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# Moderators and mediators of the association between the obesogenicity of neighbourhoods and weight status in Dutch adults

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ABSTRACT

This study aimed to assess sociodemographic, personality, and psychological moderators, and lifestyle behavioural mediators, of the association between obesogenicity of neighbourhoods and weight status in Dutch adults. This cross-sectional study used baseline data of 150,506 adult participants of the Lifelines study. To quantify obesogenicity of Dutch neighbourhoods, the Obesogenic Built Environment CharacterisTics (OBCT) index was used, calculated for 1000 m circular buffers around participant's residencies. Z-scores of components across food and physical activity (PA) environments were averaged, and rescaled from 0 to 100. Weight status was operationalised as objectively measured waist circumference. Stratified linear regression analyses by (self-reported) sociodemographic factors, perceived stress, impulsivity, self-discipline, and deliberation were conducted when interaction terms were significant ($P < .01$). Mediation by adherence to the Dutch PA guidelines and dietary behaviour was examined using the difference-in-coefficients approach. Every 10% increase in OBCT index was associated with a 0.65 ($P < .001$, 95%CI [0.59, 0.71]) centimetre larger waist circumference. The association was largest for respondents who were younger, had the lowest income, the highest educational level, the least self-discipline, the highest impulsivity scores and the most perceived stress. Adherence to PA guidelines and dietary behaviour mediated 13.3% of this association; however, the difference in coefficients was not statistically significant. Our findings enable to better target lifestyle interventions to individuals most vulnerable to obesogenic environments. Furthermore, they provide guidance for policymakers and urban planners in promoting health-enhancing environments.

## 1. Introduction

Globally, 2.5 billion adults have overweight, among whom 890 million live with obesity (World Health Organization, 2024). Obesity increases the risk of cardiovascular disease, cancer, and diabetes mellitus, which cause over 70% of deaths worldwide (Blüher, 2019). On top of that, obesity often leads to reduced quality of life and socioeconomic productivity, unemployment, and social disadvantages (Blüher, 2019), and poses a heavy economic burden on the health care system and on society (Tremmel et al., 2017).

Key behavioural risk factors for overweight and obesity include unhealthy dietary behaviour and physical inactivity (Lakerveld and Mackenbach, 2017). These obesogenic behaviours are partly driven by environmental characteristics (Lakerveld and Mackenbach, 2017). 'Obesogenic environments' are defined as "the sum of influences that surroundings, opportunities or conditions of life have on promoting obesity in individuals or a population" (Swinburn et al., 1999). Although the evidence of the influence of obesogenic environments on weight-related outcomes is not entirely consistent (An et al., 2020; Gangemi and Chennakesavalu, 2017; Luo et al., 2020; Paulo dos Anjos Souza Barbosa et al., 2019), living near fast-food restaurants has been associated with higher rates of overweight, obesity and increased adiposity (An et al., 2020; Gangemi and Chennakesavalu, 2017). Furthermore, systematic reviews on greenspace access and walkability

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found that 55% and 70% of the studies they reviewed, respectively, showed beneficial associations with obesity (Luo et al., 2020; Paulo dos Anjos Souza Barbosa et al., 2019). An umbrella review by Lam et al. (2021) found that urban sprawl (a characterisation of the expansion of urban areas, often operationalised as population density), fast-food exposure, and land use mix are built environment factors most consistently associated with weight outcomes. Urban sprawl and fast-food exposure show positive associations with weight status; land use mix shows inverse associations (Lam et al., 2021).

To date, most studies have investigated one environmental exposure at a time. In reality however, individuals are simultaneously exposed to a combination of factors. Combining factors and analysing them jointly may provide a more realistic estimation of an individual's exposure to the environment (Lam et al., 2023). To quantify the obesogenicity of all neighbourhoods in the Netherlands, the Obesogenic Built Environment CharacterisTics (OBCT) index was developed. This index combines information on exposure to objectively measured features of the food and the physical activity (PA) environment into a score from zero to 100 (Lam et al., 2023). More information on the development of the OBCT index is provided in the Methods section.

A recent multi-cohort study by Meijer et al. (2023) found that each 10% increase in OBCT index score was significantly associated with a 0.17 kg/m$^2$ higher Body Mass Index (BMI), and a 1.03 times higher prevalence of overweight/obesity. While it is hypothesised that the obesogenic environment affects weight status through lifestyle behaviours, this has not yet been investigated. As more research is needed to understand if and to what extent the association is mediated by PA and dietary behaviour (Dixon et al., 2021; Meijer et al., 2023; Schüle and Bolte, 2015), one of the objectives of the current study is to explore lifestyle behavioural mediators between the OBCT index and weight status.

Earlier studies have investigated potential pathways from single obesogenic characteristics to weight status. For example, Richardson et al. (2015) and Van Erpecum et al. (2022) observed that the relationship between fast-food outlets and weight status is mediated by higher fat intake and the consumption of obesogenic foods such as sugar-sweetened beverages and French fries. It has also been suggested that the relation between the PA environment and weight status is mediated by PA (J.-I. Kim et al., 2023; Xiao et al., 2022). However, the evidence is scarce (Drewnowski et al., 2020). A path analysis by Guo et al. (2022) found that individuals living in more obesogenic environments significantly exhibited more health-compromising behaviours, including physical inactivity and unhealthy diet, and were more likely to have at least one type of cardiovascular disease.

Additionally, the exposure to obesogenic environments may not be equally important for all population subgroups (Meijer et al., 2023). For instance, the exposure to fast-food restaurants was found to be more strongly associated with BMI for people with lower individual- and neighbourhood-level socioeconomic position (SEP) (Thornton et al., 2011; van Erpecum et al., 2022), and positive interactions with age have been found in this association (Hobbs et al., 2019). The inverse association between environments favourable to PA and the likelihood of obesity was found to exist predominantly among people with a high educational level (Hobbs et al., 2018). Latest research on the OBCT index has found that it could explain the variance in BMI slightly better for women than for men (Lam et al., 2024). Interactions between built environment characteristics and sex in the association with weight related outcomes have also been found in other studies. However, findings are inconsistent, with some studies reporting stronger associations for women, and others for men (Buszkiewicz et al., 2021; Persson et al., 2018; Sarkar et al., 2017; Schüle and Bolte, 2015). Bissell et al. (2016) have suggested that resistance to the obesogenic environment is 'classed', meaning that retaining a healthy lifestyle in current environment is more challenging for people with lower SEP. The current study will examine the moderation of sociodemographic factors in the relationship between the OBCT index and weight status.

Furthermore, certain personality traits and the amount of perceived (chronic) stress may affect susceptibility to obesogenic environments. For instance, impulsivity, characterised by the inability to control cravings and urges (Brouwer et al., 2020), is positively associated with snacking, fast-food consumption, and weight status (Bénard et al., 2017, 2019; Fazzino et al., 2022; Garza et al., 2016; Vainik et al., 2019), and negatively with diet quality (Bénard et al., 2019). It is suggested that impulsive decision making may be amplified by an obesogenic environment (Fazzino et al., 2022). Conscientiousness has been associated with greater PA frequency and protection to physical inactivity (i.e. overall physical inactivity or sedentary behaviour) (Sutin et al., 2016), less consumption of high-fat snacks (O'Connor et al., 2009a), and with lower weight status (Vainik et al., 2019). Conscientiousness includes aspects such as self-discipline and deliberation. Self-discipline pertains to task-focus, perseverance and self-control, while deliberation reflects the degree to which an individual exhibits cautious, deliberate and considerate behaviour (Brouwer et al., 2020). As the personality traits mentioned above are either associated with dietary behaviour or PA, obesogenicity of the environment may encourage those behaviours to varying extents for individuals with different personalities. Experiencing stress has been associated with more unhealthy food intake, and inversely associated with healthy food intake (Hill et al., 2022). A variety of daily stressors may lead to greater desire for, and intake of, hyperpalatable food in obesogenic environments (Yau and Potenza, 2013). This study will investigate whether the association between the OBCT index and weight status is moderated by personality traits and psychological stress.

This study contributes to the literature by investigating sociodemographic, personality, and psychological moderators, and by identifying lifestyle behavioural mediators in the association between neighbourhood obesogenicity and weight status, taking into account full neighbourhood obesogenicity with use of the OBCT index. We hypothesise that the association differs by sex, and that there is a stronger positive association between higher OBCT index score and weight status for people with lower individual- and neighbourhood-level SEP, higher age, more psychological stress, more impulsivity, and less conscientiousness. Furthermore, we hypothesise that the association between the OBCT index and weight status is mediated by PA and dietary behaviour.

## 2. Materials and methods

### 2.1. Study design and participants

This cross-sectional study used data from the Lifelines cohort. Lifelines is a multi-disciplinary prospective population-based cohort study examining in a unique three-generation design the health and health-related behaviours of 167,729 persons living in the North of the Netherlands. The Lifelines Cohort Study is a national project in collaboration with the University Medical Centre in Groningen, the Netherlands. It employs a broad range of investigative procedures in assessing the biomedical, socio-demographic, behavioural, physical and psychological factors which contribute to the health and disease of the general population, with a special focus on multi-morbidity and complex genetics. Investigations include anthropometry, blood pressure- and urine tests, electrocardiogram, cognitive function tests and questionnaires on lifestyle-related behaviours. Lifelines is an ongoing study, with follow-up visits every five years and follow-up questionnaires every 1.5 years. Between 2006 and 2013, participants were screened and included after being invited by their general practitioners or family members, or through self-registration. Demographic information of the cohort is presented in Table 2, and an elaborate cohort profile is provided elsewhere (Scholtens et al., 2015).

### 2.2. Inclusion and exclusion criteria

Adult participants (≥18 years) who participated in the baseline data collection wave in 2006 and 2007 were included in the analyses. Participants with missing data on the independent variable (i.e. the OBCT index) were excluded.

### 2.3. Measures

#### 2.3.1. Independent variable

The OBCT index consisted of 14 components, categorised into four constructs: the healthiness of the food environment (metadata sheet of the Food Environment Healthiness Index available on the website of The

**Table 1**
Exposure measurements and data sources of the OBCT index and assumed direction of association with obesity.

| Components | Definition | Source |
|---|---|---|
| **Healthiness of the food environment** | Kernel density of all food retailers, weighted by the healthfulness of each food outlet type (measured by the food environment healthfulness index) (J. Timmermans et al., 2018). A higher health score is hypothetically negatively associated with obesity. | LOCATUS for point data of all food outlets. |
| **Walkability index** | The walkability score is a product of GECCO based on seven input components (Lam et al., 2022).The components are summed and normalised to a walkability score (0–100) with higher scores indicating higher walkability. A higher walkability is hypothetically negatively associated with obesity. | GECCO |
| Population density | Component of walkability index. Population density was defined as the number of inhabitants per hectare. | CBS Statline |
| Density of retail and service destinations | Component of walkability index. Density of retail and service destinations were defined as the area proportion devoted to two land use classes "commercial" and "socio-cultural services" | National Georegister |
| Land-use mix | Component of walkability index. Land use mix was measured using the land use entropy index, which captures how evenly land uses classes are distributed. The values range from 0 to 1 with 1 representing perfect mix of all relevant land uses. | National Georegister |
| Street connectivity | Component of walkability index. Street connectivity was defined as the point density of true intersections (i.e., three or more legs) on road segments that are accessible for pedestrians (e.g., excluding highways). | TOP10 NL via ESRI |
| Green space | Component of walkability index. Green space density was defined as the proportion of land devoted to parks, public gardens, forests and graveyards. | National Georegister |
| Sidewalk surface area | Component of walkability index. Sidewalk density was defined as the area proportion of sidewalks. | TOP10 NL via ESRI |
| Public transport density | Component of walkability index. Public transport density was defined as the point density of all trams, buses, metros and ferries for short-range transport combined with density of train stations for long distance transport. | NDOV of the Geographic service of the University of Groningen |
| **Sport facility density** | Density of sport facilities per $km^2$ per postcode 4 area. Only sport facilities that are present in the Real Estate Monitor 2015database in each of the analysis years have been selected. These are: athletic tracks, indoor sport halls/gyms, swimming pools (inside and outside), ice rinks, and artificial ski slopes. A higher sport facility density is hypothetically negatively associated with obesity. | Real Estate Monitor (ABF Research) with as original source the 'BSvL – Nederlandse Sport Almanak NSA' (data 2001–2007) and KNAU, Voetbalgids.com, skibanen Nederland, KNSB, and ZwembadGids (data 2010–2015) |
| **Driveability index** | Driveability is an index based four input components that facilitate car driving. | GECCO |
| Road travel time to 10,000 jobs | Component of driveability index. Average car travel time in seconds over the OpenStreetMap road network in 2020 to 10,000 jobs. A higher average travel time is hypothetically positively associated with obesity. | The 'LISA' database. Produced by SPINlab – Vrije Universiteit |
| Distance to most nearby motorway exit | Component of driveability index. Average Euclidean distance in metres to the nearest motorway exit. A higher distance is hypothetically negatively associated with obesity. | Statistics Netherlands |
| Distance to most nearby long-distance public transport (OV) station | Component of driveability index. Average distance in metres to nearest long-distance public transport (OV) station 2018 (train, metro or ferry). Hypothetically positively associated with obesity. | NDOV of the Geographic service of the University of Groningen |
| Parking pressure | Component of driveability index. Average parking pressure 2016 (ratio of CBS registered cars neighbourhood divided by the number of parking places in that neighbourhood. A higher ratio value indicates greater parking pressure. Hypothetically negatively associated with obesity. | Developed by GECCO based on data of national data sources such as BGT, TOP10NL, BAG and RDW). |
| Driving destination accessibility index | Component of driveability index. The driving destination accessibility index is calculated with an adapted SAL (Structural Accessibility Layer) approach in which areas that are both suitable for walking and cycling are considered less attractive for driving compared to areas only suitable for walking or cycling. For this reason frequency-weighted access levels for cycling and walking are subtracted from the car level. Destination categories used were 'Shopping and groceries', 'Going out, sport & hobby' and 'Services for personal care'. Normalised results between 0 (low driveability) to 100 (high driveability). Hypothetically positively associated with obesity. | GECCO |

Locatus is a commercial retail information provider. GECCO is the Geoscience and hEalth Cohort Consortium. CBS is Statistics Netherlands. TOP10NL is the digital national topographic map. ESRI is the Environmental Systems Research Institute. NDOV is the national service for Dutch transit information by Foundation OpenGeo. SPINlab is the Free University Amsterdam's Spatial Information Laboratory. LISA is National Information System of Workplaces. BAG (Basisregistratie Adressen en Gebouwen) is the Dutch national registry of addresses and buildings. BGT is the key register for large-scale topography of the Netherlands. RDW (Rijksdienst voor het Wegverkeer) is a Dutch organisation responsible for the registration and regulation of motor vehicles and driving licenses in the Netherlands.

Geoscience and hEalth Cohort COnsortium (GECCO)), walkability, driveability, and sports facility density. See Table 1 for the constructs and components of the OBCT index, including the hypothesised directions of the association with obesity. Geographic Information Systems (GIS) data were obtained from various sources by GECCO. In GECCO, environmental variables are centralised, operationalised into personal environmental exposures, and used to enrich cohort studies by being linked to individual-level health data upon request from researchers (Makacha et al., 2020; E. J. Timmermans et al., 2018). For standardisation, z-scores were calculated for each component. Components with a hypothesised negative association with obesity were reverse scored, so that a higher score denoted higher obesogenicity. Winsorisation at the 99th percentile was applied to the food environment score to deal with skewness caused by outliers. Constructs were composed by averaging the z-scores of all components. These averages where then used to calculate the OBCT index scores. The index was calculated for circular buffers of 1000 m around each participants' home address, and rescaled from zero to 100, indicating respectively the lowest and highest obesogenicity in The Netherlands. The OBCT index was included as a continuous variable. Detailed information on the development of the OBCT index is described by Lam et al. (2023).

### 2.3.2. Outcome

In the main analysis, weight status was operationalised as waist circumference in centimetres, as it is suggested that measures of abdominal obesity are strong predictors of cardiovascular disease risk (Cao et al., 2018; Czernichow et al., 2011; Ross et al., 2020). Waist circumference was assessed by using a SECA 201 measuring tape placed between lowest rib and the iliac crest around the bare stomach, at 0.5 cm accurate, and was included as a continuous measure. For sensitivity analysis, continuous BMI was also included as outcome variable, as this is an often-used indicator for weight status. BMI was calculated by **weight (kg)/height (m2),** where weight and height were objectively measured. All measurements were carried out by trained physician assistants (Lifelines, 2020).

### 2.3.3. Confounders

All analyses were adjusted for age, sex, educational level, household income, paid labour ≥32 h per week (yes/no, assuming that more working hours reduce exposure to residential neighbourhoods), and neighbourhood SEP.

### 2.3.4. Potential moderators

***Age.*** Age was divided into quartiles: 18–29 years old, 30–50 years old, 51–66 years old, and ≥67 years old, roughly representing the important life-course stages young adulthood, early working/family life, late working life, and retirement. In the complete case analysis, the two oldest age groups were merged because only 28 participants were ≥67 years old.

*2.6.2.* ***Sex.*** Sex was included as a dichotomous variable: female and male.

***Individual socioeconomic position.*** Two indicators of individual SEP were used: household income and educational level. Household income was divided into lower (≤€2000/month), middle (≤€2500/month), and higher (>€2500/month), corresponding 2019 to country medians (Van Leeuwen and Venema, 2022). Educational level was categorised into lower (primary, lower vocational, or no education), intermediate (secondary vocational or pre-university), and higher (higher professional, university, or doctoral degree) (Pleijers and De Vries, 2021).

***Neighbourhood socioeconomic position.*** Neighbourhood SEP was assessed using a composite SEP score based on neighbourhood-average education, income and position on the labour market (*SCP Statusscores 1998-2017, 2019*), produced on a four digit postal code level (GECCO, n. d.). These postal codes contain a limited number of addresses, and range from a mean surface area of 1.54 square kilometres ($km^2$), and a mean population density of 7,845, to a mean surface area of 13 $km^2$ and a population density of 146. Neighbourhood SEP was divided into below and at/above national average.

***Impulsivity, self-discipline, and deliberation.*** An abbreviated version of the NEO Personality Inventory (NEO-PI) was used to measure impulsivity, self-discipline, and deliberation, the latter two being facets of the personality trait conscientiousness (Costa and McCrae, 2008; Lifelines, n.d.). Each trait was measured using eight questions with answer options on a five-point Likert scale ranging from completely disagree to completely agree. Answers were combined into a sum score which could range from zero to 40, where higher scores indicated more impulsive/self-disciplined/deliberate behaviour. As far as known, no clinically relevant cut-off points of the NEO-PI exist. However, for the purpose of interpretation, all three personality traits were divided into tertiles: lower, moderate, and higher.

***Stress.*** Perceived stress was reflected as the sum score of the Long-term Difficulties Inventory questionnaire (LDI), a 12-item self-report questionnaire, covering varying aspects of life, including housing, work, and relationships. Respondents rated each aspect as not stressful, slightly stressful, or very stressful in the last 12 months. Stress scores were divided into tertiles (lower, moderate, and higher), as no clinically relevant cut-off points of the LDI are known.

### 2.3.5. Potential mediators

***Physical activity.*** PA was self-reported, using the Short Questionnaire to Assess Health enhancing physical activity (SQUASH), which measures the frequency, duration, and intensity (i.e. light, moderate or vigorous) of four types of PA: active commuting to and from work, household activities, workplace activities and leisure-time physical activities. The reference period of the SQUASH is an average week in the past few months (Wendel-Vos and Schuit, 2004). The total minutes of moderate-to-vigorous PA (MVPA) per week was utilised in the analyses. Light PA was not analysed, as the literature predominantly reports evidence for the association between MVPA and weight status (Jakicic et al., 2019; Oppert et al., 2021). MVPA was right-skewed, and was therefore dichotomised based on whether individuals met the simplified Dutch exercise guidelines of engaging in ≥150 min of MVPA per week (Gezondheidsraad, 2017).

***Dietary behaviour.*** Dietary behaviour was self-reported using the Lifelines Diet Score (Vinke et al., 2018), which was based on a 110-item semi-quantitative baseline food frequency questionnaire, assessing food intake over the past month. The items were categorised in 22 food groups, which were then grouped as positive (associated with positive health effects), negative (associated with negative health effects), neutral, or unknown. Only the positive and negative food groups were included in the Lifelines Diet Score. Consumption frequency was assessed, using seven response options ranging from 'not this month' to '6–7 days a week', and intake was reflected in grams per 1000 kilocalories. To score an individual's consumption relative to others, intake of each food group per individual was divided into quintiles, ranging from zero to four. For positive food groups, four points were awarded to individuals in the highest quintile, and for negative food groups, to those in the lowest quintile. The sum score could range from zero (unhealthiest) to 48 (healthiest) (Vinke et al., 2018), and was treated as a continuous variable.

### 2.4. Statistical methods

All analyses were carried out in R Studio 4.2.2 (R Core Team, n.d.). Assumptions for linear regression were tested. Multicollinearity between the independent variables was assessed using the Variance Inflation Factor (VIF). If the VIF exceeded five, multicollinearity was indicated, and one of the variables was removed from the analyses (Kim, 2019).

#### 2.4.1. Descriptive analyses

Baseline characteristics were presented as mean±SD in case of normal distribution, and median with interquartile range was presented in case of non-normal distribution. Categorical variables were presented as proportions.

#### 2.4.2. Missing data handling

As we described the cohort on tertiles of the OBCT index (Table 2), participants with missing data on this variable (n = 574) were excluded. This resulted in an analytical sample of n = 150,506 participants. Regarding the other variables, there was more than 5% missing data on income, stress, impulsivity, self-discipline, deliberation, MVPA, and diet score. Assuming data were missing at random, imputation with 10 imputed datasets was performed, and all further analyses were performed with the imputed data.

#### 2.4.3. Moderation analysis

Moderation was tested by adding interaction terms between each potential moderator and the OBCT index. To account for the problem of multiple testing, an alpha of $< 0.01$ was used to determine statistically significant moderation. In case of significance, analyses stratified by the categories of the moderator were conducted.

#### 2.4.4. Mediation analysis

Mediating roles of adherence to PA guidelines and dietary behaviour were examined by Baron and Kenny's difference-in-coefficients approach. This approach, often applied in epidemiological studies, tests mediation by comparing the independent-dependent variable association before and after adjusting for the mediator (Fairchild and McDaniel, 2017; Mackinnon and Dwyer, 1993). This mediation method relies on assumptions which apply to regression analysis as well (Fairchild and McDaniel, 2017). It relies on the same assumptions as regression analysis, and furthermore assumes no interaction between the independent variable and the mediator (MacKinnon, 2012). Linear regression analyses were conducted to assess the association between the OBCT index and waist circumference (C-path), and the OBCT index and waist circumference, adjusted for adherence to PA guidelines and/or diet score (C′-path). All analyses were adjusted for confounders. Mediation by adherence to PA guidelines and diet were examined both separately and combined. The difference in coefficients was calculated by C-C'. Statistical significance of this difference was tested by dividing the difference by the sum of the variances of C and C′ minus the covariance between C and C′, (Mackinnon and Dwyer, 1993) where an alpha of $< 0.05$ indicated statistical significance. The proportion mediated was calculated by 1-(C'/C) (Fairchild and McDaniel, 2017). As the likelihood of partial mediation is considerable (Li et al., 2006; MacKinnon et al., 2002), full reduction of the C′-path was not required to determine mediation.

#### 2.4.5. Sensitivity analyses

To evaluate the robustness of the results, two sensitivity analyses were carried out. First, the analyses were repeated with BMI as outcome. Second, complete case analyses were conducted, excluding all cases with missing data. This latter analysis was performed to assess whether the effect estimates were sensitive to the method chosen for handling missing data (i.e. multiple imputation).

## 3. Results

The results of the VIF analysis are available in Additional file 1. No multicollinearity between the variables was identified, therefore, no variables were excluded.

### 3.1. Population characteristics

In Table 2, baseline characteristics are presented for the full study population and by tertiles of the independent variable, the OBCT index (low/middle/high), to identify potential patterns. The mean age was 44.6 (SD 13.1) years, and women accounted for 58.5% of the participants. The highest tertile of the OBCT index had the most individuals with lower education. Across all tertiles, most participants belonged to the highest income group and lived in neighbourhoods with SEP below the national average. The mean waist circumference of both women and men was above the clinical cut-off values for cardiovascular disease risk (De middel-heup-ratio en de buikomtrek, n.d.). For women, the mean waist circumference was 86.7 (SD 12.4) centimetres (cut-off value: ≤80 cm); for men this was 95.1 (SD 10.9) centimetres (cut-off value: ≤94 cm). For both sexes, the average waist circumference for people living in areas with the highest obesogenicity tertile was 1.7 cm larger than those living in the lowest tertile. Mean BMI was 26.1 kg/m$^2$, with a gradual increase from the first to the third tertile of the OBCT index. 59% of the population met the Dutch PA guidelines of engaging in ≥150 min MVPA per week, with fewer meeting them in higher OBCT index tertiles. Diet scores were similar in all three OBCT index tertiles, with an average score of 24.0 (SD 6.1).

**Table 2**
Characteristics of the total study population and by tertile of the OBCT index score (low, middle, high).

| Characteristics | Total | OBCT index low (range: 21.6–56.3) | OBCT index middle (range: 56.4–63.9) | OBCT index high (range: 64.0–100.0) |
|---|---|---|---|---|
| **n** | 150,506 | 50,169 | 50,169 | 50,168 |
| **Female sex, n (%)** | 88,108 (58.5) | 29,931 (59.7) | 29,117 (58.0) | 29,060 (57.9) |
| **Age, mean (SD)** | 44.6 (13.1) | 43.6 (14.2) | 45.0 (12.6) | 45.3 (12.4) |
| **Educational level, n (%)** | | | | |
| lower | 45,569 (30.3) | 13,705 (27.3) | 15,242 (30.4) | 16,622 (33.1) |
| intermediate | 58,745 (39.0) | 18,301 (36.5) | 19,968 (39.8) | 20,476 (40.8) |
| higher | 44,383 (29.5) | 17,544 (35.0) | 14,367 (28.6) | 12,472 (24.9) |
| missing | 1809 (1.2) | 619 (1.2) | 592 (1.2) | 598 (1.2) |
| **Paid working hours, n (%)** | | | | |
| ≥32 h per week | 59,134 (39.3) | 20,066 (40.0) | 19,067 (38.0) | 20,001 (39.9) |
| <32 h per week/not employed | 91,372 (60.7) | 30,103 (60.0) | 31,102 (62.0) | 30,167 (60.1) |
| **Household income, n (%)** | | | | |
| lower | 40,323 (26.8) | 16,389 (32.7) | 11,803 (23.5) | 12,131 (24.2) |
| middle | 19,506 (13.0) | 6310 (12.6) | 6498 (13.0) | 6698 (13.3) |
| higher | 62,514 (41.5) | 19,094 (38.0) | 22,605 (45.0) | 20,815 (41.5) |
| missing | 28,163 (18.7) | 8376 (16.7) | 9263 (18.5) | 10,524 (21.0) |
| **Neighbourhood SEP, n (%)** | | | | |
| below national average | 109,572 (72.8) | 39,161 (78.1) | 35,734 (71.2) | 34,677 (69.1) |
| national average or higher | 40,325 (26.8) | 10,987 (21.9) | 14,280 (28.5) | 15,058 (30.0) |
| missing | 609 (0.4) | 21 (<0.1) | 155 (0.3) | 433 (0.9) |
| **Waist circ., mean (SD)** | | | | |
| women | 86.7 (12.4) | 85.7 (12.4) | 86.9 (12.2) | 87.4 (12.4) |
| men | 95.1 (10.9) | 94.1 (11.3) | 95.5 (10.7) | 95.8 (10.7) |
| missing, n (%) | 100 (0.1) | 35 (0.1) | 36 (0.1) | 29 (0.1) |
| **BMI, mean (SD)** | 26.1 (4.3) | 25.8 (4.4) | 26.1 (4.3) | 26.3 (4.3) |
| missing, n (%) | 100 (0.1) | 35 (0.1) | 36 (0.1) | 29 (0.1) |
| **Stress, n (%)** | | | | |
| lowest tertile, score range 0–1 | 46,418 (30.8) | 13,549 (27.0) | 16,515 (32.9) | 16,354 (32.6) |
| middle tertile, score range 2–3 | 46,438 (30.9) | 15,078 (30.1) | 15,539 (31.0) | 15,821 (31.5) |
| highest tertile, score range 4–22 | 46,366 (30.8) | 17,080 (34.0) | 14,639 (29.2) | 14,647 (29.2) |
| missing | 11,284 (7.5) | 4462 (8.9) | 3476 (6.9) | 3346 (6.7) |
| **Impulsivity, n (%)** | | | | |
| lowest tertile, score range 1–21 | 43,956 (29.2) | 13,647 (27.2) | 15,254 (30.4) | 15,055 (30.0) |
| middle tertile, score range 22–24 | 43,905 (29.2) | 13,684 (27.3) | 14,972 (29.8) | 15,249 (30.4) |
| highest tertile, score range 25–40 | 43,903 (29.2) | 15,582 (31.0) | 13,954 (27.9) | 14,367 (28.6) |
| missing | 18,742 (12.4) | 7256 (14.5) | 5989 (11.9) | 5497 (11.0) |
| **Self-discipline, n (%)** | | | | |
| lowest tertile, score range 3–28 | 43,921 (29.2) | 15,374 (30.6) | 14,100 (28.1) | 14,447 (28.8) |
| middle tertile, score range 29–31 | 43,921 (29.2) | 13,882 (27.7) | 14,831 (29.6) | 15,208 (30.3) |
| highest tertile, score range 32–40 | 43,920 (29.2) | 13,657 (27.2) | 15,248 (30.4) | 15,015 (29.9) |
| missing | 18,744 (12.4) | 7256 (14.5) | 5990 (11.9) | 5498 (11.0) |
| **Deliberation, n(%)** | | | | |
| lowest tertile, score range 1–27 | 4,3881 (29.2) | 14,959 (29.8) | 14,136 (28.2) | 14,786 (29.5) |
| middle tertile, score range 28–30 | 43,949 (29.2) | 13,964 (27.8) | 14,813 (29.5) | 15,172 (30.2) |
| highest tertile, score range 31–40 | 43,932 (29.2) | 13,988 (27.9) | 15,231 (30.4) | 14,713 (29.3) |
| missing | 18,744 (12.4) | 7258 (14.5) | 5989 (11.9) | 5497 (11.0) |
| **MVPA, n (%)** | | | | |
| <150 min/week | 42,424 (28.2) | 12,003 (23.9) | 14,389 (28.7) | 16,032 (31.9) |
| ≥150 min/week | 88,809 (59.0) | 31,466 (62.7) | 29,925 (59.6) | 27,418 (54.7) |
| missing | 19,273 (12.8) | 6700 (13.4) | 5855 (11.7) | 6718 (13.4) |
| **Diet score, mean (SD)** | 24.0 (6.1) | 24.2 (6.1) | 24.1 (6.0) | 23.7 (6.0) |
| missing, n (%) | 23,290 (15.5) | 7727 (15.4) | 8640 (17.2) | 6923 (13.8) |

Participants with missing data on the OBCT index (n = 574 (0.4%)), were excluded. SEP = socioeconomic position. Waist circ. = waist circumference. Waist circumference is presented for women and men separately as the clinical cut-off points for a healthy waist circumference are sex specific (women: <80 cm, men: <94 cm) (De middel-heup-ratio en de buikomtrek,). BMI = Body Mass Index. MVPA = moderate to vigorous physical activity.

### *3.2. Total and stratified associations of the OBCT index with waist circumference*

#### *3.2.1. Total population*

Fig. 1 shows the results of the linear regression analyses of each 10% increase in the OBCT index on waist circumference in centimetres. Adjusted for confounders, every 10% increase in OBCT index score was associated with a 0.65 ($P < .001$, 95%CI [0.59, 0.71]) centimetre larger waist circumference.

#### *3.2.2. Stratified by sociodemographic, personality and psychological factors*

Interaction terms between the OBCT index and age, income, educational level, stress, impulsivity, and self-discipline were statistically significant ($P < .01$). Therefore, Fig. 1 displays the results stratified on the categories of each of these moderators, with all stratified analyses also being statistically significant. The effect size of the OBCT index on waist circumference was larger among people with the lowest incomes compared to those with middle and higher incomes, and larger for people with an intermediate and higher educational level compared to people with lower educational attainment. Younger people exhibited larger effect sizes than the other age groups. Additionally, there was an upward trend in effect size with each increase in the tertiles of stress and impulsivity. The lowest tertile of self-discipline showed the largest association between OBCT index and waist circumference.

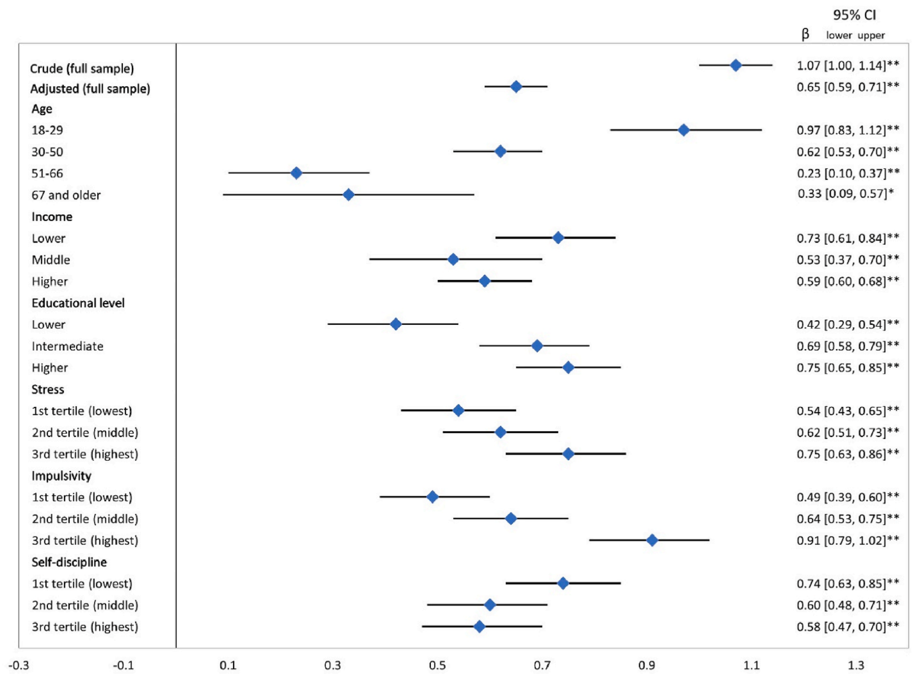


**Fig. 1.** Association between 10% increase in OBCT index score and waist circumference (full sample and stratified).
* = $P < .01$, ** = $P < .001$. Except for the crude analysis, all analyses were adjusted for age, sex, educational level, paid labour ≥32 h per week, household income, and neighbourhood SEP.

### *3.3. Total and mediated associations of the OBCT index with waist circumference*

Fig. 2 presents a graphical representation of the linear regression analyses of each 10% increase in the OBCT index on waist circumference in centimetres (C-path), and the results of the mediation analysis. After adjusting for both mediators (i.e. adherence to PA guidelines and diet score), the association between the OBCT index and waist circumference reduced by 0.09 cm (C′-path), which indicates a proportion mediated of 13.3%. However, the difference did not reach statistical significance ($P = .06$). Results of the mediation analyses stratified for all moderators are presented in Additional file 2. For all subgroups, the proportion mediated by adherence to PA guidelines was larger than by diet score; nevertheless, the mediation found was not statistically significant in any of the subgroups.

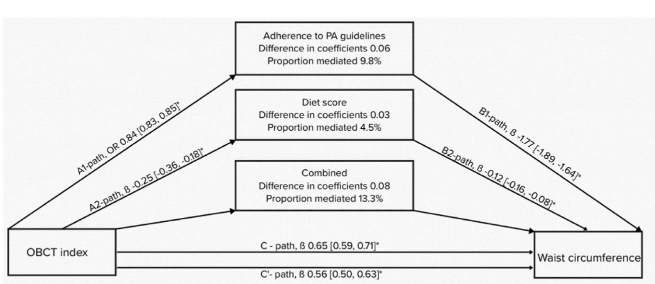


**Fig. 2.** Estimated lifestyle behavioural pathways between the OBCT index and waist circumference in the total study sample. * = $P < .001$. C-path: association between each 10% increase in the OBCT index and waist circumference, adjusted for confounders. C′-path: association between each 10% increase in the OBCT index and waist circumference, adjusted for confounders, adherence to PA guidelines, and diet. The effect estimate of the logistic regression analyses OBCT index – adherence to PA guidelines (A1-path) is expressed as odds ratio, the effect estimates of the B1-, A2-, and B2-path are expressed as β-coefficients of linear regression analyses. Proportion mediated was calculated as 1-(C'/C) and expressed as a percentage. The difference in coefficients did not reach statistical significance.

### *3.4. Sensitivity analyses*

Results for BMI as outcome and the complete case analyses can be found in Additional file 3 and 4 respectively. Both sensitivity analyses generally yielded results consistent with the main analysis. The most notable difference was that moderation by sex was found in the association between the OBCT index and BMI; a larger effect size was found for women (β0.22, $P < .001$) than for men (β0.15, $P < .001$).

## 4. Discussion

We examined sociodemographic, personality, and psychological moderators, and lifestyle behavioural mediators of the association between obesogenicity of neighbourhoods and weight status in Dutch adults. Adjusted for age, sex, and educational level, each 10% increase in the OBCT index score was associated with a 0.65 cm larger waist circumference. The association was strongest for people who were younger, had the lowest income, the highest education, the least self-discipline, the highest impulsivity scores, and the most perceived stress. Adherence to PA guidelines and dietary behaviour mediated the relationship between OBCT index score and waist circumference; however, the difference in coefficients did not reach statistical significance.

Contrary to our hypothesis, the association between obesogenicity of the environment and weight status appeared strongest in the youngest age group. Similar findings by Den Braver et al. (2023) on drivability and diabetes risk, and recent results of Lam et al. (2024) on the OBCT index suggest that younger adults may be more vulnerable to obesogenic environments. The large association found in younger as compared to older adults might be a result from differences in lifestyle and engagement with the food environment. Older adults potentially have developed stronger dietary habits and self-regulation skills which were shaped in a different food landscape. This may make them less responsive to food retail cues. However, this explanation remains speculative and further research is needed. Furthermore, the inconsistency in results between our study and those from Hobbs et al. (2019) may be attributed to differences in the operationalisation of environmental obesogenicity. Unlike our study, combining several features of both the food- and PA environment, Hobbs et al. (2019) exclusively assessed residential fast-food outlet availability.

Against expectations, we found the effect estimate to be largest for people with the highest education. A mediation analysis by Bartoskova Polcrova et al. (2024) demonstrated that sedentary behaviour reduces the protective potential of higher education on adiposity risk, which may explain our findings. In the Netherlands, people with a higher education more often have sedentary occupations than people with lower education (Leefstijlmonitor et al., 2021; Loyen et al., 2016), and sedentary behaviour is linked to increased waist circumference, independent of PA levels (Healy et al., 2008). Bernaards et al. (2016) found that individuals with sedentary jobs spend more time sitting than people with non-sedentary jobs, especially on workdays. This may suggest that people with lower education may offset the obesogenic effects of their residential neighbourhood through greater PA at work. The broader literature shows mixed associations between occupational sedentary- and PA behaviours and health outcomes. For example, studies on occupational sitting and cardiovascular risk report both null and positive findings (Jingjie et al., 2022; Reichel et al., 2022). Cillekens et al. (2020) found higher occupational PA linked to positive outcomes, such as reduced cancer and heart disease risks, but also to negative outcomes like increased all-cause mortality in men, mental ill health, and poor sleep. Given these mixed findings, future studies are needed to better understand if and how occupational contexts influence the relationship between the obesogenic environment and health outcomes.

We found the effect size between the OBCT index and weight status to be dependent on the amount of perceived stress, which is in line with earlier literature (Hill et al., 2022; Yau and Potenza, 2013). Chronic and high levels of stress can lead to elevated cortisol levels, which in turn increase cravings for high-energy, hyperpalatable foods. Moreover, exposure to hyperpalatable foods might activate brain reward regions and increase dopamine transmission, also leading to increased cravings for these foods (Sinha and Jastreboff, 2013; Spencer and Tilbrook, 2011). A quasi-experimental study by Massicotte et al. (2019) found that food cravings predict the consumption of hyperpalatable food. Considering that cravings for hyperpalatable food might be stimulated by both the presence of stress and external food cues, it is understandable that people who experience more stress have difficulties resisting these cravings, especially in an obesogenic environment.

Previous studies have found associations between smaller numbers of daily stressors and higher self-discipline (O'Connor et al., 2009b), and between higher reported stress and the lack of self-discipline (Cheema et al., 2022). A study among students aged 18–39 years old found higher stress scores to be associated with less engagement in PA. Notably, one of the barriers to exercise was a lack of self-discipline (Cheema et al., 2022). Consistent with earlier studies, we found the effect estimate of the OBCT index and waist circumference to be smallest for people with higher self-discipline. This might indicate that higher self-discipline protects individuals from giving in to environmental temptations and so contributes to a healthier weight status through healthier food- and PA behaviours (Cheema et al., 2022; O'Connor et al., 2009b; Sutin et al., 2016).

Of all personality traits measured, we found the largest effect size for people with the most impulsive personalities. This result is similar to that of a meta-analysis by Vainik et al. (2019), where the association between personality and BMI was studied. Vainik and colleagues reasoned that this large effect size could be attributable to the fact that two statements in the NEO-PI questionnaire regarding the impulsivity facet directly measure dietary behaviour: "When I am served my favourite food, I often eat too much", and "I sometimes eat until I feel sick". These items relate to uncontrolled eating, a behaviour that is positively associated with BMI (Vainik et al., 2019; Vainik et al., 2015; Vainik et al., 2019). A systematic review by Hohmann and Garza (2022) revealed a moderating role of impulsivity between the intention to change behaviour and the magnitude of behaviour change, where higher impulsivity was associated with less behaviour change. An obesogenic environment may pose challenges for individuals with an impulsive character to convert their initial intentions (such as engaging in PA or adopting healthier eating habits) into behaviour change due to the presence of tempting, unhealthy contextual factors that lure them into alternative behaviours.

The direction of our mediation results align with previous studies (J.-I. Kim et al., 2023; Richardson et al., 2015; van Erpecum et al., 2022; Xiao et al., 2022). Richardson et al. and Van Erpecum et al. studied dietary behaviour in the food environment, while Kim et al. (2023) focused on PA behaviour in the PA environment. Xiao et al. (2022) found significant mediation by PA intensity and duration in the association between some built environment aspects (land use mix, distance to public transport, and destination accessibility) and BMI, but not for road networks and population density. Xiao et al. (2022) argue that neighbourhoods in the district they studied might not be distinct enough in terms of road networks and population density to impact PA levels significantly. Kim et al. (2023) found significant mediation by leisure walking, but not utilitarian walking, in the association between the PA environment and obesity. These nuanced results together with our results from the combined PA and food environment, complement each other well in gaining knowledge about pathways from the built environment to weight status.

Our study had several strengths. First, we used a multiple exposure method captured in a comprehensive environmental index. As people are always exposed to multiple obesogenic environmental factors at a time, the results found are probably closer to reality than when a single exposure is examined. Furthermore, the large sample size enabled subgroup investigations and improved generalisability to other contexts. Other elements contributing to the generalisability of our study were the use of standardised questionnaires and objectively measured outcomes. Additionally, the use of objectively measured waist circumference and BMI also provided more accurate estimates than subjectively measured anthropometry, as self-reported waist circumference tends to be either over- or underestimated (Dekkers et al., 2008; Okamoto et al., 2017; Ortiz-Panozo et al., 2017; Pasalich et al., 2014), and self-reported BMI tends to be underestimated (Dekkers et al., 2008; Maukonen et al., 2018; Pasalich et al., 2014). Another strength was the inclusion of a set of sensitivity analyses, which yielded similar results as the main analyses and thus contributed to the robustness of our findings.

This study also has a number of limitations. First, self-reported PA is in general higher than device-measured PA (e.g. accelerometery) (Colley et al., 2018; Fukuoka et al., 2016; Garriguet et al., 2015), which increases the potential for biased results. Nevertheless, SQUASH has been proven to be fairly reliable and valid when compared with accelerometery (Spearman correlation 0.45) (Wendel-Vos, 2003). Second, although the Lifelines Diet Score is based on recent international evidence (Vinke et al., 2018), self-reported dietary behaviours are prone to recall bias (Naska et al., 2017), and may induce over- or underestimation of daily fat- and kilocalorie intake (Hebert et al., 1997). Third, we did not take into account residential self-selection. People may choose where to live based on behavioural preferences (e.g. active people are more likely to live in areas that facilitate PA) (Garfinkel-Castro et al., 2017), so reverse causation cannot be ruled out. Another limitation is our use of circular buffers around home addresses rather than employing street network-based buffers. We are aware that street network-based buffers may provide a more realistic representation of accessible areas. Furthermore, while some study strengths enhance the generalisability of the findings, it is important to note that the Lifelines cohort may not be representative for the entire country. The northern Netherlands is less densely populated and generally has a lower SEP than other regions, with more people having lower education levels, fewer with higher education, and a greater concentration of municipalities with low disposable income (Centraal Bureau voor de Statistiek, n.d.; VZinfo, n.d.). Also, Lifelines includes individuals from the same household, but due to lack of data on household membership, we could not account for clustering. This may have affected the independence of observations and hence our results. Furthermore, due to our cross-sectional study design, no conclusions can be drawn on causal inference of the results. Lastly, during the imputation process, we assumed the data were missing at random. However, individuals with both very high and low incomes are potentially less likely to report their income, which might have introduced bias. In our complete case analysis, which included only those with reported income data, we observed similar results, suggesting that the impact of the missing income data might be limited. Nonetheless, the results should be interpreted with caution.

Future research could obtain even more differentiated effect estimates for subpopulations, by adding three-way interaction terms to the model (e.g. to explore if the OBCT index – education interaction varies by income). Furthermore, examining the mediating role of sedentary behaviour in the association between the obesogenicity of the environment and weight status, could enhance the understanding of lifestyle behavioural pathways in abovementioned association. While the largest effect size was found for people aged 18–29, the mediators included in this study explained this association to the smallest extent for this subgroup, suggesting further research into other pathways. We further recommend conducting more (natural) experiments and longitudinal studies, to assess causality of the associations found. Finally, future studies could explore how work environment obesogenicity contributes to the association between obesogenic residential environment and weight status.

The findings of this study are relevant for public health, particularly in the context of cardiovascular disease risk. Our results imply that people living in the most obesogenic neighbourhoods have an average waist circumference 6.5 cm larger than those living in neighbourhoods with the lowest obesogenicity, when the OBCT index scores would range from zero to 100. Individuals with a waist circumference of $\geq$80 cm (women) or $\geq$94 cm (men) are classified as having increased cardiovascular disease risk (De middel-heup-ratio en de buikomtrek, n.d.). Figures from the National Institute for Public Health and the Environment, although somewhat outdated, report average waist circumferences of 86.3 cm (women) and 96 cm (men) in The Netherlands aged 30–70 years old (Rijksinstituut voor Volksgezondheid en Milieu, 2012). Given these values, a 6.5 cm increase translates into a meaningful increase in health risks for large population groups. Minimising the number of people reaching the waist circumference thresholds for cardiovascular disease risk is essential for population health. Although at first glance the effect estimates found may not seem large, the exposure of entire populations to obesogenic environments suggests a substantial impact on public health. Our findings could inform the development of lifestyle interventions by providing knowledge on target groups most susceptible to obesogenic environments. Moreover, policymakers and urban planners could use our findings, prioritising making the environment more conducive to PA and healthy food choices. Neighbourhoods with a high proportion of individuals vulnerable to their environment may be prioritised in policy changes. While understanding individual environmental indicators are valuable for various stakeholders in obesity prevention, the OBCT index offers a comprehensive tool to identify which neighbourhoods require urgent attention for improvement.

## 5. Conclusions

We showed that the association between the obesogenicity of the residential neighbourhood and waist circumference was the largest for respondents who were younger, had the lowest income, the highest education, the least self-discipline, the highest impulsivity scores, and the most perceived stress. Furthermore, the mediation results suggest that the association might partially be mediated by physical activity and dietary behaviour. Our findings enable to better target lifestyle interventions to individuals most vulnerable to obesogenic environments. Additionally, they provide guidance for policymakers and urban planners in promoting health-enhancing environments.

## Declarations

All participants signed an informed consent form before they received an invitation for the physical examination. The Lifelines Cohort Study is conducted according to the principles of the Declaration of Helsinki, and is approved by the medical ethical committee of the University Medical Centre Groningen, The Netherlands.

## Consent for publication

Not applicable.

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## CRediT authorship contribution statement

**Jet D.S. van de Geest:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Paul Meijer:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Sharon Remmelzwaal:** Writing – review & editing, Formal analysis. **Jeroen Lakerveld:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.healthplace.2024.103364.

## List of abbreviations

| | |
|---|---|
| OBCT | Obesogenic Built Environment CharacterisTics |
| PA | Physical activity |
| BMI | Body Mass Index |
| SEP | Socioeconomic position |
| NEO-PI | Neo Personality Inventory |
| LDI | Long-term difficulties Inventory |
| SQUASH | Short Questionnaire to Assess Health enhancing physical activity |
| MVPA | Moderate-to-vigorous physical activity |
| VIF | Variance Inflation Factor |

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