-0.300, 0.394)	-0.098 (-0.382, 0.189)
500	0.562 (0.078, 1.020) *	0.272 (-0.373, 0.921)	0.068 (-0.297, 0.425)	0.305 (0.083, 0.552) *	0.298 (0.052, 0.523) *	0.055 (-0.290, 0.404)	-0.179 (-0.441, 0.121)
600	0.615 (0.170, 1.059) *	0.352 (-0.320, 1.019)	0.038 (-0.258, 0.345)	0.417 (-0.056, 1.018)	0.410 (-0.067, 0.982)	0.073 (-0.259, 0.413)	-0.133 (-0.423, 0.152)
700	0.651 (0.222, 1.101) *	0.439 (-0.181, 1.062)	0.015 (-0.273, 0.313)	0.560 (0.078, 1.210) *	0.552 (0.052, 1.137) *	-0.013 (-0.350, 0.333)	-0.076 (-0.381, 0.237)
800	**0.649 (0.201, 1.122)** *	0.494 (-0.131, 1.119)	0.057 (-0.269, 0.394)	**0.701 (0.179, 1.359)** *	**0.696 (0.178, 1.322)** *	-0.057 (-0.462, 0.333)	-0.111 (-0.437, 0.205)
900	0.622 (0.132, 1.135) *	0.516 (-0.123, 1.134)	0.124 (-0.219, 0.473)	0.244 (-0.180, 0.713)	0.245 (-0.173, 0.693)	0.038 (-0.382, 0.490)	-0.190 (-0.545, 0.148)
1000	0.558 (0.039, 1.049) *	0.521 (-0.093, 1.156)	0.152 (-0.213, 0.502)	0.224 (-0.166, 0.681)	0.226 (-0.182, 0.705)	0.003 (-0.499, 0.507)	**-0.299 (-0.580, -0.003)** *
1100	0.502 (0.010, 1.000) *	0.455 (-0.064, 0.957)	0.161 (-0.284, 0.591)	0.206 (-0.179, 0.645)	0.208 (-0.206, 0.686)	-0.091 (-0.620, 0.426)	0.062 (-0.258, 0.374)
1200	0.457 (-0.083, 0.990)	0.625 (0.027, 1.280) *	0.174 (-0.227, 0.618)	0.060 (-0.345, 0.497)	0.061 (-0.327, 0.502)	-0.047 (-0.510, 0.434)	-0.178 (-0.458, 0.122)
1300	0.387 (-0.162, 0.915)	0.652 (-0.015, 1.327)	0.218 (-0.197, 0.630)	-0.044 (-0.448, 0.382)	-0.044 (-0.445, 0.409)	-0.055 (-0.517, 0.399)	-0.311 (-0.621, 0.008)
1400	0.394 (-0.167, 0.972)	**0.689 (0.019, 1.383)** *	0.200 (-0.204, 0.641)	-0.109 (-0.541, 0.331)	-0.110 (-0.561, 0.327)	-0.150 (-0.609, 0.335)	-0.244 (-0.579, 0.093)
1500	0.456 (-0.158, 1.077)	0.698 (-0.025, 1.414)	0.123 (-0.299, 0.558)	-0.194 (-0.637, 0.257)	-0.196 (-0.618, 0.282)	-0.159 (-0.615, 0.304)	-0.250 (-0.592, 0.069)

Notes: Adjusted for sex, age, disabilities, education, income, occupation, years lived in the neighbourhood, perceived neighbourhood safety, satisfaction with shops, leisure facilities, public transport, population density and city. **Abbreviations:** (A) Surrounding GN: Surrounding Greenness (measured as mean NDVI within Euclidean Distance), (B) Accessible GN: Accessible Greenness (measured as mean NDVI within network distance), (C) Accessible GS: Accessible Green spaces (measured as public green space within network distance), (D) Accessible GC: Accessible Green Corridors (measured as public green space accessible from network distance), (E) Accessible TGS: Accessible Total Green Space (measured like E, but with private or semi-public green spaces included), (F) Quantity of GSU: Quantity of Green Space Uses (measured as sum of points within network distance), (G) Mix of GSU: Mix of Green Space Uses (measured as sum of different uses within network distance) ; *****: Coefficient is statistically significant**;** bold estimates indicate highest significant positive and negative estimate within specific indicator.

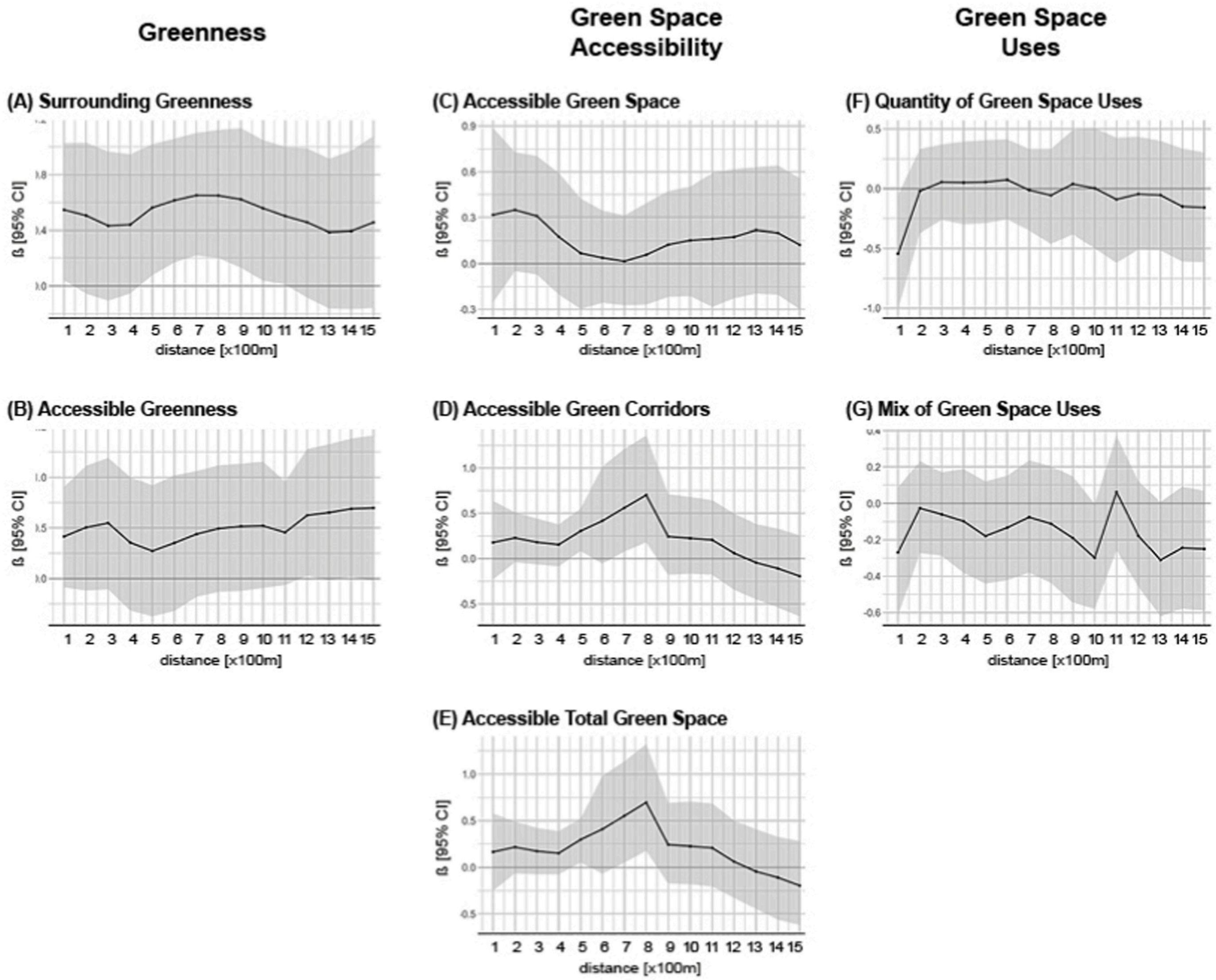

Fig. 8. Total Effects (a*b + c). Green Space – Physical Activity – Health Sensitivity Analysis. Standardized Estimated ß (95% CI) of the 105 structural equation models; adjusted for sex, age, disabilities, years of education, income, occupation, years lived in the neighbourhood, perceived neighbourhood safety, satisfaction with shops, leisure facilities, public transport, population density and city; 5000 Bootstrap Samples; shaded grey area show 95% confidence interval.

4. Discussion

4.1. Main findings

In our study, we examined associations between 105 different green space indicators, physical activity and health in a sample across four European cities. We found that greenness was associated with physical activity and indirect health benefits in the immediate surroundings (100 m). Accessible green corridors, preferably with a mix of use, were associated with higher levels of physical activity and possible indirect health benefits when they can be reached within 800 m or a 10 min walk. On the contrary, direct health effects were only associated with green space at intermediate or larger buffers depending on the green space indicator. Surrounding greenness (500 m-1100 m) and accessible green corridors (500 m, 800 m) were significantly associated with direct health effects and identified as unique green space characteristics. We also found significant negative patterns. A high quantity of green space uses in larger network distances (1100–1500 m) showed negative associations with physical activity and negative indirect health effects. A high number of green spaces uses in immediate distance (100 m) and a high mix of uses in 1000 m and 1300 m network distance was associated with negative health outcomes. To our knowledge, we are the first to test such a rigorous sensitivity analysis for the green space physical activity health pathway, expanding our understanding of how and where these mechanisms occur.

Our results support the theory that different mechanistic pathways between green space and health rely on different green space characteristics, work at different distances and may even change direction depending on the analysed green space characteristics and proximity. Furthermore, our total effects suggest that different mechanistic pathways may mask each other. This should be considered when further disentangling the specific pathways in order to improve our understanding of the effects of green spaces on health. Lastly, the comparison between green space indicators showed that the inclusion of connectivity of green spaces as well as semi-public and private green spaces led both to stronger and more robust patterns of significant associations with physical activity and with health, highlighting the risk of bias on the one side and the importance of these aspects on the other side.

4.2. Green space health effects via physical activity

Our study indicates that greenness in immediate proximity (100 m), as well as green space, green corridors reachable within a 10-min walk (up to 800 m distance) and green space uses up to 1000 m are significantly associated with higher physical activity and indirect health effects. This is consistent with previous research that found a positive association between public open spaces and leisure-time physical activity, as well as maintaining or initiating recreational walking (Motomura et al., 2022; Sugiyama et al., 2013). Specifically, our results support the theory that the immediate surroundings, connectivity and usability of green spaces seem to matter the most, which is in line with previous studies (Akpinar, 2016; McCormack et al., 2010; Sugiyama et al., 2010). Together, our findings add to the body of evidence that suggests a positive relationship between nearby green space, physical activity, and general health (Luo et al., 2020; Markevych et al., 2017; Yang et al., 2021) and they show in more detail how and where these relationships might occur.

Our findings also suggest that more greenness might not always be beneficial for physical activity and health if it is not accessible. We observed a pattern of (non-significant) negative indirect health effects for surrounding greenness, but not for accessible greenness in buffer distances of 1100–1500 m. In addition, we found a very similar significant plateau of negative indirect effects on health for the quantity of green space uses at the same distances of 1100–1500 m. This might be related to physical inactivity and the car-dependent lifestyle (Chandrabose et al., 2022; Kleinert and Horton, 2016; Sallis et al., 2016) prevalent in satellite districts that are usually much greener than their central urban counterparts and thus often may also have a higher quantity of green space uses. In addition, peer behaviour in these districts may also play a role, as evidence suggests that individuals' physical activity levels are influenced by the behaviour of their peers (Finnerty et al., 2010), although not consistent (Tucunduva Philippi et al., 2016).

However, it is also plausible that larger distance associations stem from changes in the signal-to-noise ratio. Arguably, the inviting character of green space uses or pure greenery might disappear at larger distances, gradually reducing the association to physical activity and therefore allowing the noise in the dataset to dominate the results. There seem to be certain thresholds, or necessary perspectives, that form boundaries in which the hypothesized positive relationship is detectable. For example, accessible green spaces (Fig. 6C) showed a non-significant negative association in immediate distances, before turning positive and significant when measured in intermediate surroundings of 400–700 m. This might be related to the necessary quantity of green spaces needed to trigger physical activity and is also in line with the results on green space corridors and total accessible green spaces where this widened perspective is built into the indicator (e.g. it is measuring the green space area beyond the buffer boundaries and semi-public green spaces), leading to detectable positive significant effects at immediate distances.

Furthermore, our study results might help to explain why half of the previous mediation analyses on physical activity did not find a significant relationship (Dzhambov et al., 2020). Firstly, we could demonstrate that the results react very sensitively to the buffer distance used in the analysis and might even turn a positive association into a negative association in some cases. Secondly, our results highlight the differences in greenness and green space indicators for studies exploring physical activity. These differences corroborate the theory that physical activity is more related to the green space characteristics of accessibility, connectivity and green space uses than to greenness, especially at the common distances researched of 300–500 m (Cardinali et al., 2023b; Labib et al., 2020). In our study, physical activity was stronger and more consistently related to spatial green space indicators than to indicators based on vegetation indices. Thirdly, our findings suggest that the way in which the green space indicators are set up plays an important role in increasing the consistency and magnitude of the findings, which is important due to the very low signal-to-noise ratio in green space health research (Hartig et al., 2014). In our study the connectivity of green spaces and how private and semi-public green spaces were included made a significant difference in the estimates, which - to our knowledge – were both mostly not included in previous research.

4.3. Green space health effects via other pathways

All measured positive direct patterns (factually adjusted for physical activity) are associated with intermediate distances. We hypothesize that this might be mainly related to mitigation effects, as restoration effects are more likely to be associated with immediate contact with nature (Cardinali et al., 2023b), which might be able to explain our almost significant association for greenness and health at immediate distances of 100 m. The clear pattern of positive direct relations with health for surrounding greenness within 500–1100 m is in line with previous research on mitigation which might be related to better air quality due to fewer pollution sources and the associated mechanisms of vegetation of deposition and dispersion (Mueller et al., 2022). Furthermore, our results are in line with the review of Browning and Lee (2017), who found a trend that plateaued between 500–1000 m distance in studies where individual addresses were used, a trend that is quite consistent with our results. Additionally, our results suggest that the connectivity of green spaces could play a role since only access to green corridors (D) and total access to green space (E) showed a significant pattern while green space in network distance (C) did not (Fig. 3). This might especially be related to the importance of air-exchange corridors which have been studied in their ability to reduce urban heat island effects (Gunawardena et al., 2017; Kuang et al., 2015; Ren et al., 2016; Wong et al., 2010), to reduce air pollution through their cooling (Aram et al., 2019) and cleaning effect, through deposition and dispersion (Hewitt et al., 2020). However, the pattern is not as consistent as the surrounding greenness pattern, which might be explained by the general problems with the quality of available green space data (Cardinali et al., 2023b).

The negative associations between health and quantity and mix of green space uses might be a spurious relation reflecting the typically high amount of green space uses in satellite districts instead of a real direct association between green space uses and health. It is important to consider that these direct associations are factually adjusted for physical activity, which is likely the main link to green space uses. This may lead to a true null or very small relationship, which allows for spurious relations to be observed, reflecting the high signal-to-noise ratio (Hartig et al., 2014). Thus, these negative health outcomes are likely caused by other factors associated with these neighbourhoods. Although we controlled for socio-demographic indicators, we did not specifically control for peer behaviour like smoking, drinking or an unhealthy diet (Lazzeri et al., 2014; Morton et al., 2020), which could be more prevalent in these districts (Sorensen et al., 2013; Warren Andersen et al., 2016) and partially explain these negative associations between green space uses and health.

4.4. Trade-offs and masking between pathways

Our findings indicate that information on specific pathways may remain concealed if they are not disentangled. This aligns with recent theories that the *Instoration* pathway via physical activity operates differently than mitigation or restoration pathways (Cardinali et al., 2023b; Labib et al., 2020; Markevych et al., 2017). In our results, the degree of surrounding vegetation (A) in buffer distances of around 500–1100 m shows a clear positive direct relation to health while we observed a negative trend for the indirect effects via physical activity. Similarly, accessible green corridors (D) and accessible total green space (E) from 500 to 1000 m, show differing patterns of significance when comparing direct and indirect effects. Moreover, while the mix of green space uses (G) shows positive relations to physical activity and thus indirectly to health, they showed consistent negative direct associations to health. This mechanism might be able to partly explain the heterogeneity of past results, frequently recognized as a barrier in the field (Cardinali et al., 2023b; Markevych et al., 2017). Lack of information on specific pathways may hinder making well-informed policy and urban design decisions regarding green spaces as these choices may depend on the specific health problems in an area and therefore the specific green space characteristics or distances.

4.5. Strengths and limitations

To the best of our knowledge, our study is the first to conduct rigorous analyses of the area of effect of the green space - physical activity - health pathway, while also testing different green space characteristics considered crucial for this relationship. Due to our study design, we could reveal patterns of significance, as well as peaks in significant estimates, and changes in the direction of the relationship due to proximity. Similarly, it allowed for the comparison of green space characteristics, revealing potential important nudging effects of connectivity and usability of green spaces.

However, several limitations of the study need to be considered when interpreting the findings. Our study primarily relied on self-reported data for most of its indicators, making it vulnerable to biases such as social desirability, recall or reporting bias. Particularly, the use of the International Physical Activity Questionnaire Short Form (IPAQ-SF) as a measure of physical activity may have limited the accuracy of the data collected. Previous research has shown that the IPAQ-SF tends to overestimate physical activity levels, with a weak correlation to objective measures of activity or fitness (Lee et al., 2011). We also had to transform the variable into an ordinal indicator to resolve the zero-inflated count variable issue. While this may mitigate some of the aforementioned overestimation, it essentially led to a loss in data granularity. Similarly, using Likert items for the control indicators may not have provided a fully accurate measure of these variables. Furthermore, the use of an ordinal item to measure health as one of the main variables of interest allows only for a general picture of the analysed pathways. Moreover, while we adjusted for seasonal differences (through the data acquisition of the satellite image which formed the basis of the greenness indicators and the dummy city variable) there may still be considerable variation in weather conditions within the weeks of the data collection, which might affect the studied associations.

More limiting factors emerge from the study design. The methodological approach that compared 105 structural equation models made it unfeasible to further stratify by gender or age, potentially overlooking differences in associations between green space, physical activity and health for these groups. This also limits the ability to include variables that act as confounders on physical activity and health but which are also mediators on the pathway from green space to physical activity, like environmental pollution indicators. In addition, we cannot rule out residual confounding, despite controlling for the main confounders like socio-economic status. For example, unmeasured variables like smoking, alcohol and dietary habits might affect our results, although the expected bias is low since these variables are also associated with socio-economic status (Fewell et al., 2007). Furthermore, the study employed a cross-sectional design, which precludes establishing causal relationships between green space and health outcomes. Finally, there is a potential selection bias, as the study recruited participants from a specific geographic area, and participants who agreed to participate may differ from those who did not. All of the above-mentioned factors limit the generalisability of our findings.

4.6. Future research and implications

Further research is needed to confirm these results and expand on them, preferably with more objective measures of physical activity and more detailed health outcomes. In addition, our findings may serve as an important point of departure for designing more complex and resource-intensive longitudinal studies to establish causality. They might also serve as a starting point for more detailed analysis with effect modification, e.g. to analyse the differences for different age groups. Moreover, the negative indirect and direct relationship between the quantity of green space uses with physical activity and health should be further explored, e.g. by including peer behaviour in future studies. In addition, while we hypothesize that our measured direct health effects are mainly mitigation effects, more research is needed to confirm this. Given that we conducted our study on European satellite districts, exploring other regions in the world and even more central parts of cities is needed to confirm our findings in other areas. These avenues of research could contribute to a more comprehensive understanding of the relationship between different green space characteristics, physical activity and health outcomes. Despite the need for further research, our results show potentially important implications for future studies in this research area.

Our findings suggest that studies should carefully consider which green space characteristic they want to examine since this will likely determine the calibration of buffer types and distances in order to capture the desired effects on physical activity and health. Where greenness seems to function only in immediate surroundings, accessible green spaces and green space uses are associated with physical activity and health in walkable distances of up to 800 m. According to our results, most of these indicators show the clearest associations, e.g. the highest estimate, at 600 m network distance. Going beyond these walkable catchment areas may allow for spurious relations to show and lead to insignificant or even negative findings.

These results further indicate that more attention should be paid to counteracting effects between pathways and noise in the dataset that might cover the relationship of interest. In our study, many of the green space characteristics showed significant indirect effects, but most of them summed up to non-significant total effects. This indicates the necessity of isolating the specific pathway of interest in study designs, for instance through pathway analysis. Specifically, when there's a high signal-to-noise ratio in one pathway and a low one in another, it may result in inconclusive outcomes. Furthermore, if one pathway reveals a distinct relationship at a certain distance while the other shows no relationship, the aggregated results might be rendered insignificant. It seems that without calibrating green space characteristics and buffer distance for one specific pathway, potential trade-offs or obscured effects can arise. We anticipate that more of these offsetting effects exist between green space health pathways and sub-pathways at specific distances. Further research is needed to better understand these trade-offs.

For practitioners and decision-makers, our results also suggest that current urban greening strategies may not be sufficient to exploit the full range of positive effects of green spaces on health. Currently, many green space strategies are based on simple green space/resident or green space/hectare ratios that are not able to take into account the connectivity and mix of use of those spaces. Instead, green space strategies should rather strive to further extend and interconnect existing green spaces if the target is to encourage physical activity. This applies in particular to the linkage of semi-public green spaces with the urban green network. Furthermore, our results suggest that it can make sense to check existing green spaces for their usability and accessibility and thus use the hidden potentials of green spaces in the city, with less effort.

Although there is a mounting body of evidence about the beneficial effects of green spaces, most of it is based on cross-sectional studies. To better inform policy analysis, planning, and design processes with robust implications, it is essential to advance the field with more longitudinal and quasi-experimental studies reflecting on the impact of urban green regeneration. These studies are vital for developing a comprehensive understanding of the implications of green spaces in urban settings.

5. Conclusion

We implemented a unique study design that compared 105 structural equation models, to explore the roles of green space characteristics and proximity in the green space-physical activity-health pathway. Our results indicate that residents are more likely to increase their physical activity, and experience indirect health effects when living in immediate proximity to greenness, as well as to green corridors, preferably with multiple potential uses and within a distance of up to 800 m. Additionally, we discovered that intermediate distances of 500–1100 m are associated with direct health effects, which we hypothesize to be mainly mitigation effects. Although our study is limited to four European satellite districts, it provides important implications for green space health research by unveiling the influence of proximity to green spaces and their characteristics. Moreover, our results suggest that it is important for urban planning strategies to consider not only the ratio of green spaces per hectare or person but also the potential of well-connected green spaces and their mix of uses to reduce physical inactivity, a major risk factor for non-communicable diseases.

CRediT roles

MC: Conceptualisation; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Validation; Visualization; Writing - original draft; Writing - review & editing. **MB:** Formal analysis; Investigation; Methodology; Resources; Supervision; Validation; Writing - review & editing. **AT:** Conceptualisation; Methodology; Resources; Supervision; Validation; Writing - review & editing. **UP:** Conceptualisation; Methodology; Resources; Supervision; Validation; Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT 4.0 in order to proofread the text. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2023.117605.

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