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Cities and mental health: The role of the built environment, and environmental and lifestyle factors in Barcelona☆

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ABSTRACT

Built environment characteristics and related environmental exposures and behaviors have been, separately, implicated in the development of poor mental health. However, it is unclear how these factors act together in relation to mental health. We studied these factors simultaneously to evaluate the impact of the built environment, and the mediating role of environmental exposures and physical activity, on mental health, while also studying moderation by sex, age, and length of residence. We used a cross-sectional population-based sample of 3145 individuals aged 15–97 years from Barcelona, Spain. Time spent walking and mental health status were assessed with validated questionnaires, administered through a face-to-face interview. We characterized the built environment (e.g., building, population and intersection density and green space), road traffic noise, and ambient air pollution at the residential level using land cover maps, remote sensing, noise maps and land use regression models. Adjusted regression models accounting for spatial clustering were analyzed to study associations between built environment attributes and mental health, and mediation and moderation effects. Density attributes were directly or indirectly, through air pollution and less consistently through walking, associated with poor mental health. Green space indicators were associated with lower prevalence of poor mental health, partly through lower air pollution exposure and more walking. In some cases, these associations differed by sex, age or length of residence. Non-linear associations of density indicators with environmental exposures, and of particulate matter with poor mental health indicated threshold effects. We conclude that living in dense areas with high air pollution concentrations was associated with poor mental health. On the other hand, green areas with lower air pollution concentrations were protective against poor mental health. Greater urban density might benefit health, but might only do so when air pollution concentrations are low.

1. Introduction

The urban environment plays an important role in human health (Kivimäki et al., 2021). Built environment characteristics, for example density, transport infrastructure and green space can influence morbidity directly and indirectly through behavior (e.g., walking, cycling, car use) and environmental exposures (e.g., traffic-related air pollution and noise exposure) (Cerin, 2019; Nieuwenhuijsen, 2018). Urban living has been associated with a higher risk of mental health problems (Hoare et al., 2019; Peen et al., 2010; Zijlema et al., 2015). It has been hypothesized that this can be related to certain selection processes, but also to physical characteristics of the environment and urban lifestyle (Peen et al., 2010; van den Bosch and Meyer-Lindenberg, 2019). Some suggest mental health problems can be the result of urban density

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itself, but characteristics related to density are probably better at explaining such an association (Generaal et al., 2019b, 2019a). For example, the lack of green space (Bratman et al., 2019; Gascon et al., 2015; Nieuwenhuijsen et al., 2022), and traffic-related noise (Orban et al., 2015; Tzivian et al., 2015) and air pollution (Kim et al., 2016; Kioumourtzoglou et al., 2017; Klompmaker et al., 2019) have shown to be potentially detrimental to mental health. Furthermore, car-oriented, non-walkable environments are not only associated with low levels of physical activity, but also with higher risks of poor mental health (Avila-Palencia et al., 2017, 2018; Berke et al., 2007).

Risk factors for poor mental health related to the built environment have been receiving an increasing amount of attention, mainly due to the ongoing urbanization worldwide (Helbich, 2018; Hoare et al., 2019), but also because mental health problems cause a large burden of disease, result in considerable healthcare costs and loss of productivity, and because they are prevalent across the world in all ages (GBD 2019 Mental Disorders Collaborators, 2022; Steel et al., 2014; Vigo et al., 2022). Previous studies have often examined the effects of built environment characteristics, environmental exposures and behaviors on health separately, but understanding such complex relationships requires the examination of the links between urban design, environmental exposures, behavior and health (Cerin, 2019; Hankey and Marshall, 2017; Nieuwenhuijsen, 2018). For example, while urban density improves walkability (Cerin et al., 2017; Kerr et al., 2016), it has also been associated with air pollution (Beelen et al., 2013; Eeftens et al., 2012b) and with poor mental health outcomes (Generaal et al., 2019a; Hoare et al., 2019; Peen et al., 2010; Zijlema et al., 2015). Moreover, air pollution and poor mental health may also be associated with each other (Kim et al., 2016; Kioumourtzoglou et al., 2017), and a connection between density, traffic-related noise and poor mental health could also exist (Orban et al., 2015; Tzivian et al., 2015).

It has been suggested that cities need to be more compact, should be less dependent on cars, and instead, should be greener, have mixed land use, and should promote public and active transport in order to promote public health (Nieuwenhuijsen, 2018, 2020). In line with that, the potential harmful effect of urban density on mental health could be mitigated by the increased opportunities for physical activity through walkability (Cerin, 2019), but the available evidence on such a mitigating effect is still very scarce (Zhang et al., 2019). It is also unclear whether density allows for green space availability (Cerin et al., 2020) and how this affects mental health. The complexities of the built environment and related environmental exposures and behaviors that can affect mental health underline that these multiple factors should be studied simultaneously. In addition, the interplay between these factors may differ by gender (Barnett et al., 2018; Van Dyck et al., 2015; Zhang et al., 2019), age (Barnett et al., 2018; Van Dyck et al., 2015) and depend on the length of residence (Barnett et al., 2018; Szabo et al., 2018).

Therefore, this study had several aims. First, we aimed to examine the associations between attributes of the built environment and mental health. Second, we aimed to examine the mediating roles of road traffic noise, air pollution and physical activity in these associations. Third, we aimed to identify sociodemographic moderators of associations between the built environment and poor health and its mediators. We hypothesized that land use mix and green space would be protective against poor mental health and that these associations would be mediated by lower concentrations of noise and air pollution and more physical activity. Furthermore, we hypothesized that building, population and intersection density might be risk factors for poor mental health, through noise and air pollution exposure; but that harmful effects of density might be mitigated by more physical activity.

2. Methods

2.1. Study population

This cross-sectional study was based on a population-based sample of 3145 individuals aged 15–97 years residing in Barcelona, Spain who participated in the Barcelona Health Survey (2016). Respondents were randomly selected from the municipal register of residents, while taking into account the age and sex structure of the 10 districts for representativeness purposes. A face-to-face interview was carried out by trained interviewers at the respondent's residence on socio-demographic characteristics and mental and physical health and well-being (Bartoll et al., 2018).

2.2. Exposure assessment

Residential addresses during the study period were geocoded and assessment of the urban built environment and environmental exposures was carried out following the HELIX methodology using a geographic information system (GIS) (Robinson et al., 2018).

2.2.1. Built environment indicators

Where available, built environment indicators for 100- or 300-m Euclidean residential buffers were obtained to represent the immediate residential environment (Smith et al., 2017; Zijlema et al., 2019). *Building density* within 100-m buffers was calculated by dividing the area of building cover (km^2) by the area of buffer (km^2) using a topographic map at scale 1:5000 (Institut Cartogràfic de Catalunya (ICC), 2015). *Population density* within 300-m buffers was calculated as inhabitants/km^2 using a grid population dataset from the Institut d'Estadística de Catalunya (IDESCAT, 2016). *Facility richness,* operationalized as a 0 to 1 index for the variety of facilities within a 300-m buffer contained *POI* (Points of Interests, including e.g. businesses, community services, educational institutions, entertainment, restaurants, shopping, transportation hubs) from Navteq street data, year 2012 (under ArcGIS software license). *Land use mix* within 300-m buffers was based on Shannon's Evenness Index (SEI) using Urban Atlas 2012 data (European Environment Agency, 2014), and describes the number of different land cover types and their relative abundances (Eurostat, 2018). The mean *slope* within 50-m buffers was calculated based on altitude data from the topographic map at scale1:5000 (Institut Cartogràfic de Catalunya (ICC), 2015) and was used as an indicator of walkability. Intersection density was calculated as the number of intersections within 300-m buffers, with data inputs from the Barcelona traffic map from year 2014. Green space was assessed with a number of indicators. The total *green space area* within 300-m buffers, and the linear *distance to the nearest green space,* representing amount of and access to green space respectively, were calculated with data inputs from Catalan (Land Cover Map of Catalonia, MCSC version 4) and European (Urban Atlas, 2012) land use maps (CREAF, 2009; European Environment Agency, 2014). *Residential surrounding greenness* was calculated as the mean Normalized Difference Vegetation Index (NDVI) in 300-m buffers and represents the amount of vegetation around the residence. NDVI imagery was obtained from Landsat 8 and processed to remove the influence of negative pixels from water bodies. The index ranged from 0 to 1, with higher values indicating higher density of green vegetation (Weier and Herring, 2000).

2.2.2. Environmental exposures

Road traffic noise concentrations (*Lden*, the mean 24-hr sound pressure with a 5 dB added penalty for evening values and a 10 dB added penalty for night values) were obtained from the Barcelona Strategic Noise Map (2012) developed in accordance with the European Commission Environmental Noise Directive 2002/49/EC. Noise concentrations were estimated at the street-level that was closest to participants' residences. Ambient air pollutants (NO_2, NO_x, $PM_{2.5}$, PM_{10}, PM_{coarse}, and PM2.5absorbance [a measure of blackness of the filter and marker of elemental carbon]) were estimated with Land Use Regression (LUR) models for Barcelona developed in the context of the ESCAPE project (Beelen et al., 2013; Eeftens et al., 2012a). Exposure concentrations were temporally adjusted from the modelling year of reference (2009) to the period of interest (2016) using annual mean concentrations from background routine monitoring stations within the study area.

2.3. Physical activity

Physical activity, operationalized as time spent walking, was assessed with the short format of the International Physical Activity Questionnaire (IPAQ) (Craig et al., 2003). This questionnaire assessed the time spent on walking and on moderate and vigorous physical activity in the last seven days. We computed minutes of walking in the previous week by multiplying the mean duration of walking in a day by the number of days walked. Values above 180 min/d were truncated at 180 min according to guidelines.

2.4. Mental health status

Mental health status was assessed with the 12-item General Health Questionnaire (GHQ-12). The GHQ-12 is a valid and reliable screening tool for non-psychotic psychiatric problems (i.e., mental health status) that was validated in the Spanish population (Sánchez-López and Dresch, 2008). The multidimensional scale assessed distinct aspects of distress in the last 30 days (Sánchez-López and Dresch, 2008) with questions that were answered on a 4-point Likert scale (from 1 to 4). According to guidelines, items were recategorized into 0–1 and summed, resulting in a score ranging from 0 to 12 with higher scores reflecting poor mental health. A score of ≥3 indicated being at risk of psychiatric problems (Goldberg, 1978).

2.5. Covariates

We chose the covariates *a priori* based on previous studies (Dadvand et al., 2016; Zijlema et al., 2015). Age, sex, marital status (single, married, widow(er) divorced/separated), place of birth (Barcelona/Catalonia, other place in Spain, outside Spain), education level (no education, primary education, secondary education, tertiary education), perceived income situation (very difficult, difficult, some difficulties, quite easy, (very) easy), and social class (5 groups based on occupation, ranging from unskilled worker to company director with >10 employees), and length of residence (months) were collected within the Barcelona Health Survey (BHS) during the interview (Bartoll et al., 2018). Unemployment rate (% persons aged >16 years unemployed at census tract level) was used as an indicator for area-level socioeconomic status and was obtained from the atlas of the Urban Vulnerability Index of Spain 2011; Instituto Nacional de Estadística, 2015).

2.6. Statistical analysis

Descriptive statistics were used to characterize the study sample, and were calculated by mental health status (at risk of poor mental health *vs.* good mental health). Spearman's correlations between the exposures were calculated to quantify the relations between built environment and exposure variables.

Analyses were conducted in three steps. Step 1: associations (linear or quadratic) between each of the built environment indicators and poor mental health were estimated (total effect, γ-path in Fig. S1). Interaction terms were added to identify sex, age and length of residence as moderators of associations. Moderation effects and quadratic (vs. linear) relationships were deemed statistically significant if the respective term had a p-value ≤0.05. Step 2: mediation was examined by first estimating associations (linear or quadratic) between each of the built environment indicators and the mediators (road traffic noise, air pollutants, walking; α-path in Fig. S1). For walking, moderation by sex, age and length of residence was also examined. Step 3: we estimated the associations between the mediators and poor mental health adjusted for each built environment indicator (β-path in Fig. S1) and the unmediated effects of built environment indicators on mental health (γ′-path in Fig. S1). Again, moderation by sex, age and length of residence of the β-path was tested and, when appropriate, the interaction term (built environment indicator x sex, age, or length of residence) and quadratic association identified in step 1 and 2 were included. The statistical significance of the mediating effect was tested using the joint-significance test (Cerin, 2010; MacKinnon et al., 2002; Zhao et al., 2010), in which simultaneous significance of both α- and β-paths provide evidence for mediating effects. Statistically significant moderation effects were further assessed by calculating associations at meaningful values of the moderators: males/females; and for age and length of residence: mean ± 1SD.

Analyses were conducted using mixed effects regression models with random intercepts for districts and robust standard errors to take into account clustering within districts, which is the preferred model for samples with 10–30 clusters (Cerin, 2011). Step 1 and 3 were conducted with mixed effects logistic regression models, and step 2 with mixed effects linear (noise and air pollution) or gamma (walking) regression models. Analyses were adjusted for age, sex, marital status, place of birth, education level, perceived income situation, social class, length of residence and area-level unemployment rate. The variables building density, population density, facility richness, land use mix, distance to green space, residential surrounding greenness and minutes of walking were rescaled in order to facilitate interpretation of regression results. Analyses were undertaken using STATA version 14.2 (StataCorp, 2015).

3. Results

Among the 3145 respondents, the mean age was 49 years (SD 19 years), 52% were female, and 18% were at risk of having mental health problems. Compared with respondents with good mental health, those with poor mental health tended to be older, male, widow(er), separated or divorced, born outside Catalonia, and have lower education level,

Table 1
Sample characteristics of the Barcelona Health Survey by mental health status (n = 3145).

		Good mental health n = 2578	Poor mental health n = 567
		n (%)/mean (SD)	n (%)/mean (SD)
Age (yr)		48.8 (18.4)	50.7 (20.1)
Sex	females	1312 (50.9)	239 (57.9)
	males	1266 (49.1)	239 (42.2)
Marital status	single	940 (36.5)	207 (36.5)
	married	1308 (50.7)	258 (45.5)
	widow(er)	142 (5.51)	49 (8.64)
	separated or divorced	188 (7.29)	53 (9.35)
Place of birth	in Barcelona/Catalonia/ Spain	1998 (77.5)	401 (70.7)
	outside Spain	580 (22.5)	166 (29.3)
Education	no formal education/ primary	833 (32.3)	280 (49.4)
	secondary	690 (26.8)	162 (28.6)
	university	1055 (40.9)	125 (22.1)
Perceived income situation	very difficult/difficult	257 (9.97)	190 (33.5)
	somewhat difficult	564 (21.9)	163 (28.8)
	somewhat easy	984 (38.2)	133 (23.5)
	(very) easy	773 (30.0)	81 (14.3)
Social class	company director/manager with >10 employees; university-level profession	623 (24.2)	72 (12.7)
	company director/manager with <10 employees; artist; sports professional	278 (10.8)	35 (6.17)
	administrative worker; self-employed	652 (25.3)	109 (19.2)
	manual worker	723 (28.0)	220 (38.8)
	unskilled worker	302 (11.7)	131 (23.1)
Length of residence (months)		234 (207)	265 (248)
Minutes of walking in the last week, median (IQR)		210 (280)	210 (315)

financial problems, and lower social class jobs. Minutes of walking was higher in respondents with good mental health (Table 1). Some of the built environment and environmental exposure variables differed by mental health status (Table 2). Intersection density and walkability were higher among respondents with poor mental health, but residential surrounding greenness was lower compared to respondents with good mental health. Air pollution estimates of PM_{10} and PM_{coarse} were slightly higher among those with poor mental health, and those with poor mental health lived more often in neighborhoods with higher rates of unemployment compared to respondents with good mental health. Correlations between urban built environment and environmental exposure variables ranged between −0.75 and 0.88 and are shown in Table S1.

3.1. *Associations between built environment indicators and poor mental health*

Associations between built environment indicators and the odds of poor mental health (γ-path) are shown in Table 3. Higher intersection density was associated with a higher likelihood of poor mental health. A higher slope within a 50-m buffer around the residence was associated with a lower likelihood of poor mental health. Some of the associations between built environment attributes and poor mental health were moderated by sex, age, or length of residence. Age moderated the association between building density and poor mental health, whereby younger participants (−1 SD from mean age (30.4 years)) showed a positive association and older participants did not. Age also moderated the association between green space area and poor mental health, with a negative association in younger participants (30.4 years) but not in older participants. The association between population density and poor

Table 2
Descriptive statistics of built environment attributes, environmental exposures and area-level socioeconomic status in the Barcelona Health Survey (n = 3145) by mental health status.

	Good mental health n = 2578			Poor mental health n = 567		
	Median (IQR)	Min	Max	Median (IQR)	Min	Max
Building density 100-m (index 0–1)	0.53 (0.25)	0.03	0.86	0.54 (0.27)	0.06	0.84
Population density 300-m (inhabitants/km^2)	1640 (719)	113	5949	1685 (725)	279	5981
Facility richness 300-m (index 0–1)	0.25 (0.12)	0.02	0.48	0.23 (0.12)	0.02	0.47
Land use mix 300-m (index 0–1)	0.39 (0.20)	0.12	0.73	0.38 (0.20)	0.12	0.70
Slope 50-m (mean %)	1.93 (2.28)	0.00	27.84	1.77 (2.24)	0.00	21.77
Intersection density 300-m (count)	44 (23)	1	174	47.0 (26.0)	12	176
Green space area 300-m (ha)	17.9 (17.0)	0	111.4	17.9 (16.9)	0	89.8
Green space distance (m)	233 (261)	0	1333	231 (269)	0	1308
Residential surrounding greenness 300-m (index 0–1)	0.20 (0.06)	0.019	0.576	0.20 (0.06)	0.048	0.363
Road traffic noise Lden (dBA)	66.0 (8.00)	36.0	80.0	66.0 (8.00)	48.0	79.0
NO_2 (μg/m^3)	43.5 (5.77)	11.6	85.8	43.5 (5.46)	14.9	86.5
NO_x (μg/m^3)	69.9 (13.4)	23.8	196.3	68.9 (10.7)	23.8	189.2
$PM_{2.5}$ (μg/m^3)	9.29 (1.36)	5.0	16.7	9.17 (1.36)	5.1	15.0
PM_{10} (μg/m^3)	20.7 (3.01)	12.3	29.9	21.0 (2.91)	14.7	29.8
PM_{coarse} (μg/m^3)	11.9 (2.00)	6.2	15.7	12.3 (1.98)	8.5	15.7
$PM_{2.5absorbance}$ (μg/m^3)	2.12 (0.38)	0.7	4.0	2.07 (0.35)	0.7	3.9
Area-level unemployment rate (%)	20.2 (10.8)	0.0	61.2	21.1 (11.8)	0.0	61.2

Table 3
Associations between built environment attributes and poor mental health in the Barcelona Health Survey (n = 3145) (γ-path).

	OR (95% CI); p-value
Building density (per 10)[#]	**1.248 (1.089, 1.430); p=0.001**
Building density by age	**0.996 (0.993, 0.999); p=0.003**
−1 SD from mean age (30.4 yr)	**1.104 (1.029, 1.185); p=0.006**
Mean age (49.2 yr)	1.024 (0.967, 1.084); p = 0.421
+1 SD from mean age (67.9 yr)	0.949 (0.876, 1.029); p = 0.206
Population density (per 1000 inhabitants/km^2)[#]	1.187 (0.950, 1.483); p = 0.132
Population density by length of residence	**0.999 (0.999, 1.000); p=0.049**
−1 SD from mean length of residence (23.6 months)	1.168 (0.941, 1.449); p = 0.159
Mean length of residence (239.1 months)	1.006 (0.820, 1.235); p = 0.951
+1 SD from mean length of residence (454.7 months)	0.867 (0.653, 1.153); p = 0.327
Slope	**0.955 (0.917, 0.996); p=0.030**
Intersection density	**1.004 (1.000, 1.008); p=0.040**
Facility richness (per 10%)	1.132 (0.973, 1.028); p = 0.109
Land use mix (per 10%)	0.955 (0.874, 1.043); p = 0.304
Green space area (hectares)	**0.973 (0.960, 0.987); p < 0.001**
Green space area by age[#]	**1.000 (1.000, 1.001); p=0.004**
−1 SD from mean age (30.4 yr)	**0.987 (0.981, 0.993); p < 0.001**
Mean age (49.2 yr)	0.997 (0.990, 1.002); p = 0.149
+1 SD from mean age (67.9 yr)	1.004 (0.994, 1.015); p = 0.405
Distance to green space (per 100 m) – linear term[#]	0.997 (0.895, 1.110); p = 0.952
Distance to green space – quadratic term[#]	1.006 (0.996, 1.015); p = 0.255
Distance to green space by sex (ref: male) – linear term	**0.801 (0.677, 0.947); p=0.009**
Distance to green space by sex (ref: male) – quadratic term	**1.019 (1.007, 1.031); p < 0.001**
Linear term of distance to green space in males	0.997 (0.895, 1.110); p = 0.952
Quadratic term of distance to green space in males	1.006 (0.996, 1.015); p = 0.255
Linear term of distance to green space in females	**0.798 (0.707, 0.901); p < 0.001**
Quadratic term of distance to green space in females	**1.024 (1.015, 1.034); p < 0.001**
Residential surrounding greenness (per 0.1)	0.851 (0.689, 1.052); p = 0.136

Mixed effects logistic regression models adjusted for age, sex, marital status, place of birth, education level, perceived income situation, social class, length of residence and area-level unemployment rate. Note. [#] This does not represent a main effect because the interaction term with a moderator was statistically significant (see row below); ref: reference group (in categorical variables). Estimates in bold indicate p-value ≤0.05.

mental health was moderated by length of residence, with a tendency for those with shorter residence to have positive associations and those with longer residence negative associations with poor mental health. The association between distance to green space and poor mental health was positive and quadratic and differed by sex (Fig. S2). The associations of facility richness, land use mix, and residential surrounding greenness on mental health were not statistically significant (Table 3).

3.2. Mediators and mediated moderation of associations between built environment indicators and poor mental health

Table S2 and Table S3 and Figs. S3–S11 provide a summary of the statistically significant mediation effects. Evidence was found for a mediating role of NO2, PMcoarse, PM10 and PM2.5absorbance in the associations between poor mental health and built environment attributes. The associations of building density, population density, slope, facility richness, land use mix, green space area, and residential surrounding greenness with poor mental health were mediated by NO2 and PM2.5absorbance but differently in males and females. Males tended to show worse mental health outcomes than females with higher concentrations of NO2 and PM2.5absorbance. Similarly, mediated moderation by sex was also found for the associations of intersection density and NO2 on poor mental health. Curvilinear associations were observed for a number of built environment attributes and the environmental exposures, indicating inverted U-shape or J-shape associations. For example, population density and the associations with the air pollutants start positive, reach a plateau around 3500 inhabitants/km2 and are followed by a descending curve (Figs. S12–S21). Furthermore, associations between PMcoarse and PM10 with poor mental health were consistently J-shaped: an ascending curve that reaches a plateau around 12.5 μg/m3 and 23 μg/m3 respectively, after which it declines again.

Walking was found to mediate associations between poor mental health and population density, land use mix and distance to green space. There was also support for moderation by length of residence and sex, and mediated moderation by age. Population density was positively associated with walking (in those with longer length of residence), and walking was negatively associated with poor mental health (in those with age ≥49 years). Although land use mix was associated with fewer minutes of walking (in those with long length of residence, +1 SD from mean length of residence (454.7 months)), walking was negatively associated with poor mental health (in those aged ≥49 years). Distance to green space was associated with fewer minutes of walking (in females only), and walking itself was negatively associated with poor mental health (in those aged ≥49 years). Road traffic noise, PM2.5 and NOx were not mediating any of the associations between the built environment indicators and poor mental health since these environmental exposures were not statistically significantly associated with poor mental health.

4. Discussion

4.1. Summary of findings and comparison with previous literature

4.1.1. Direct associations and moderators

Albeit in specific subgroups, building density, population density, intersection density and a longer distance to green space were directly associated with a higher prevalence of poor mental health and slope and green space area were directly associated with a lower prevalence of poor mental health. These findings are in line with studies that observed a higher prevalence of mental health problems in urbanized areas (Hoare et al., 2019; Peen et al., 2010; Zijlema et al., 2015), and with the growing evidence on the mental health benefits of green space (Bratman et al., 2019; Gascon et al., 2015; Kivimäki et al., 2021).

Moderation analyses suggested that younger participants may experience mental health benefits from larger green spaces, while higher concentrations of building density may result in mental health problems in this age group. Population density seemed to be negatively associated with poor mental health in those with a long length of residence, but positively in those with a short length of residence. The curvilinear association (U-shape for women) between distance to green space and poor mental health may indicate that a 400–600 m distance from home is optimal. The detrimental effect of larger distances to green space on mental health was only present in females and may indicate the importance of nearby green space for females' mental health. This might be because females need nearby green space for restoration or social interaction, while males may have other preferences. These differential effects in subgroups underline potential differences in vulnerability, needs and preferences of such populations, but are not always consistent across contexts and should be further studied to reduce urban health inequity (De Snyder et al., 2011; Lorenc et al., 2013).

4.1.2. Mediation by air pollution and moderators

The associations between the density indicators and poor mental health were partly mediated by air pollution. Building density, population density, intersection density and facility richness were positively associated with NO2, PMcoarse, PM10 and/or PM2.5absorbance, which were positively associated with poor mental health. This is consistent with findings showing that urban density may increase poor mental health through air pollution (Pun et al. 2019) and with studies showing associations between air pollution and poor mental health (Braithwaite et al., 2019; Kim et al., 2016; Kioumourtzoglou et al., 2017; Klompmaker et al., 2019), but contrary to others that found no associations (Fan et al., 2020; Zijlema et al., 2016). We found that after a certain level of density, further increases in density are associated with lower air pollution concentrations and the association between PM and poor mental health reaches a plateau. This is a novel finding since most previous research reports on linear associations, but a study in Medellin (Colombia) found U-shaped associations between population and amenity density with a number of poor health outcomes (Patino et al., 2021). Their findings indicate that density might be beneficial to health, but extremely high density probably means overcrowding and congestion. The observed inverted U-shape associations between several density indicators and noise and air pollutants in our study indicate that very low and very high density are associated with lower concentrations of these environmental exposures. This might be specific to Barcelona's urban lay-out, where some of the high-density areas are pedestrianized and have therefore lower exposure concentrations. Assessing non-linear associations is helpful for establishing thresholds of effects but may be context specific. We therefore call for more research on threshold effects of density on pollution and health to better inform urban planning policy.

The observed benefit of green space and surrounding greenness on mental health through lower concentrations of air pollution is in line with a study from the Netherlands that found that NO2 and PM2.5 partially mediated the association between surrounding greenness and mental health (Klompmaker et al., 2019); and with another study from Barcelona where air pollution mediated the association between green space and mental health outcomes (Gascon et al., 2018). Similarly, Generaal et al. (2019a) found that higher concentrations of PM2.5absorbance and fewer green spaces were associated with a higher risk of depression in a pooled analysis of eight Dutch studies, but did not perform mediation analysis (Generaal et al., 2019a). However, a recent review concluded that empirical evidence on the mediating effect of air pollution in the relation between green space and health is still scarce and that further research is needed (Kumar et al., 2019).

The observed association between slope and lower risks of poor mental health is not supported by previous research or by a plausible biological mechanism. The mean slope in a neighborhood might be associated with poor health because it may discourage physical activity (Patino et al., 2021), but this was not the case in our sample. We did observe that the degree of slope was strongly correlated with high concentrations of greenness and low concentrations of PMcoarse and

PM10 and our results indicated full mediation by PMcoarse of the association between slope and poor mental health. We therefore postulate that not the slope itself, but high levels of greenness and low concentrations of PM are driving these associations with mental health in this study. Furthermore, sloped areas are in the outskirts of Barcelona and tend to have a wealthier population and residual confounding by SES may also explain this finding.

Moderation analyses showed that men's mental health may be more negatively affected by NO2 and PM2.5absorbance than women's mental health. This may be because men tend to spend more time outdoors and are thus more exposed to air pollution than women (Clougherty, 2010). The unexpected results in women may be due to residual confounding. Areas with higher concentrations of air pollution may be a proxy for better access to commercial destinations that may have a positive influence on women's mental health. The measures of destination richness included in this study may not be effective in picking up the 'desirability and popularity' of some destinations, while air pollution concentrations can be proxies of such destinations. Previous studies have reported mixed results regarding sex differences, with either males (Pun et al., 2019; Shin et al., 2018) or females (Gatto et al., 2014) being more vulnerable to air pollution effects, indicating that more research is needed.

4.1.3. Mediation by walking and moderators

Walking was not a consistent mediator in this study. Although walking was associated with lower odds of poor mental health, especially in older age groups, it only mediated associations with three out of nine built environment attributes. As hypothesized, population density and distance to green space were respectively positively and negatively associated with walking; but the negative association between land use mix and walking was unexpected. Previous studies have reported mixed results, for example a US study showed that walkability was associated with higher levels of poor mental health outcomes (James et al., 2016), and another study from Barcelona showed that physical activity was not mediating the association between green space and mental health (Gascon et al., 2018). Other studies have shown that higher levels of physical activity were associated with population density, facility richness, and density of public transport stations and street connectivity (Cerin et al., 2018; Chandrabose et al., 2019; Gascon et al., 2019). An explanation for our findings might be that the short IPAQ measures overall walking, while density has found to be related to walking for transport rather than walking for recreation (Cerin et al., 2007). Furthermore, the land use mix indicator might not have been able to distinguish between areas attractive for walking, and specific land use mix profiles might motivate walking more than others (Cerin et al., 2007). Another potential explanation is that the buffer sizes we used for the density/walkability attributes are suitable to examine the mediating effect of air pollution, but might be too small to examine the effects on walking.

4.1.4. Mediation by road traffic noise

Road traffic noise did not mediate any of the associations between the built environment and poor mental health because it was not associated with poor mental health. This is in contrast to a previous study where road traffic noise was associated with prescription of anxiety medication and partly mediated the association between surrounding greenness and anxiety medication (Klompmaker et al., 2019), and in contrast other studies reporting associations between noise and poor mental health (Dreger et al., 2015; Nieuwenhuijsen et al., 2011; Okokon et al., 2018; Orban et al., 2015; Shi et al., 2023). The lack of association with noise in our study might be due to relative low accuracy of the noise model that estimated levels on the nearest road and because of lacking information on bedroom orientation, window opening habits and other noise sources.

4.2. Limitations and strengths

This study has some limitations. Some of the built environment attributes were used as predictor variables in the land use regression models for estimation of air pollution concentrations. These were population density (in NOx, NO2, and PM2.5 abs LUR models), slope (in PMcoarse and PM10 LUR models) and green space area (1000-m buffer; in PM2.5 LUR model). Models with these attributes and exposures should therefore be interpreted with caution. We hypothesized a certain order of effects, but the cross-sectional design does not allow us to establish the direction of the observed associations. Furthermore, this study focused on residential exposures and this exposure does not reflect other exposure people have outside their residential environment. To tackle causality and incomplete exposure assessment issues, future studies need to focus on environmental exposures and mental health over space and across time (Helbich, 2018; Reichert et al., 2020). Nonetheless, this study was based on a rich dataset that enabled us to assess multiple environmental factors at a time whereas many previous studies focused on one environmental factor in isolation. The objective assessment of various built environment indicators is a major strength since it provides a depiction of the living environment that can inform urban planning. Finally, we were able to adjust for a number of covariates to avert confounding by demographic and socioeconomic differences in our sample and we were able to study associations in different subgroups.

4.3. Implications and future studies

Cities play a crucial part in public health and have the opportunity to make a difference to public health through local planning and policy for health (Lowe et al., 2022; Nieuwenhuijsen, 2020; Tsouros, 2019). Our findings, and those of others (Mueller et al. 2017; 2019) underline that lowering air pollution concentrations and increasing green space and physical activity opportunities are crucial for healthy cities. This can be achieved through moving from private motorized transportation to public and active transportation and greening of cities (Khreis et al., 2023; Nieuwenhuijsen, 2020; Nieuwenhuijsen et al., 2023). Our findings also have implications for future studies that should aim to disentangle complex relationships between the built environment, exposures, and behaviors on mental health. The analyses presented here should be repeated in other cities to examine whether the observed associations in Barcelona can be generalized to other cities or whether they are city context specific. More research on threshold effects of density on pollution and health to better inform urban planning policy is also needed. Finally, future studies should consider moderation effects in order to reduce urban health inequity.

5. Conclusion

This cross-sectional study with 3145 individuals from Barcelona suggests that living in dense areas with high air pollution concentrations may be associated with poor mental health. On the other hand, green areas with lower air pollution concentrations may be protective against poor mental health. We conclude that greater urban density might benefit health, but might only do so when air pollution concentrations are low. We observed non-linear associations of density indicators with environmental exposures, and of particulate matter with poor mental health that might indicate threshold effects. Our findings further suggest that females are more affected by the lack of green spaces than males, but that males may be more vulnerable to the air pollution effects compared to females. Younger respondents seemed to benefit more from a larger amount of green space area than older respondents, and they were more affected by building density than the older participants. Our findings show that urban design can be a powerful tool to confront public health challenges and create healthy cities. Further research is needed to untangle the complex and non-linear relationships between the built environment, exposures, and behaviors on mental health.

CRediT authorship contribution statement

Wilma Zijlema: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Visualization, Writing – review & editing. **Ester Cerin:** Conceptualization, Investigation, Methodology, Supervision, Writing – review & editing. **Marta Cirach:** Formal analysis, Investigation, Methodology, Software, Writing – review & editing. **Xavier Bartoll:** Data curation, Funding acquisition, Methodology, Writing – review & editing. **Carme Borrell:** Data curation, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – review & editing. **Payam Dadvand:** Data curation, Investigation, Methodology, Supervision, Writing – review & editing. **Mark J. Nieuwenhuijsen:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

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

Data availability

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.envpol.2024.123559.

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