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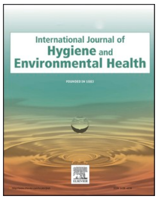

Physical urban environment and cardiometabolic diseases in the five largest Bulgarian cities

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ABSTRACT

This study investigated the associations between residential environmental characteristics and the prevalence of cardiometabolic diseases in the five largest Bulgarian cities. Representative cross-sectional survey data (N = 4640 adults) was collected in Sofia, Plovdiv, Varna, Burgas, and Ruse. Participants self-reported diagnosis or medication intake for hypertension, ischemic heart disease (IHD), stroke, and diabetes mellitus, as well as domestic burning of solid fuel and having a domestic garden. Residential addresses were linked to greenspace (overall vegetation level, tree cover, urban greenspace), bluespace, walkability, air pollution (NO_2), and traffic noise (L_{den}). In the 300 m buffer, bluespace presence was inversely associated with hypertension (odds ratio [OR] = 0.67; 95% CI: 0.45, 1.00), IHD (OR = 0.45; 95% CI: 0.21, 0.99), and diabetes (OR = 0.51; 95% CI: 0.25, 1.04). Higher walkability and tree cover were inversely associated with hypertension ($OR_{\text{per 2 units}} = 0.85$; 95% CI: 0.75, 0.96) and diabetes ($OR_{\text{per 10\%}} = 0.77$; 95% CI: 0.62, 0.97), respectively. These associations were stronger in larger buffers. Solid fuel burning was associated with IHD (OR = 1.63; 95% CI: 1.07, 2.50). There was an indication of a positive association between aircraft L_{den} and both stroke and IHD. The direction of the associations for domestic gardens, NO_2, road traffic and railway L_{den} was counterintuitive. We detected some nonlinear associations. In conclusion, people living in urban neighborhoods that were more walkable, closer to bluespace, and greener had lower prevalence of cardiometabolic diseases, while solid fuel burning was associated with higher odds of cardiovascular diseases. Unexpected associations with some exposures may be due to unaccounted for urban fabric characteristics. This study is among the first assessing an understudied region in Southeastern Europe. Its findings have the potential to inform public discourse and provide evidence to support the implementation of urban design conducive to cardiometabolic health.

1. Introduction

Cardiovascular diseases (CVD) represent the leading cause of the global burden of disease (World Heart Federation, 2023), with 20 million CVD deaths from ischemic heart disease (IHD) and stroke registered in 2021 (World Heart Federation, 2023). Globally, 1.3 billion people have hypertension (World Health Organization, 2023), and one in ten adults live with diabetes mellitus (GBD 2021 Diabetes Collaborators, 2023), both of which are significant major risk factors for CVD.

In addition to the well-established biomedical and behavioral risk

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factors, such as high blood pressure, diabetes, poor diet, smoking, and physical inactivity (World Health Organization, 2023), there is a growing recognition of the residential environment as a determinant of general (Bird et al., 2018) and cardiovascular health (Liu et al., 2023). For example, a substantial body of evidence indicates that higher outdoor (de Bont et al., 2022; Haddad et al., 2023) and household air pollution (Lee et al., 2020) and traffic noise (Kempen et al., 2018; Fu et al., 2023) are associated with an elevated risk of developing or dying from CVD and diabetes. Air pollution and noise induce a stress response in the body, increase oxidative stress and systemic inflammation levels, which can subsequently adversely affect vascular function and metabolism (Münzel et al., 2022). An umbrella review revealed compelling evidence that ambient air pollution is linked to CVD morbidity and mortality (de Bont et al., 2022). Another review indicated that there is an increased risk of CVD and IHD mortality with higher road traffic noise levels (Cai et al., 2021). Conversely, greater residential greenspace is hypothesized to confer health benefits (Liu et al., 2022) since the availability and utilization of greenspace are associated with reduced exposure to traffic emissions, higher levels of physical activity, diminished stress (Markevych et al., 2017), and enhanced biopsychosocial resilience (White et al., 2023). Furthermore, access to and engagement with private greenspace, such as domestic gardens, can support overall health (Brindley et al., 2018; de Bell et al., 2020) and reduce the risk of CVD (Roscoe et al., 2022). There is a paucity of research examining the relationship between bluespace (i.e., water-dominated landscapes) and cardiometabolic outcomes. Bluespace is generally regarded as a beneficial factor for human health (Gascon et al., 2017), activating much the same mechanisms as greenspace (White et al., 2020). Nevertheless, the evidence regarding the protective effects of coast or inland proximity to water on CVD or diabetes is mixed (Klompmaker et al., 2022). In some studies, an increased likelihood of diabetes was observed among individuals residing in proximity to a water body (Poulsen et al., 2021; Li et al., 2021). Other studies have indicated that while proximity to bluespace was not associated with CVD, the total number of green and blue spaces was negatively associated with CVD incidence (Li et al., 2024). Additionally, some research has demonstrated that proximity to bluespace may offer protection against coronary artery calcification in specific population groups (Kim et al., 2024).

Walkable neighborhoods also have the potential to support cardiometabolic health. A number of studies have reported inverse associations between walkability and a range of health outcomes, including hypertension (Sarkar et al., 2018; Adhikari et al., 2021; de Courrèges et al., 2021), IHD, and diabetes (Makhlouf et al., 2023). However, the majority of existing studies have seldom considered the influence of multiple physical urban characteristics on cardiometabolic health (Groenewegen et al., 2018; Sørensen et al., 2022; Howell et al., 2019; Zhou et al., 2023; Poulsen et al., 2023). For instance, Poulsen et al. (2023) investigated the associations of air pollution, green space, and noise and stroke in a large Danish cohort. The authors found support for the effect of air pollution and noise in multi-exposure models. In other studies, all these three exposures were associated with an increased risk of diabetes (Sørensen et al., 2022). To the best of our knowledge, no study has yet explored the joint effects of air pollution, traffic noise, greenspace, bluespace, and walkability.

A further consideration is the potential for observed effects to vary significantly depending on the context. The geographic heterogeneity of these relationships may impede the effective implementation of evidence-based policies designed to reduce the environmental burden of disease (Dyer et al., 2024). The socioeconomic, land use, and cultural differences between geographies have promoted concerns that epidemiological evidence of exposure-outcome relationships generated in more affluent counties, which are better represented in the environmental health field, may only be partially transferable to lower-income counties (Dyer et al., 2024). Therefore, local evidence is essential to gain a deeper understanding of the intricate relationships between the built environment and cardiometabolic health, taking into account the diverse spatial patterns of these exposures and the varying socioeconomic contexts.

This study addresses these gaps using data from Bulgaria, a country located in Southeast Europe, a region where the field of environmental epidemiology is still in its infancy. Bulgaria has the lowest life expectancy (74.3 years in 2022) among European Union (EU) member states (OECD/European Observatory on Health Systems and Policies, 2023). Over 60% of deaths in Bulgaria are attributed to diseases of the circulatory system (Eurostat, 2023). Approximately 45% of Bulgarians are affected by hypertension (World Health Organization, 2023), while 7.4% have diabetes (International Diabetes Federation, 2021). Additionally, the Balkan region is distinguished by elevated levels of outdoor air pollution (Health Effects Institute, 2022), and a considerable proportion of Bulgarians are energy poor, necessitating the use of firewood and coal for domestic heating and cooking (European Clean Air Centre, 2020). Bulgarian cities have also been found to have high rates of CVD mortality attributable to road traffic noise. Sofia, in particular, has been identified as having the highest mortality rate among EU capitals (Khomenko et al., 2022).

In this study, we examined the potential relationships between various physical characteristics of urban environments and the prevalence of cardiovascular diseases and diabetes in the five largest cities in Bulgaria. We hypothesized that the prevalence of cardiometabolic diseases would be positively associated with lower levels of greenspace, bluespace, and walkability, and higher levels of air pollution and noise. Additionally, we hypothesized that these environmental factors would interact with one another.

2. Methods

2.1. Study areas

The study areas encompass the Bulgarian cities of Sofia, Plovdiv, Varna, Burgas, and Ruse (see Supplementary Fig. S1). The cities of Sofia, Plovdiv, and Ruse are land-locked cities, while Varna and Burgas are resort cities located on the Black Sea coast. Ruse is situated on the southern bank of the Danube, while smaller rivers run through Sofia and Plovdiv. With the exception of Sofia, the other cities are characterized by a compact urban form, which facilitates pedestrian mobility. The vegetation in these cities is predominantly represented by a few larger parks, local neighborhood green spaces, and street trees, which are, however, not well connected. Sofia and Plovdiv exhibit relatively high levels of air pollution and traffic noise. Sofia, Varna, and Burgas have airports, whereas Plovdiv is situated relatively farther from an airport in a neighboring village to the southeast, resulting in low levels of aircraft noise.

2.2. Participant sampling

A cross-sectional sample of adults was collected between August and October 2023 (Helbich et al., 2024). The sample was selected to be representative of the general population with respect to age, sex, education, and ethnicity. The respondents were selected at random from eight spatial typologies defined by their address locations: within ≥/<50 m of a major road; within ≥/<100 m Euclidean distance to ≥10 households registered as using fossil fuel for heating; and within ≥/< 300 m of a green urban area. To this end, harmonized spatial data from OpenStreetMap (OpenStreetMap, 2023), the Bulgarian cadastre (GCCA, 2023), and the Urban Atlas (Copernicus Land Monitoring Service, 2021) were employed. A professional survey company conducted an omnibus environmental health survey among 4640 participants. Of the 10 914 individuals who were contacted by the interviewers, 43% participated in the survey. The response rate varied from 30% in Sofia to 58% in Plovdiv. The sample size was determined based on the feasibility of data collection and was deemed sufficient to ensure statistical power for an omnibus health survey. To be included in the survey, respondents were required to meet the following criteria: they had to be at least 18 years of age, possess proficiency in the Bulgarian language, demonstrate the capacity for mental intent, and have resided at their current address for a minimum of one year.

Following pre-testing, which involved debriefing a small convenience sample and a focus group discussion with sociologists from the survey company, the survey questionnaire and instructions for interviewers were refined to address feedback regarding the duration of the survey and the clarity of some questions. Subsequently, a training session was conducted with the interviewers from each city. This involved a mock interview, followed by a discussion. The interviewers were provided with printed maps of the sampling areas, information regarding the sociodemographic quotas they were required to meet (which were based on census data), and a list of all addresses within the sampling areas, as well as a designated starting address.

The participants were visited at their respective residences. They were informed about the study and were allowed to ask questions. The participants provided verbal informed consent. The pertinent EU data protection regulations were followed. The study was approved by the Scientific Ethics Committee at the Medical University of Plovdiv (Protocol No. 4/May 04, 2023 and Opinion No. P-1253/May 17, 2023). This study followed the STROBE guidelines (von Elm et al., 2007).

2.3. Outcomes

The participants were queried as to whether they had been diagnosed by a medical professional or were taking medication prescribed by a doctor for a number of diseases. The initial prompt for the questions was as follows: "*I will now proceed to enumerate a series of diseases, after which I will inquire as to whether you have been diagnosed with any of them. By that I mean that you have been diagnosed with the disease by a medical professional and/or you have been prescribed by a doctor medication to treat the disease or its symptoms.*" In the present study, we used data on hypertension ("high blood pressure/hypertension"), ischemic heart disease ("ischemic heart disease/stenocardia or myocardial infarction/heart attack"), stroke ("brain stroke, cerebral hemorrhage, thrombosis"), and diabetes mellitus ("sugar diabetes"). Individuals who reported a disease were also asked how long ago they had been diagnosed or how long had they been taking medication ("*For how many years have you had the disease*?"). Responses were recorded in years and/or months, and in the event of uncertainty, participants were instructed to provide their best estimate.

2.4. Residential neighborhood environment

The residential environment was assessed in terms of a number of different variables. Following each interview, a Global Positioning System-based device was employed to record the coordinates of participant's residence. Additionally, the street address was recorded in narrative form. In the event of a discrepancy between the geocoded address and the actual location of the building, manual locational adjustments were made using the relevant cadaster data. The corrected address locations were used in the calculation of physical environment exposures within circular buffers of varying sizes. The R-4.3.2 environment (R Core Team, 2024) and QGIS 3.28.2 (QGIS.org, 2022) were employed for geospatial analyses.

2.4.1. Greenspace and bluespace

For our main analyses, we utilized 300 m address-based Euclidean buffers (Nieuwenhuijsen et al., 2022; Konijnendijk, 2023), a common approach in compact European cities. For sensitivity analyses, we employed 1000 m buffers, in accordance with the proposition that larger buffers may prove more effective in predicting physical health outcomes (Browning et al., 2017). Several greenspace and bluespace indicators were used, including the normalized difference vegetation index (NDVI), tree cover, urban greenspace, domestic gardens, and bluespace.

The NDVI measures the chlorophyll content in vegetation (Tucker, 1979). The NDVI values range between −1.0 and 1.0. As positive values increase, the quantity of green biomass also rises. The NDVI was derived from the Sentinel-2 imagery from Copernicus for the year 2022 (https://developers.google.com/earth-engine/datasets/catalog/COPERNICUS_S2_SR_HARMONIZED#description) with a 10 m resolution. We used images with cloud cover of less than 10%, captured between May and September 2022 when vegetation is greenest. A pixel-based quality check was conducted to filter out poor-quality surface reflectance values using cloud mask and quality assessment band (QA60) information (Chen et al., 2022) prior to computing the median NDVI pixel values across overlapping scenes. The mean NDVI value for each address was utilized in the subsequent analyses.

Tree cover density data were obtained at a resolution of 10 m from the European Urban Atlas layer for the year 2018, as provided by the Copernicus Land Monitoring Service (https://land.copernicus.eu/en/products/high-resolution-layer-tree-cover-density). This layer provides the proportional crown coverage per pixel, derived from multispectral high-resolution satellite data and/or aerial ortho-imagery, which serve as the reference data. The mean percentage of tree cover was calculated for each address and used as the basis for subsequent analyses.

Urban greenspace (UGS) with a minimum mapping unit of 0.25 ha was extracted from the Urban Atlas 2018 (Copernicus Land Monitoring Service, 2021). We aggregated the following land use greenspace-related classes in accordance with the methodology proposed by Barboza et al. (2021). The following categories were used: 14100, 14200, 21000, 22000, 23000, 24000, 31000, 32000, and 40000. The percentage of UGS coverage within the respective buffer was employed for analyses.

Another indicator of proximal greenspace was the presence (no/yes) of a domestic garden. The participants were asked to indicate whether their residence had a garden or yard with vegetation where they could engage in leisure activities.

Bluespace data at a 10 m resolution were also obtained for the year 2018 from the Copernicus Land Monitoring Service (https://land.copernicus.eu/en/products/high-resolution-layer-water-and-wetness). The presence of permanent water was determined through the analysis of multi-temporal and multi-seasonal optical high-resolution satellite imagery and Sentinel-1 data. Due to the sparsity of water bodies in the area, we created a binary bluespace variable to indicate their presence or absence within the buffer.

2.4.2. Walkability

Walkability quantifies how pedestrian-friendly and accessible a neighborhood is for walking (Cervero et al., 2009; Gao et al., 2020). In light of the available Bulgarian data, our walkability index was constructed on the basis of population density, land use diversity, and four-way intersection density. Population density was calculated using cadastral data for buildings with housing function, the number of floors, and the number of people per address location based on the average housing area per person for every city using the 2021 census data (National Statistical Institute, 2023). Land use diversity was quantified based on Shannon's diversity index, which was calculated using cadastral data (GCCA, 2016) and the 2018 European Urban Atlas data (Copernicus Land Monitoring Service, 2021). We considered the following land use categories: mixed, residential, public and commercial, green and recreational, industrial, transportation and communication, agriculture, forest and natural, water, and others. The data regarding the number of intersections in each area were obtained from OpenStreetMap (OpenStreetMap contributors, 2023). To ascertain a walkability index for each address, we summed the z-scores of the three input variables within buffers.

2.4.3. Air pollution

Nitrogen dioxide (NO_2) served as a proxy for traffic-related air pollution. The NO_2 data for 2019 were obtained at a 50 m spatial resolution from a global land use regression (LUR) model (Larkin et al., 2023). We converted the ppb units to μg/m^3 (i.e., 1 ppb = 1.88 μg/m^3) and computed mean NO_2 in a 50 m buffer around each address.

Additionally, participants were queried as to whether they used coal, firewood, briquettes, or pellets for the purposes of domestic heating or for cooking, irrespective of the season. This binary measure (no/yes) of the burning of solid fuel in the home served as a proxy for indoor air pollution.

2.4.4. Traffic noise

In order to obtain the A-weighted day-evening-night sound level (L_{den}) for road traffic, railway, and aircraft, we relied on data sourced from the Bulgarian strategic noise maps for the year 2017, delivered under the Environmental Noise Directive (EEA, 2020). Participants' addresses were then linked to these maps. Modeling was commissioned by local authorities from an acoustic engineering company (SPECTRI, 2016, 2017a, 2017b, 2017c, 2017d). The L_{den} was modeled using the CNOSSOS-EU framework and calibrated and validated with short-term field measurements (SPECTRI, 2016, 2017a, 2017b, 2017c, 2017d) (see Dzhambov et al. (2023)). The maps were produced at a spatial resolution of 10 m and later reported in the form of polygon-based isophones. We generated pseudo-continuous L_{den} variables by assigning each 5-dB noise band its respective midpoint value (e.g., the 50–55 dB polygons received a value of 52.5 dB) (Dzhambov et al., 2023; Floud et al., 2013; Jarup et al., 2008). Addresses exposed to railway and aircraft L_{den} below 40 dB were assigned a value of 37.5 dB L_{den} (Romero et al., 2023). Addresses outside of the contours of these maps were considered unexposed and were treated as missing values in the analyses. In a sensitivity analysis, we recoded railway and aircraft L_{den} into categorical variables, with the unexposed population serving as the reference group (Babisch et al., 2006; Dratva et al., 2012).

2.5. Confounders and effect modifiers

Potential confounding variables were selected with the help of a directed acyclic graph (DAG) (see Supplementary Fig. S2). Participants reported their age and self-identified biological sex. Due to the low number of individuals reporting non-Bulgarian ethnicities, self-identified ethnicity was dichotomized into Bulgarian and other. The highest level of education completed was classified as follows: *1 = "primary education not completed*", *2 = "primary education*", *3 = "secondary education (high school/vocational)*", and *4 = "higher education (BSc, MSc, PhD)*". The employment status of respondents was classified as either "unemployed" or "employed." Income adequacy was gauged using a single item on coping with perceived financial difficulties considering the total monthly income of the household, where responses were given on a 6-point scale (*1 = Very difficult, 2 = Difficult, 3 = With some difficulty, 4 = Mostly easy, 5 = Easy, 6 = Very easy*).

History of smoking tobacco products was recorded as "never smoker", "former smoker", and "current smoker". An individual who had smoked a total of 100 cigarettes in their lifetime was classified as a smoker. Body mass index (BMI) was calculated from self-reported height and weight, and was used as a measure of adiposity. The variable was collapsed into the following categories: underweight (BMI <18.5 kg/m^2), normal weight (BMI 18.5–24.99 kg/m^2), overweight (BMI 25–29.99 kg/m^2), and obese (BMI ≥30 kg/m^2). Information regarding family history of CVD or diabetes was obtained by asking participants whether either of their biological parents had ever been diagnosed with "high blood pressure (hypertension), heart disease, or stroke" or "diabetes", respectively.

To control for the level of urbanicity of the home surroundings, we used the 100 m population raster from the 2021 census provided by the National Statistical Institute of Bulgaria (National Statistical Institute, 2023). We calculated the number of people residing within a 300 m buffer around the home address. To incorporate city-specific differences, we included dummy variables. Area-level socioeconomic status (SES) was operationalized through the percentages of employed people and people with higher education. Area-SES data were aggregated into an overall of 17 619 cadastral map polygons across the five cites. Each residential address in the sample was then linked to the closest polygon.

2.6. Statistical analysis

The proportion of missing values for the outcome variables was less than 1% in each case. The questionnaire variable with the highest percentage of truly missing data was income adequacy (n = 213; 4.59%). Therefore, we proceeded with complete-cases analyses. Descriptive statistics, bivariate polychoric correlations, Kruskal-Wallis, and Chi-Square tests were used to explore general patterns and associations in the data.

Logistic regression models were employed to assess the association between each exposure and health outcome separately, while controlling for potential confounding factors. The models were adjusted for the minimally sufficient set suggested by the DAG, which included age, sex, ethnicity, education, employment status, income adequacy, city, and urbanicity. The buffered variables (with the exception of NO_2) derived for the 300 m buffer were used in the main analyses. Inspection for nonlinear exposure-outcome relationships was conducted using generalized additive models (Hastie and Tibshirani, 1986; Royston and Ambler, 1998), fitted with different degrees of freedom (1 [linear term], 3, and 5), with 3 degrees of freedom finally used for the estimated smooth functions to prevent overfitting. The presence of nonlinearity was inferred based on visual inspection of the relationships and a significant Gain statistic, which quantifies the deterioration in fit that occurs if a linear term is used instead of the smooth term. The estimated functions were plotted with the "gamplot" package for Stata. Since we detected some nonlinear associations for some exposures and for age, logistic models were constructed that included these exposures and age grouped into quartiles (see Supplementary Figs. S3–S11).

Multi-exposure models were rendered with the exposures adjusted for each other. However, NDVI and railway and aircraft L_{den} were excluded from the multi-exposure models due to a high correlation between NDVI and tree cover, and a lack of railway and aircraft noise data for a considerable number of observations. Multicollinearity between the remaining independent variables was not detected according to variance inflation factors <5 and tolerance values > 0.2.

The robustness of the results obtained from the main models was evaluated through the implementation of several sensitivity analyses. First, we refitted the single-exposure models with NDVI, tree cover, UGS, walkability, and bluespace derived for the 1000 m buffer. Secondly, we further adjusted the main models for smoking, BMI, and family history of CVD or diabetes, which are theoretically influential causal ancestors of the health outcomes. Thirdly, the main model was adjusted for the percentages of the population who are employed and who have attained higher education, as area-SES may simultaneously influence both the exposures and the outcomes. Fourth, we recalculated the main models after the exclusion of participants who had been diagnosed with the analyzed disease prior to their relocation to their current residence. Fifth, we imputed the missing values on income adequacy, ethnicity, and education using multiple imputation by chained equations. The main logistic regression models were then fitted on the 10 imputed datasets to make use of the full sample (see Supplementary Fig. S12). Finally, since many participants were unexposed to railway and aircraft noise, we rerun the models with railway and aircraft L_{den} as categorical variables, with the unexposed group serving as the reference (Babisch et al., 2006; Dratva et al., 2012).

We probed additive interactions between the exposures (VanderWeele and Knol, 2014) in case the direction of exposure – outcome associations was consistent with theory. Interactions were tested after dichotomizing continuous exposure variables by splitting them at the median to avoid loss of statistical power. In the case of railway and aircraft L_{den}, the reference group comprised individuals exposed to low noise levels and those who were unexposed. “Preventive” exposures were recoded so that the category hypothesized to be associated with a “protective effect” was designated as the reference category (e.g., high tree cover was coded as 0 and low tree cover as 1) (Knol et al., 2011). We calculated relative excess risk due to interaction (RERI) using Stata’s “reri” command. An RERI = 0 indicates the absence of an additive interaction, RERI >0, positive or super-additive interaction, and RERI <0, negative or sub-additive interaction (VanderWeele et al., 2014). If the 95% confidence interval (CI) of RERI included 0, it was taken as evidence of no significant interaction on the additive scale.

We adopted a level of statistical significance of $p < 0.05$ (two-tailed). All analyses were conducted in Stata/MP v. 18 (StataCorp, 2023).

3. Results

3.1. Sample characteristics and bivariate associations

Fig. 1 shows the flowchart of participant selection. A summary of the participants’ characteristics is provided in Table 1. On average, participants were 49 years old with an age range from 18 to 90 years. Approximately half of the participants were female, and nearly all identified as ethnic Bulgarians. The majority of participants had completed secondary education, with a smaller proportion having pursued higher education. Participants indicated that they were able to manage their income, although they encountered some difficulties. Two-thirds of the participants were employed. A comparison with the general population obtained from the 2021 census demonstrated that the sample was largely representative of the population’s sociodemographic characteristics, although it exhibited a higher percentage of individuals with higher education (see Supplementary Table S1).

Approximately one in three people reported hypertension; 8% had IHD, 3% had stroke, and 9% had diabetes. The prevalence of hypertension and diabetes was lowest in Plovdiv, and Ruse had the highest IHD prevalence. The majority of participants indicated a family history of CVD, while approximately one-quarter reported a family history of diabetes. More than half were overweight or obese, and about half were former or current smokers. The results of the Pearson chi-square tests and Kruskal-Wallis tests demonstrated statistically significant differences in the characteristics of the sample between the cities (Table 1). Correlations between the main variables were in line with theory and supported the covariate choice (see Supplementary Fig. S13).

3.2. Main analyses

In the main single-exposure models, bluespace presence in the 300 m buffer was associated with lower prevalence of hypertension (OR = 0.67; 95% CI: 0.45, 1.00) and IHD (OR = 0.45; 95% CI: 0.21, 0.99), and potentially diabetes (OR = 0.51; 95% CI: 0.25, 1.04) (Table 2). Additionally, a higher walkability score was inversely associated with hypertension ($\mathrm{OR}_{\text{per 2 units}} = 0.85$; 95% CI: 0.75, 0.96). Higher tree cover was associated with lower odds of diabetes ($\mathrm{OR}_{\text{per 10\%}} = 0.77$; 95% CI: 0.62, 0.97). With regard to NDVI and UGS, we observed a suggestive (non-linear) association pattern with reduced odds in the low and high but not intermediate quartiles.

Conversely, domestic burning of solid fuel was found to be positively associated with IHD (OR = 1.63; 95% CI: 1.07, 2.50). A similar, albeit less pronounced, pattern was observed in the case of hypertension. The data indicated a 17–19% higher prevalence of stroke and IHD for every 5 dB increase in aircraft L_{den}, though the estimates were not precise.

It was unexpected that higher road traffic L_{den} was associated with lower prevalence of the outcomes, most notably stroke ($\mathrm{OR}_{\text{per 5 dB}} = 0.82$; 95% CI: 0.68, 0.98). A comparable trend was observed with regard to NO_2 levels. The odds of diabetes were also below 1.00 when railway L_{den} was higher ($\mathrm{OR}_{\text{per 5 dB}} = 0.80$; 95% CI: 0.66, 0.96). The presence of a domestic garden was found to be consistently associated with 20–27% higher odds for all outcomes.

In the multi-exposure models, we observed associations with somewhat wider confidence intervals that nonetheless remained consistent with the main models. These associations were observed for walkability and less hypertension, bluespace and less hypertension, IHD, and diabetes, tree cover and less diabetes, and burning solid fuel and IHD. However, the protective direction of the associations with NO_2 and L_{den} persisted. The detrimental association with domestic gardens also persisted (see Supplementary Table S2).

3.3. Sensitivity analyses

Within a 1000 m buffer, the estimated protective associations between walkability and both IHD and stroke were more pronounced with narrower confidence intervals. The protective associations between tree

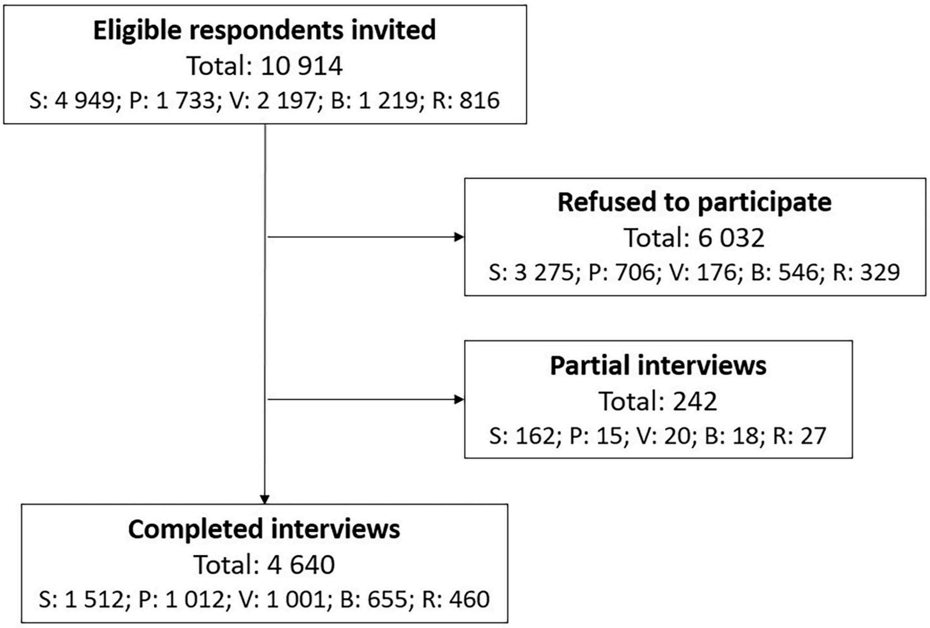

Fig. 1. Selection of participants in the study. Note. Abbreviations: B – Burgas, P – Plovdiv, R – Ruse, S – Sofia, V – Varna.

Table 1
Characteristics of the study participants.

	Total sample (N = 4640, 100%)	Sofia (N = 1512, 32.6%)	Plovdiv (N = 1012, 21.8%)	Varna (N = 1001, 21.6%)	Burgas (N = 655, 14.1%)	Ruse (N = 460, 9.9%)
Sociodemographics						
Age [years]	49 (37, 65)	49 (37, 65)	49 (35, 66)	49 (36, 65)	49 (38, 64)	51 (38, 65)
Male	2117 (45.6%)	684 (45.2%)	464 (45.8%)	471 (47.1%)	298 (45.6%)	200 (43.5%)
Non-Bulgarian ethnicity	193 (4.2%)	21 (1.4%)	30 (3.0%)	71 (7.1%)	16 (2.5%)	55 (12.0%)
Education						
None	17 (0.4%)	0 (0.0%)	2 (0.2%)	12 (1.2%)	2 (0.3%)	1 (0.2%)
Primary	217 (4.7%)	40 (2.6%)	56 (5.5%)	58 (5.8%)	28 (4.5%)	35 (7.6%)
Secondary	2622 (57.0%)	696 (46.1%)	665 (65.8%)	610 (61.2%)	369 (58.9%)	282 (61.6%)
Higher	1746 (37.9%)	774 (51.3%)	287 (28.4%)	317 (31.8%)	228 (36.4%)	140 (30.6%)
Employed	2948 (63.5%)	984 (65.1%)	627 (62.0%)	620 (61.9%)	416 (63.5%)	301 (65.4%)
Income adequacy	3 (3, 4)	3 (3, 4)	3 (3, 4)	3 (3, 4)	3 (2, 4)	3 (3, 4)
Residential environment						
NDVI $_{300\text{ m}}$	0.38 (0.33, 0.43)	0.40 (0.36, 0.45)	0.40 (0.35, 0.43)	0.33 (0.28, 0.37)	0.36 (0.31, 0.40	0.38 (0.36, 0.43)
Tree cover $_{300\text{ m}}$ [%]	6.01 (2.57, 10.41	6.91 (3.04, 10.78	8.35 (5.27, 11.50	2.15 (1.29, 4.09)	9.89 (3.98, 15.26)	5.05 (2.88, 7.37)
UGS $_{300\text{ m}}$ [%]	6.40 (1.67, 15.95)	9.72 (3.24, 20.56)	5.12 (0.00, 11.17)	3.51 (0.89, 12.55)	5.57 (1.88, 15.35)	10.76 (4.54, 19.23)
Garden	1347 (29.0%)	604 (39.9%)	330 (32.6%)	215 (21.5%)	111 (16.9%)	87 (18.9%)
Bluespace $_{300\text{ m}}$	228 (4.9%)	16 (1.1%)	115 (11.4%)	53 (5.3%)	41 (6.3%)	3 (0.7%)
Walkability index $_{300\text{ m}}$	0.07 (−0.92, 1.08)	−0.09 (−1.09, 0.91)	−0.10 (−0.78, 0.75)	0.22 (−0.83, 1.82)	0.86 (−0.39, 1.39)	−0.16 (−1.10, 0.47)
NO_2 [μg/m^3]	20.68 (16.92, 23.86)	22.56 (20.67, 24.51)	24.44 (22.47, 26.53)	18.79 (16.92, 20.68)	13.16 (11.28, 13.43)	18.80 (17.09, 19.91)
Burning solid fuel	311 (6.7%)	64 (4.2%)	50 (4.9%)	113 (11.3%)	41 (6.3%)	43 (9.3%)
L_{den} road traffic [dB]						
40–59 dB	1020 (22.1%)	352 (23.6%)	74 (7.3%)	169 (16.9%)	169 (25.9%)	256 (55.7%)
60–64 dB	1953 (42.4%)	659 (44.2%)	170 (16.9%)	643 (64.4%)	352 (54.0%)	129 (28.0%)
65–69 dB	962 (20.9%)	228 (15.3%)	416 (41.3%)	167 (16.7%)	93 (14.3%)	58 (12.6%)
70–80 dB	675 (14.6%)	252 (16.9%)	348 (34.5%)	20 (2.0%)	38 (5.8%)	17 (3.7%)
L_{den} aircraft [dB]						
Unexposed	1013 (24.2%)	487 (32.2%)	34 (3.4%)	0 (0.0%)	492 (75.1%)	–
< 40 dB	2322 (55.6%)	897 (59.3%)	978 (96.6%)	340 (34.0%)	107 (16.3%)	–
40–44 dB	481 (11.5%)	96 (6.3%)	0 (0.0%)	329 (32.9%)	56 (8.5%)	–
45–49 dB	244 (5.8%)	24 (1.6%)	0 (0.0%)	220 (22.0%)	0 (0.0%)	–
50–60 dB	120 (2.9%)	8 (0.5%)	0 (0.0%)	112 (11.2%)	0 (0.0%)	–
L_{den} railway [dB]						
Unexposed	2375 (51.2%)	353 (23.3%)	498 (49.2%)	874 (87.3%)	395 (60.3%)	255 (55.4%)
< 40 dB	1523 (32.8%)	922 (61.0%)	110 (10.9%)	84 (8.4%)	257 (39.2%)	150 (32.6%)
40–44 dB	265 (5.7%)	112 (7.4%)	99 (9.8%)	27 (2.7%)	1 (0.2%)	26 (5.7%)
45–49 dB	258 (5.6%)	67 (4.4%)	157 (15.5%)	9 (0.9%)	2 (0.3%)	23 (5.0%)
50–54 dB	139 (3.0%)	34 (2.2%)	94 (9.3%)	7 (0.7%)	0 (0.0%)	4 (0.9%)
55–70 dB	80 (1.7%)	24 (1.6%)	54 (5.3%)	0 (0.0%)	0 (0.0%)	2 (0.4%)
Urbanicity $_{300\text{ m}}$ [people]	3482 (2399, 4747)	3595 (2496.50, 4644)	3698.50 (2606, 5004)	3146 (1969, 4672)	4011 (2906, 5039)	2860 (1987.50, 3546)
Area-employment (%)	35.95 (27.23, 45.94)	44.22 (35.23, 54.73)	37.86 (29.64, 44.35)	33.72 (23.75, 42.90)	32.04 (25.86, 37.11)	21.79 (18.57, 29.13)
Area-higher education (%)	49.12 (45.11, 52.81)	52.27 (50.00, 55.93)	49.21 (45.00, 53.01)	47.37 (43.28, 50.20)	46.90 (44.21, 49.28)	44.75 (42.42, 46.09)
Health status						
Hypertension	1467 (31.8%)	483 (32.1%)	235 (23.3%)	356 (35.6%)	224 (34.9%)	169 (36.7%)
IHD	349 (7.6%)	104 (7.0%)	65 (6.4%)	80 (8.0%)	45 (7.0%)	55 (12.0%)
Stroke	131 (2.8%)	45 (3.0%)	20 (2.0%)	27 (2.7%)	20 (3.1%)	19 (4.1%)
Diabetes	401 (8.7%)	155 (10.3%)	59 (5.8%)	94 (9.4%)	43 (6.6%)	50 (10.9%)
Body mass index [kg/m^2]						
Underweight	114 (2.5%)	35 (2.4%)	26 (2.6%)	27 (2.7%)	13 (2.2%)	13 (2.9%)
Normal weight	2014 (44.8%)	639 (44.2%)	457 (46.2%)	402 (40.2%)	330 (54.9%)	186 (40.9%)
Overweight	1595 (35.5%)	487 (33.7%)	357 (36.1%)	384 (38.4%)	193 (32.1%)	174 (38.2%)
Obese	771 (17.2%)	286 (19.8%)	150 (15.2%)	188 (18.8%)	65 (10.8%)	82 (18.0%)
Other risk factors						
Smoking						
Never smoker	2188 (48.5%)	629 (42.1%)	519 (54.2%)	490 (50.4%)	371 (59.1%)	179 (39.3%)
Former smoker	791 (17.6%)	319 (21.3%)	129 (13.5%)	162 (16.7%)	101 (16.1%)	80 (17.6%)
Current smoker	1528 (33.9%)	547 (36.6%)	309 (32.3%)	320 (32.9%)	156 (24.8%)	196 (43.1%)
Family history of CVD	2652 (58.3%)	956 (64.2%)	360 (36.2%)	648 (64.9%)	409 (66.4%)	279 (61.3%)
Family history of diabetes	1155 (25.3%)	454 (30.5%)	106 (10.8%)	325 (32.5%)	137 (21.6%)	133 (29.4%)

Note. Abbreviations: CVD – cardiovascular disease, IHD – ischemic heart disease, L_{den} – day-evening-night sound level, NDVI – normalized difference vegetation index, NO_2 – nitrogen dioxide, UGS – urban green space. Statistics shown in the table are median value with 25th and 75th percentiles or frequency and percentage within columns.

Table 2

Relationships between residential environment characteristics tested one-at-a-time and the prevalence of cardiometabolic diseases.

Exposures	Hypertension	IHD	Stroke	Diabetes
	N = 4361	N = 4358	N = 4363	N = 4371
NDVI $_{300\ m}$ (per 0.1)	1.06 (0.94, 1.20)	0.93 (0.77, 1.12)	–	–
0.19–0.32	–	–	1.00	1.00
0.33–0.37	–	–	1.34 (0.75, 2.38)	0.89 (0.64, 1.26)
0.38–0.43	–	–	1.44 (0.80, 2.58)	1.32 (0.95, 1.85)
0.42–0.75	–	–	0.95 (0.50, 1.79)	0.84 (0.59, 1.20)
Tree cover $_{300\ m}$ (per 10 %)	0.94 (0.81, 1.10)	0.87 (0.68, 1.11)	–	0.77 (0.62, 0.97)
0.02–2.56 %	–	–	1.00	–
2.57–3.00 %	–	–	0.82 (0.48, 1.40)	–
3.01–10.40 %	–	–	0.76 (0.43, 1.35)	–
10.41–53.34 %	–	–	0.86 (0.48, 1.54)	–
UGS $_{300\ m}$ (per 10 %)	0.96 (0.89, 1.03)	–	1.05 (0.89, 1.23)	–
0–1.66%	–	1.00	–	1.00
1.67–6.39%	–	0.97 (0.68, 1.40)	–	0.68 (0.48, 0.94)
6.40–15.94%	–	1.09 (0.76, 1.55)	–	1.02 (0.74, 1.40)
15.95–74.36%	–	0.87 (0.60, 1.27)	–	0.81 (0.58, 1.13)
Domestic garden	1.20 (1.00, 1.44)	1.21 (0.91, 1.60)	1.26 (0.83, 1.92)	1.28 (1.00, 1.63)
Bluespace $_{300\ m}$	0.67 (0.45, 1.00)	0.45 (0.21, 0.99)	0.99 (0.38, 2.62)	0.51 (0.25, 1.04)
Walkability $_{300\ m}$ (per 2 units)	0.85 (0.75, 0.96)^{a}	0.90 (0.74, 1.09)^{e}	0.92 (0.67, 1.24)^{i}	1.04 (0.87, 1.23)^{m}
NO_2 (per 5 μg/m^3)	0.93 (0.82, 1.05)	–	0.96 (0.71, 1.29)	0.91 (0.77, 1.08)
6.17–16.91 μg/m^3	–	1.00	–	–
16.92–20.67 μg/m^3	–	0.57 (0.38, 0.86)	–	–
20.68–23.85 μg/m^3	–	0.58 (0.37, 0.91)	–	–
23.86–35.29 μg/m^3	–	0.61 (0.38, 0.98)	–	–
Burning solid fuel at home	1.19 (0.87, 1.65)	1.63 (1.07, 2.50)	1.05 (0.52, 2.12)	0.92 (0.60, 1.42)
L_{den} road traffic (per 5 dB)		0.91 (0.80, 1.02)^{f}	0.82 (0.68, 0.98)^{j}	0.93 (0.83, 1.03)^{n}
40–59 dB	1.00^{b}	–	–	–
60–64 dB	0.84 (0.68, 1.04)	–	–	–
65–69 dB	0.78 (0.60, 1.02)	–	–	–
70–80 dB	0.98 (0.73, 1.31)	–	–	–
L_{den} railway (per 5 dB)	1.00 (0.89, 1.13)^{c}	0.99 (0.82, 1.21)^{g}	0.98 (0.71, 1.34)^{k}	0.80 (0.66, 0.96)^{o}
L_{den} aircraft (per 5 dB)	0.98 (0.84, 1.14)^{d}	1.20 (0.96, 1.49)^{h}	1.17 (0.83, 1.66)^{l}	1.01 (0.83, 1.24)^{p}

Note. Abbreviations: IHD – ischemic heart disease, L_{den} – day-evening-night sound level, NDVI – normalized difference vegetation index, NO_2 – nitrogen dioxide, UGS – urban green space. Effect estimates shown are odds ratios with 95% confidence intervals in parentheses. The models are adjusted for age, sex, ethnicity, education, income adequacy, employment, city, and urbanicity. Reduced analytic samples are as follows: ^{a}N = 4359, ^{b}N = 4333, ^{c}N = 2078, ^{d}N = 2991, ^{e}N = 4356, ^{f}N = 4330, ^{g}N = 2075, ^{h}N = 2987, ^{i}N = 4361, ^{j}N = 4335, ^{k}N = 2076, ^{l}N = 2989, ^{m}N = 4369, ^{n}N = 4343, ^{o}N = 2087, ^{p}N = 2993.

cover and both diabetes and IHD were more precise in terms of the confidence interval, and NDVI was clearly inversely associated with diabetes (see Supplementary Table S3).

Adjusting the main models for smoking, BMI, and family history of disease did not result in any significant alterations to the associations (Supplementary Table S4). Nevertheless, when area-SES was considered, the confidence intervals for the majority of effect estimates widened, although not for all. The estimates for walkability became very imprecise and were attenuated in magnitude (Supplementary Table S5).

We did not see much change when the analysis excluded participants for whom the residential exposure preceded the disease diagnosis (Supplementary Table S6). The use of imputed data did not result in notable alterations to the observed results either (Supplementary Table S7). Treating railway and aircraft L_{den} as categorical predictors with unexposed individuals as the reference category suggested higher odds of hypertension, IHD, and stroke at higher noise levels, although the confidence intervals were wide (Supplementary Table S8).

3.4. Interaction analysis

Supplementary Table S9 presents the interactions between dichotomized exposures where the direction of associations was deemed plausible and the RERI had a narrow confidence interval. Compared with the theoretically most beneficial combination of each pair, all other exposure categories had odds ratios >1.00. However, we found no evidence of a supra-additive effect since all RERIs were <0.

4. Discussion

4.1. Overall findings

The objective of this study was to investigate the relationships between multiple residential environmental characteristics and self-reported CVD and diabetes in urban Bulgaria. Our findings indicate that individuals residing in neighborhoods with greater walkability and access to bluespace exhibited a reduced likelihood of hypertension. Furthermore, bluespace was found to be protectively associated with these outcomes. Higher tree cover and bluespace were associated with lower odds of diabetes. In the larger buffer, some of these associations were clearer.

Conversely, the burning of solid fuel in the home was found to be positively associated with IHD, while aircraft noise was possibly associated with IHD and stroke. Some unexpected associations were identified with domestic gardens, road and rail traffic noise, and air pollution.

4.2. Interpretation

Our findings align with those of previous studies. A substantial body of evidence indicates that greater levels of overall greenspace and access to UGS are protectively associated with CVD (Liu et al., 2022) and diabetes (Ccami-Bernal et al., 2023). The associations for NDVI were weaker and associations for UGS appeared nonlinear. The data indicated robust protective associations between tree cover and both diabetes and CVD within the larger 1000 m buffer; NDVI in this larger buffer was also more clearly associated with less diabetes, suggesting that more distal areas may be more relevant for physical health (Browning et al., 2017).

As our UGS measure did not account for the presence of small greenspace or street trees, the null findings for it are to be expected. Of note was the finding that domestic gardens had counterintuitive associations with higher disease prevalence. Given the consistency of evidence that access to a garden confers multiple (mental) health benefits, this was unexpected. However, we know relatively little about the role of private gardens in noncommunicable disease morbidity (de Vries et al., 2024). To date, only one study has specifically examined the association between private green space and diagnosed diseases beyond mental or self-rated health (de Vries et al., 2024). The authors found protective associations with CVD, which were stronger with greater amounts of garden greenery, which we could not measure. In light of the positive correlation between garden presence and the burning of solid fuel in the house, it is possible that the presence of a domestic garden reflected socioeconomic dimensions or dwelling characteristics that were not adequately accounted for in the analysis.

In contrast to the extensive research on the relationship between greenspace and health outcomes, relatively little research has been done on the impact of bluespace. The majority of studies to date have concentrated on either mental health outcomes or general self-rated health (Gascon et al., 2017; Geneshka et al., 2021). The studies that considered cardiometabolic outcomes yielded disparate findings. Klompmaker et al. (2022) found no evidence to suggest that bluespace cover reduced CVD hospitalizations in a large cohort of Medicare beneficiaries. In a Canadian cohort, CVD mortality was found to be reduced in those living in close proximity to bluespace (Crouse et al., 2018). However, a Chinese study reported an increased risk of diabetes in those living close to bluespace (Li et al., 2021). In recent studies, cardiovascular benefits of the total count (Li et al., 2024) or proximity to bluespace have been reported (Kim et al., 2024). In general, the effects of bluespace appear to be context-dependent and contingent on the specific definition of bluespace in question. The pathways that are thought to mediate the health benefits of bluespace exposure are similar to those that have been proposed for greenspace (Markevych et al., 2017). The bluespace in our study was comprised of rivers (Ruse, Sofia, and Plovdiv), the Black Sea coastline, nearby lakes (Varna and Burgas), and even a rowing canal (Plovdiv). The associations identified were largely robust in sensitivity analyses.

Higher levels of walkability have been demonstrated to have protective associations with cardiometabolic health (Sarkar et al., 2018; Adhikari et al., 2021; de Courrèges et al., 2021; Makhlouf et al., 2023). This may be due to an increase in outdoor physical activity (de Courrèges et al., 2021). Like ours, a Canadian cross-sectional study found that walkability was associated with a reduced likelihood of self-reported hypertension (Adhikari et al., 2021). Using data from the UK Biobank, another study revealed that neighborhood walkability was beneficial for both prevalent hypertension and measured blood pressure (Sarkar et al., 2018). In the larger 1000 m buffer, the association between walkability and lower odds of CVD was more pronounced. It is important to note that the effect size for walkability was noticeably suppressed following the adjustment for area-SES. It, therefore, remains challenging to isolate the effect of highly walkable central urban areas, where traffic emissions and area-SES are typically high. To some extent, walkability may reflect socioeconomic gradients in our study areas.

Consistent with the literature (Lee et al., 2020), there were strong indications that the burning of solid fuel at home can be harmful. In the main model, it was associated with higher IHD odds, and across the analyses, its effect size was largely preserved. However, an inverse relationship was observed between outdoor air pollution, proxied by NO_2 levels, and the health outcomes. This finding is at odds with the established harmful effects of air pollution (de Bont et al., 2022; Haddad et al., 2023). The reasons for the absence of harmful associations may be twofold. First, it is possible that NO_2 is not the most appropriate marker of exposure for the outcomes under study. Second, at the time of this study, the only available source of air pollution data for all study areas at sufficient granularity was a global LUR-based NO_2 dataset (Larkin et al. 2023). The NO_2 LUR exhibited only a moderate fit for Europe ($R^2 = 0.56$) and probably resulted in exposure misclassification. For example, modeled NO_2 may not reflect high pollution sites and poorly ventilated areas well enough, nor physical transportation, dispersion, and chemical reactions. Moreover, NO_2 levels in our sample were moderate with no steep contrasts, which we also attribute to the data source. It is also possible that a confounding interaction with walkability has occurred (Howell et al., 2019). The seemingly protective associations with NO_2 are more challenging to elucidate. Given that similar associations were observed for road and rail traffic noise, it is possible that other urban factors have been insufficiently accounted for. Similarly, the relationship between road and rail traffic noise and the outcomes was either non-existent or yielded counterintuitive results, with lower disease prevalence being observed. Although traffic noise is a recognized risk factor for CVD and diabetes (Kempen et al., 2018; Fu et al., 2023), which undermines endothelial function and metabolic pathways (Münzel et al., 2021a), the evidence is still growing and null findings have been reported in some studies (Dzhambov et al., 2018). The sampling framework was developed with the intention of capturing a range of exposure situations. However, our data may have still lacked sufficient diversity in spatial typologies to fully disentangle the unique roles of traffic sources. As already mentioned, city centers where traffic noise and NO_2 are higher also have protective characteristics like urban parks, walkable street network, and higher SES. In the interaction tests, when different combinations of urban characteristics were considered together, we found that there were associations between traffic noise and air pollution and some of the outcomes that were in the expected direction. When railway and aircraft noise were treated as categorical variables, a trend towards higher odds of some outcomes at high noise levels was also observed. This suggests that nonlinear effects may be a factor in this context and that taking unexposed individuals as the reference category is required to ensure sufficient exposure gradient for harmful associations to emerge.

4.3. *Strengths and limitations*

Southeast Europe is very scarcely covered in environmental epidemiology. This study used the largest environmental health survey in Bulgaria to date. We collected a representative urban sample, which enabled the generalizability of results to the urban population. Previous Bulgarian environmental health studies have been limited to convenience samples, with unknown external validity of the results (e.g., Dzhambov et al., 2016; Dzhambov et al., 2018). Another strength of this study is that we considered multiple exposures simultaneously, which few studies have done (e.g., Sørensen et al., 2022; Poulsen et al., 2023). We are also unaware of a study that has jointly investigated different measures of greenspace and bluespace, outdoor and household air pollution, different traffic sources, and walkability. Various robustness checks were employed to model different levels of adjustments, spatial scales of exposures, combinations of exposures, and conceptual time sequence of exposure and outcome data.

Several limitations are also noteworthy. Despite the known duration of exposure and time of diagnosis, a cross-sectional study cannot infer causality. Moreover, we carried out a large number of tests, which may be prone to familywise error.

It is unlikely that residential self-resection bias affected our sample of long-time non-movers (i.e., the median duration of residence was 25 years). However, it is possible that recall bias may have influenced the self-reported health outcomes. Though self-reported diagnoses demonstrate reasonable sensitivity and specificity when compared to confirmed medical diagnoses, making them useful in epidemiological research (Engstad et al., 2000; Okura et al., 2004; Yamagishi et al., 2009; Schneider et al., 2012), we have likely underestimated the disease prevalence (Oksanen et al., 2010). In a similar vein, the present study focused on individuals who had not had a fatal coronary or cerebrovascular event. It is therefore possible that the survivor effect has attenuated associations with environmental factors. It is also possible that differential access to healthcare has influenced diagnosis. However, we were only able to partially account for this by adjusting for multiple individual and area-level socioeconomic confounders. Another limitation regarding the outcomes is that we did not inquire about the specific medications participants were taking, which would have enhanced the precision of the outcome ascertainment. Furthermore, we did not make use of information collected on participants' time spent at home, physical activity, and diet since those were deemed unlikely to reflect long-term habits pertinent to disease onset.

The absence of particulate matter data and the moderate resolution of the NO_2 and noise data may have contributed towards a shift of the effect sizes towards the null. Our noise data were also somewhat crude and unavailable at the building façade-level. Information was lacking regarding the type of appliance used for the burning of solid fuel in the home. The impact of stoves and fireplaces on indoor air quality and human health is contingent upon their design, ventilation, and insulation characteristics. Furthermore, the type and quality of fuel used, as well as stove use patterns, are additional variables that were not collected. Readers should consider with caution results from multi-exposure models, which included closely related pollutants, despite the absence of evidence of multicollinearity.

As is common in such studies, we employed address-based exposure assessment, rather than out-of-home environmental exposures at the locations where people engage in daily activities and on their commuting routes (Wei et al., 2023). We did not use network buffers, which may prove more pertinent for the identification of health effects driven by behavioral and perceptual pathways, such as visual experiences of nature and time spent in greenspace (Markevych et al., 2017).

4.4. Policy implications

We echo the call for a more holistic approach to urban planning and disease prevention that extends beyond the mitigation of specific urban stressors. Instead, we advocate for the reshaping of urban form with the aim of reducing traffic emissions, enhancing urban greenery, and promoting physical activity (Nieuwenhuijsen, 2021, 2024; Dyer et al., 2024). It is estimated that thousands of annual deaths in Bulgaria could be prevented if the country levels of air pollution, noise, and greenspace were to align with the WHO guideline values (Barboza et al., 2021; Khomenko et al., 2021, 2022; Health Effects Institute, 2022). The successful implementation of healthy urban planning principles (Mueller et al., 2021) underlying innovative urban models that support cardiometabolic health (Münzel et al., 2021b; Nieuwenhuijsen et al., 2024) can inform interventions that aim to address the issues exemplified here. In order to achieve this, it is essential to establish local exposure-response relationships, which facilitate the raising of awareness and enable more precise health impact assessments of ongoing interventions and the planning of future ones (Dyer et al., 2024).

The urban form of Bulgarian cities is generally compact, which allows for the implementation of interventions that support active commuting and a reduction in the reliance on motorized transport. However, predominantly sectoral and non-integrated approaches in urban and peri-urban development prioritize high-capacity primary transit transport infrastructure over active mobility (Madzhirski and Dimitrova, 2019). This is frequently accompanied by poor street connectivity at the neighborhood level, with numerous barriers (Dimitrova and Madzhirski, 2019; Karamitov and Petrova-Antonova, 2022). The quality of existing greenspace varies, it is often inadequately maintained, and its accessibility is limited at the urban fringes (Sofia Development Association, 2018; Sofiaplan, 2021). Our findings can encourage the continuation of ongoing interventions, such as the integration of green wedges along the small rivers from the periphery to the center of Sofia (Vision for Sofia, 2018) or the overcoming of the often-missing connectivity between the Maritsa River and Plovdiv's natural hilly landforms. Varna can also benefit from improvement of the accessibility and recreational use of green and blue seaside and lakeside infrastructure. Except for Sofia and to some extent Varna, the other big cities in Bulgaria are lagging behind in terms of political initiatives promoting walkability and access to greenspace.

5. Conclusions

People living in urban neighborhoods that are more walkable, closer to bluespace, and greener may be less likely to have cardiometabolic diseases, while domestic solid fuel burning is associated with higher odds of cardiovascular diseases. Some unexpected associations with certain exposures may be attributed to unmeasured urban characteristics or socioeconomic confounding. This study represents one of the first assessments of an understudied region in Southeastern Europe. Its findings have the potential to inform public discourse and provide evidence to support the implementation of urban design that is conducive to cardiometabolic health.

CRediT authorship contribution statement

Angel M. Dzhambov: Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Donka Dimitrova:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Angel Burov:** Writing – review & editing, Methodology, Investigation, Data curation. **Marco Helbich:** Writing – review & editing, Methodology, Investigation, Data curation. **Iana Markevych:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Mark J. Nieuwenhuijsen:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization.

Availability of data and materials

Participant microdata generated and/or analyzed for the current study are not publicly available due confidentiality clauses in participant informed consent forms. Data are however available from the authors upon reasonable request and with permission of the Ethics Committee at Medical University of Plovdiv.

Declaration of generative AI in scientific writing

During the preparation of this work the authors used DeepL in order to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijheh.2024.114512.

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