Journal Pre-proof

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Kate E. Mason, Neil Pearce, Steven Cummins

PII: S0277-9536(20)30461-5

DOI: https://doi.org/10.1016/j.socscimed.2020.113242

Reference: SSM 113242

To appear in: *Social Science & Medicine*

Revised Date: 12 May 2020

Accepted Date: 20 July 2020

Please cite this article as: Mason, K.E., Pearce, N., Cummins, S., Do neighbourhood characteristics act together to influence BMI? A cross-sectional study of urban parks and takeaway/fast-food stores as modifiers of the effect of physical activity facilities, *Social Science & Medicine*, https://doi.org/10.1016/j.socscimed.2020.113242.

Do neighbourhood characteristics act together to influence BMI? A cross-sectional study of urban parks and takeaway/fast-food stores as modifiers of the effect of physical activity facilities

Kate E. Mason[1,2], Neil Pearce[2] and Steven Cummins[3]

Affiliations:

1. Department of Public Health and Policy, University of Liverpool

2. Faculty of Epidemiology and Population Health, London School of Hygiene and Tropical Medicine

3. Faculty of Public Health and Policy, London School of Hygiene and Tropical Medicine

Corresponding Author:

Kate Mason

Department of Public Health and Policy, Institute of Population Health Sciences, University of Liverpool, Waterhouse Building Block F, Liverpool, L69 3GL, UK.

kate.mason@liverpool.ac.uk

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Keywords: built environment; neighbourhoods; physical activity; body mass index; United Kingdom; effect modification; food environment; greenspace

ABSTRACT

Studies exploring associations between neighbourhood environment and obesity often overlook the fact that neighbourhoods are multi-dimensional and that the effects of one environmental exposure may be modified by another. We examine whether associations between neighbourhood density of formal physical activity (PA) facilities and body mass index (BMI) are modified by the density of neighbourhood green spaces and takeaway stores. We used cross-sectional data from the UK Biobank cohort and linked UK Biobank Urban Morphometric Platform (UKBUMP) for 345 269 urban-dwelling adults aged 40-69. We examined associations between objectively measured BMI and the number of formal PA facilities (gyms, pools, etc.) within 1km of each individual's home, testing separately for interactions with the number of local public green spaces, and number of takeaway stores, within the same 1km buffers. We estimated modifier-stratified associations using multivariable, multilevel models to account for a clustered sampling design and potential confounding. Likelihood ratio tests were used to assess statistical interaction. We found that the association between a greater number of local PA facilities and lower BMI was stronger among people with fewer urban green spaces in their neighbourhood than among those with more green spaces ($P_{interaction}$=0.021). The same relationship between PA facilities and BMI was also noticeably attenuated among those with more takeaway stores near home, compared with people with none ($P_{interaction}$=0.014). We conclude that formal PA facilities may buffer against a lack of informal, green resources for PA in areas where the latter are scarce. However, the potential benefits of formal PA facilities in terms of obesity risk may be undermined by an unhealthy food environment close to home. Locating formal PA facilities in places with fewer public green resources and reducing the prevalence of takeaway stores in areas with formal PA resources may maximise the health benefits to be derived from these neighbourhood resources.

BACKGROUND

Characteristics of neighbourhood environments, such as access to physical activity facilities, green space and takeaway or fast-food outlets, may be linked to obesity risk. However, the evidence base remains inconsistent for many of these neighbourhood exposures (Cobb et al., 2015; Lachowycz and Jones, 2011; Mackenbach et al., 2014; Mayne et al., 2015). One possible explanation for the inconsistencies across studies is that the effects of specific neighbourhood environmental risks may not be universal, but instead vary according to other neighbourhood factors. For example, formal physical activity (PA) facilities are a potentially health-promoting neighbourhood resource (Sallis et al., 2012). Such facilities – e.g. gyms, swimming pools, sports fields – may play a larger role in areas with fewer informal resources that encourage PA (e.g. parks and other urban green space). Conversely, the potential health-promoting influence of the neighbourhood physical activity environment on energy balance and resulting adiposity may be dampened or overridden by the potentially 'obesogenic' influence of a neighbourhood food environment dominated by takeaway/fast-food stores. Put another way, the local availability of takeaway stores and of spaces such as parks may act as effect-measure modifiers of the relationship between the formal PA environment and obesity.

There is growing recognition that recent increases in obesity prevalence can be viewed as an emergent property of a complex system (Butland et al., 2007; Rutter et al., 2017; Swinburn et al., 2011), and it is therefore important to consider any given exposure or risk factor for obesity within its wider context. The presence of effect modification between neighbourhood characteristics is an example of where context might matter – ignoring the underlying distribution of other effect-modifying neighbourhood characteristics may obscure important effects in some places, and give rise to heterogeneity in findings across different settings. This need to take context into account has been highlighted in a number of recent publications with respect to population health (Craig et al., 2018) and the determinants of the major behavioural risks to health (Panter et al., 2017; Watts et al., 2011). Most studies of neighbourhood built environments and obesity-related outcomes have tended to focus on the influence of single neighbourhood exposures (Feng et al., 2010; Caspi et al., 2012; Van Holle et al., 2012). Yet, recognising the importance of context and the complexity of obesity and its determinants, it follows that attempts to isolate effects of individual neighbourhood characteristics on health can only ever paint an incomplete picture of how environmental factors influence the health of local residents (Giskes et al., 2011; Myers et al., 2016).

While there have been studies in the past decade seeking to unpack some of this complexity in various ways, very few have explicitly examined how multiple dimensions of the neighbourhood built environment interact with one another such that one neighbourhood characteristic may modify or moderate the effect of another (Boone-Heinonen et al., 2013). Instead, efforts have been focussed on characterising overall neighbourhood 'obesogenicity' by combining multiple neighbourhood attributes into a single composite measure (Saelens et al., 2012; Tseng et al., 2014) or using methods such as cluster analysis to identify neighbourhood typologies (Adams et al., 2013; Hobbs et al., 2018a; Meyer et al., 2015). By understanding whether the effect of one neighbourhood characteristic is modified by the presence of other neighbourhood characteristics, we may better describe how neighbourhoods shape health and behaviour. We may also start to identify settings in which interventions targeting a particular feature of the built environment may have greater (or lesser) potential for reducing or preventing obesity in the populations residing there, and optimise future interventions accordingly (Economos et al., 2015).

In this paper we focus on potential modification of the relationship between the formal PA environment and adiposity by neighbourhood availability of parks, and neighbourhood food environment. Many formal PA facilities are businesses, and as such they are potentially modifiable via regulatory and commercial levers. Some are run by local authorities, and thus are potentially also amenable to other policy interventions aimed at locating these facilities where they may have the greatest benefit to local populations. In a recent cross-sectional study using UK Biobank, we observed a pattern of lower mean waist circumference, BMI and body fat associated with increasing neighbourhood density of PA facilities (Mason et al., 2018). As described above, other neighbourhood resources such as parks and fast food outlets are potential effect-measure modifiers of these relationships; parks because they can provide alternative opportunities for informal outdoor PA that may be more accessible and appealing than formal PA facilities, and takeaway/fast-food outlets because unhealthy food environments may negate healthy PA environments. Examining these elements of the relationship between the formal PA environment and BMI may deepen our understanding of where intervening on the formal PA environment may be more beneficial, or, alternatively, other modifiable neighbourhood attributes that may boost the potential for local residents to benefit from local formal PA facilities.

We assess these possible environmental effect-modification relationships among adults living in urban residential areas in the United Kingdom by testing the following hypotheses. First, that the availability of formal PA facilities will be more strongly associated with BMI among people with no parks or other public open/green spaces near their home than it is among those with greater park availability. Second, that the association between formal PA resources and BMI will be weaker among people with more takeaway stores near their home than it is among those with no or fewer takeaway stores near home.

METHODS

Study design and data collection

In this cross-sectional study, we used baseline data from the UK Biobank (project 17380), a population-based sample of half a million UK adults for whom the scientific rationale and more detailed study design and survey methods of UK Biobank have been described elsewhere (UK Biobank, 2007). Data were potentially available from 502, 656 individuals who visited one of 22 UK Biobank assessment centres across the United Kingdom between 2006 and 2010, where they provided baseline data spanning health, sociodemographics, behaviour, psychosocial and other factors, and were subject to a range of sampling and testing procedures. All individuals aged 40–69 years living within a 25-mile radius of an assessment centre and listed on National Health Service (NHS) patient registers were invited to participate in the study. The age range was chosen by UK Biobank as an important period for the development of many chronic diseases.

Local environment data

Linked to UK Biobank is the UK Biobank Urban Morphometric Platform (UKBUMP), a high-resolution spatial database of objectively measured characteristics of the physical environment surrounding each participant's exact residential address. Environmental data in UKBUMP are derived from multiple national spatial datasets using automated processes (Sarkar et al., 2015). The available measures of the local environment include: densities of various land uses; proximity to various health-relevant destinations (e.g. GP practices, industrial sites, fast-food outlets); street network accessibility; and pollution. The metrics were constructed using data collected during the baseline individual assessment phase. No environmental data were collected for the Stockport assessment area, which was the UK Biobank pilot site, leaving 21 assessment areas in scope.

Outcomes

Our primary outcome of interest was Body Mass Index (BMI, kg/m^2). Height and weight measurements were made by trained staff using standard procedures (UK Biobank, 2007) and

BMI was treated as a continuous variable. In sensitivity analyses, waist circumference (in cm, measured manually by trained nurses) and body fat percentage (measured using a bioimpedance machine) were examined as secondary outcomes to assess the consistency of the results across alternative measures of adiposity.

Primary exposure

Our primary exposure was the total number of formal PA facilities within a one-kilometre street-network buffer around each individual's place of residence (categorised as 0, 1, 2-3, 4 or more, to account for the data being positively skewed). Formal PA facilities were defined at address level as any land use classified in the Commercial-Leisure subcategory of the UK Ordnance Survey AddressBase Premium database. This subcategory comprises a range of indoor and outdoor facilities designed for sporting and leisure activities, such as gyms, swimming pools and playing fields (for details see Supplementary Material). A 1-km buffer has been used in numerous other studies; it equates to about a 10-15 minute walk and has been reported to be roughly the area that people perceive to be their neighbourhood (Lee and Moudon, 2006).

Potential effect-measure modifiers

To test hypothesis 1 (i.e. that the association between availability of PA facilities and BMI will be stronger among people with no parks near their home), we examined effect-measure modification by *urban park availability*, measured as the number of parks or other public open/green spaces in a one-kilometre street-network buffer around each participant's home address. As with formal PA facilities, the number of parks is derived from the UK Ordnance Survey AddressBase Premium database, and we included any land use categorised as Park; Public Park/Garden; Public Open Space/Nature Reserve; Open Space/Heath/Moorland; or Playground. The distribution of the number of these sites in a buffer was highly positively skewed, and for this analysis was therefore categorised as no parks, one or two parks, or at least three parks.

To test hypothesis 2 (i.e. that the association between PA facilities and BMI will be weaker among people with more takeaway stores near their home), we examined possible effect-measure modification by *takeaway/fast-food store availability*, measured as the number of addresses classified as a 'hot/cold fast-food outlet/takeaway' in the UK Ordnance Survey AddressBase Premium database (Sarkar et al., 2015), again within a one-kilometre street-network buffer around each participant's home address. As with parks, the distribution of the number of takeaways in a buffer was highly skewed, so we categorised the count into three levels (0 / 1-2 / 3 or more).

Statistical analysis

We first examined the distributions of the various neighbourhood attributes across the sample by cross-tabulating categories of the number of formal PA facilities in people's neighbourhoods with categories of each of the potential modifiers (urban park availability and takeaway store availability). To test each effect-measure modification hypothesis, we compared multilevel linear models of the independent association between the formal PA environment and BMI with and without interaction terms for the product of the formal PA environment and each potential modifier. Multilevel models were used to account for the clustering by assessment centre in the sampling design, and were estimated with random intercepts and random coefficients for the main exposure. We used likelihood ratio tests to compare the models and we report the P value from these tests to indicate the strength of the evidence against the null hypothesis of no effect modification on the additive scale. We then stratified the sample by the potential effect modifier and estimated stratum-specific mean differences (and 95% CIs) in BMI for categories of increasing numbers of formal PA facilities, relative to people with no PA facilities with one kilometre of home.

Models were adjusted for potential confounding by age (years), sex (male or female), self-reported ethnicity (white, south Asian, black, other Asian, mixed white and black, mixed white and Asian, mixed other, or other), highest education level attained (college or university degree, post compulsory education, higher secondary education, secondary education, vocational qualifications, other professional qualification, or none of the above), annual household income (<£18 000, £18 000–30 999, £31 000–51 999, £52 000–100,000, or >£100 000), employment status (paid work, retired, unable to work, unemployed, or other), area deprivation (2001 Townsend index score (National Centre for Research Methods); higher score=greater deprivation), and neighbourhood residential density (count of residential dwellings within a 1-km street-network buffer of home address, log transformed). The focus of the analysis was to identify moderation or enhancement of the estimated effect of the primary exposure – the formal PA environment – by other neighbourhood features (specifically parks/fast-food). Therefore, we adjusted each model for the set of covariates that represents potential confounders of the relationship between the primary exposure and the outcome, and which we identified with the aid of a directed acyclic graph. While adjustment for the confounders of the modifier-outcome associations was therefore not essential (Vanderweele, 2015, p. 269), those sets of confounders are, in this context, likely to be very similar.

We also adjusted each model for the other potential modifier not under examination in that model (i.e. we included takeaway store availability as a covariate in the models testing for effect modification by number of parks, and controlled for urban park availability in the model testing for effect modification by takeaway store availability). This made no substantive difference to the point estimates but slightly improved precision of the estimates. In a previous analysis of the association between the formal PA environment and adiposity, we also found that adjustment for diet (total energy intake) did not lead to substantively different conclusions, but did artificially inflate point estimates due to extensive missing data; therefore, we deemed it inappropriate to adjust the models in this paper for diet, particularly as we identified an additional risk of inducing collider bias by adjusting for diet (Mason et al., 2018).

Missing data and sample restrictions

Perceptions of access to food outlets and public amenity of parks and other public open/green spaces are both likely to differ in urban residential areas compared with non-urban areas (Dennis and James, 2017; Maas et al., 2006). For example, to a person living in a rural area, many facilities will be relatively far away, so having takeaway stores near home won't mean the same thing as it does to someone living in an urban area if both are measured on the same scale. And in rural areas close to natural landscapes, parks in the immediate neighbourhood may be less important as a potential site of PA than they are for people in the middle of a city. We therefore restricted the analysis to the 86% of the UK Biobank cohort living in areas that are classified by the Office of National Statistics as urban (specifically, where a person's home postcode is located within a city or a town with a population of at least 10,000 people).

Participants without complete data on all covariates were excluded from analysis. Approximately three percent of individuals were missing data on their neighbourhood environment. Data for all other variables were missing at a frequency of <2%, with the exception of income (14.9% missing). The final complete case sample comprised 345, 269 individuals.

Sensitivity analyses

Although BMI is a very widely used measure of adiposity, other objective measures may be better predictors of adiposity-related ill-health in some segments of the population, and all measures have their own strengths and weaknesses. We checked for consistency of our findings across alternative measures of adiposity, by repeating the analyses for waist circumference and body fat percentage rather than BMI. To examine the impact of our decision to exclude non-urban participants rather than adjust models for urbanicity, we repeated the primary analyses on the full urban and non-urban sample combined, adjusting for urban/non-urban status. A proximity measure of takeaway stores (distance from home address to nearest store) was also available in the dataset so we also checked whether our results were sensitive to the measure of the fast-food environment. Although density and proximity measures of the UK food environment have been shown to be correlated, they are nonetheless theoretically distinct constructs (Burgoine et al., 2013).

Ethics approval

As part of an approved UK Biobank research project, the study is covered by the ethics approval granted to UK Biobank by the North West Multi-centre Research Ethics Committee (reference number 16/NW/0274). Institutional ethics approval was also granted via the London School of Hygiene and Tropical Medicine's Observational/Intervention Research Ethics Committee in September 2016 (LSHTM Ethics Reference 11897).

RESULTS

The mean BMI of the analytical sample was 27·5kg/m², and the median number of formal PA facilities within a 1000m street-network distance of participants' homes was two, with just over a quarter of participants having no facilities close to home (Table 1). Participants had a median of one park or other public green space within one kilometre of home, and 41% had no parks near home. Half the sample had no takeaway stores within one kilometre of home, while 23% of the sample lived within a kilometre of three or more such stores.

[Insert Table 1 here]

There is a strong positive correlation between number of parks and number of formal PA facilities, with 58% of people who have no formal PA facilities within 1km of home also having no parks close to home, while 41% of those with at least four PA facilities nearby also have at least three parks nearby (Table 2). Number of takeaway/fast-food stores is also correlated with access to formal PA facilities, reflecting the clustering of commercial and public services in more densely populated areas. Seventy percent of people with no nearby PA facilities also have no takeaway stores within 1km of their home, compared to only one third of people with at least four PA facilities having no takeaways near home.

[Insert Table 2 here]

Comparison of models with and without a product term for the interaction between formal PA facilities and parks suggests the number of parks within one kilometre of a person's home does modify the association between the formal PA environment and BMI ($P_{interaction}$=0.021). Figure 1 shows estimates of the association between formal PA facilities and BMI, stratified by urban park availability. As hypothesised, stratification shows that the association between PA facilities and BMI is weak in the areas with the most urban parks, while in contrast there is a clear association between lower BMI and higher density of formal PA facilities in the areas with no parks (Figure 1). People living in areas with no parks have a mean BMI 0.21 kg/m^2 smaller if they have 2-3 formal PA facilities near home, and 0.48kg/m^2 smaller if they have at least four PA facilities near home, when compared with those who have neither PA facilities nor parks within a kilometre of home.

[Insert Figure 1 here]

There is also good statistical evidence that the PA environment-BMI association is modified by availability of takeaway/fast-food stores ($P_{interaction}$=0.014). In line with our second hypothesis, stratified results showed that among people living in areas with at least three takeaway stores, the association between density of nearby formal PA facilities and BMI is considerably weaker than it is among those who live in areas with fewer or no takeaway stores (Figure 2). Among people with three or more takeaways near home, those with at least four PA facilities near home have a mean BMI 0.22 kg/m^2 smaller than those with no PA facilities within a kilometre of home, but among people with none, one or two takeaways near home, the magnitude of that effect is more than doubled.

[Insert Figure 2 here]

Results were broadly consistent across alternative measures of adiposity: very similar patterns of effect-measure modification to those we observed for BMI were also present for waist circumference and particularly body fat percentage (see Supplementary Material). When we included respondents living in non-urban areas and adjusted for urban/non-urban status, the patterns across stratum-specific models mirrored those observed in the urban-only sample. Statistical evidence of an interaction was similar (for park availability) or stronger (for takeaway store availability) (see Supplementary Material). The primary results were also replicated when using proximity to takeaway store as an alternative measure of the fast-food environment – in that case the primary association between PA environment and BMI was notably weaker among people living within 500m of a store compared with those living further away ($P_{interaction}$ < 0.001).

DISCUSSION

In this study we examined whether the association between neighbourhood availability of formal PA facilities and BMI is moderated by the availability of parks and takeaway food stores in the neighbourhood environment. We found evidence to support the presence of environmental effect-measure modification in this large sample of mid-life adults from across the UK. In stratified models we observed that the relationship between greater access to formal PA facilities and lower BMI is stronger among people living in areas with fewer urban parks and other public open/green spaces than it is among people with more of these, where there is likely to be greater opportunity for informal, outdoor PA. Furthermore, the association between the formal PA environment and BMI is of a much smaller magnitude among people living close to several takeaway stores than it is among those who do live near fewer or no such stores.

These findings suggest that locating formal PA facilities close to residential areas has the potential to reduce BMI among local residents, but that other contextual features of the neighbourhood are likely to influence these potential benefits. To date, the formal PA environment has received less research attention than some other neighbourhood characteristics, particularly in Europe, and findings have been inconsistent (Mackenbach et al., 2014; Sallis et al., 2012). Our deeper examination of its relationship with BMI sheds new light on settings where intervening on the formal PA environment may be more beneficial, and how other neighbourhood attributes could be modified to boost the potential for local residents to benefit from local formal PA facilities.

While we cannot infer causality from this cross-sectional observational study, our results suggest that increasing the availability of formal PA facilities may have the most potential to reduce population obesity in areas that have the lowest densities of parks and least exposure to takeaway/fast-food stores. This is consistent with the hypothesis that in areas with fewer parks and other green spaces, formal PA facilities provide valuable opportunities for PA that are otherwise lacking. Meanwhile, formal PA facilities may have limited influence in areas with takeaway stores close to people's homes – even if they do serve to increase PA there, our findings suggest the positive benefits for body weight may be dampened by the influence of an unhealthy food environment. As a public health intervention, the introduction of PA resources such as gyms, swimming pools and other sports facilities in neighbourhoods with numerous takeaway stores may be ineffective unless coupled with other interventions aimed at minimising the influence of those stores. In urban areas well served by parks, interventions involving formal PA facilities may not be a priority and a focus on other environmental interventions may be more effective in improving population health. More causally focused study designs are needed to confirm these implications.

Our findings also highlight the possibility that closer examination of the relationships between other neighbourhood exposures and obesity-related outcomes may also reveal effect heterogeneity according to additional characteristics of the area. Such heterogeneity may, at least partially, explain inconsistent results across studies and settings. We examined only three neighbourhood characteristics, motivated by two plausible effect modification hypotheses. Similar interactions may also exist between other neighbourhood characteristics.

PA environment effects on obesity in the UK have sometimes been shown to be concentrated in individuals with higher incomes (Mason et al., 2018) or more education (Hobbs et al., 2018b). While we have not examined an additional interplay with socioeconomic status in this paper, it is likely that an important caveat applies to our findings: that the potential for the benefits of local access to formal PA facilities to be maximised via a supportive broader neighbourhood environment relies on PA facilities being accessible and affordable for all.

Strengths & Limitations

These findings are a novel contribution to this area of research. To our knowledge, no other studies in the UK, and few outside it, have explicitly examined modification of the association between the formal neighbourhood PA environment and adiposity (or any other obesity-related outcome) by other neighbourhood built environment characteristics. One similar study in the United States concluded that combined changes to the food and PA environments would have stronger and more consistent effects on BMI than changes that addressed only one dimension or the other. Our findings provide similar evidence in a European context (Boone-Heinonen et al., 2013). Others have examined composite measures of neighbourhood obesogenicity or other similar constructs, and while such research importantly recognises and draws attention to the complex and multidimensional nature of neighbourhood environments, it lends itself to more general conclusions about the importance of holistic healthy urban planning, rather than moving towards specific policy recommendations. Furthermore, these studies typically rely on data-driven approaches such as latent class analysis, and this makes generalising to other populations challenging. Here, although our findings require confirmation using longitudinal data and more causally focussed methods, the results provide evidence in support of two clearly defined and theoretically grounded effect modification hypotheses, and point to prioritisation of built environment interventions that take into account local context. Our findings were also consistent across multiple adiposity measures, and robust to various modelling choices including operationalisation of the effect modifiers, as shown in the sensitivity analyses we performed.

UK Biobank is a very large and geographically diverse cohort, providing unique opportunities in this field of research. However, as a sample it may not be representative of the broader population, being based on only a 5.5% response rate, and indeed, the sample does show some evidence of 'healthy volunteer' bias (Fry et al., 2017). A further potential source of selection bias is the exclusion of a large number of observations without data on household income. With its focus on adults in mid-life, we also cannot generalise our conclusions beyond this age range. Due to the cross-sectional nature of this study it is impossible to draw strictly causal inferences about these patterns of association, but the results do lend support to two *a priori* hypotheses about plausible interactive effects of multiple aspects of the neighbourhood environment. There remains the possibility that the observed main associations are driven by people with lower BMIs self-selecting into 'healthier' neighbourhoods. Studies that have directly examined the influence of self-selection on neighbourhood-health effects have reached inconsistent conclusions about the likely bias this may induce (Grafova et al., 2014; James et al., 2015; McCormack and Shiell, 2011). For those fortunate enough to have substantial choice over where they live, the presence of formal PA facilities alone is unlikely to be a major governing factor in that choice, but the presence of such facilities is likely to coincide with other facilities that may enhance the desirability of a neighbourhood, including parks and other green space (as we observed in Table 2). That said, in this sample, the individuals living in neighbourhoods with high densities of parks and PA facilities are, contrary to expectation, not necessarily those with the highest incomes, or living in the least deprived postcodes in the study.

Due to the size of the sample and the breadth of the neighbourhood characterisation, large-scale automated processes were used to derive the environmental metrics on which we have relied here (Sarkar et al., 2015). While the best readily available for conducting these analyses at scale, those metrics are of varying quality, accuracy and suitability. It should be noted that the takeaway store measure in particular may be susceptible to some misclassification error: the source database is supplied by local authorities and might misclassify some fast-food outlets as restaurants rather than takeaways. In addition, the measure of park availability does not account for the quality of those spaces, and we also do not have any information about whether respondents actually use their local PA facilities. There is also a possibility that if any of the main associations are confounded in one stratum of the potential effect modifier and not another, we may erroneously infer effect modification when none is present (Kamangar, 2012).

These findings therefore provide preliminary observational evidence for plausible interplay between multiple aspects of the built environment in the UK, but further research using more causally focussed approaches such as longitudinal or quasi-experimental study designs is needed. An additional implication of our findings is that evaluations of PA environment interventions, particularly those pertaining to formal PA facilities, may be underestimating the impact of the intervention if possible moderation by local park availability and food environments are ignored.

CONCLUSIONS

Residential neighbourhoods are complex and multidimensional and the examination of the effect of individual environmental characteristics on obesity in isolation overlooks this complexity. Here we examined whether some neighbourhood characteristics modify the effect of others to better understand how they may operate in concert to influence BMI. Our findings suggest that formal PA facilities may buffer against a lack of informal, green resources for PA such as parks, in areas where the latter are scarce, but that potential benefits of formal PA facilities in terms of BMI may be undermined by the presence of takeaway/fast-food stores close to home. Reducing the prevalence of unhealthy food stores in areas with formal PA resources, and prioritising the location of formal PA facilities in places without public parks, may maximise the potential for PA facilities to influence BMI. An approach to urban planning that takes into account moderating effects of other neighbourhood characteristics is required in order to maximise the population health benefits of the urban built environment.

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Table 1. Summary of sample characteristics (N=345 269)

BMI (kg/m2)	Mean (SD)	27.5 (4.8)
Formal PA environment		
Number of facilities in 1km buffer	Median (IQR)	2 (0 - 4)
0	n (%)	94 717 (27.4)
1	n (%)	67 570 (19.6)
2-3	n (%)	86 006 (24.9)
4 or more	n (%)	96 976 (28.1)
Park availability		
Number of parks and other public/open green spaces in 1km buffer	Median (IQR)	1 (0 - 3)
0	n (%)	142 491 (41.3)
1 or 2	n (%)	108 803 (31.5)
3 or more	n (%)	93 975 (27.2)
Fast food environment		
Number of takeaway/fast-food stores in 1km buffer	Median (IQR)	0 (0 – 2)
0	n (%)	174 405 (50.5)
1 or 2	n (%)	91 030 (26.4)
3 or more	n (%)	79 834 (23.1)
Covariates		
Age	Mean (SD)	56.1 (8.1)
Sex (female)	n (%)	181 896 (52.7)
Ethnicity		
White	n (%)	327 583 (94.9)
South Asian/South Asian British	n (%)	5 295 (1.5)
Black/Black British	n (%)	5 323 (1.5)
Chinese/other(non-South) Asian	n (%)	2 209 (0.6)
Mixed: White/Black	n (%)	733 (0.2)
Mixed: White/Asian	n (%)	598 (0.2)
Mixed: Detail unknown	n (%)	709 (0.2)
Other	n (%)	2 819 (0.8)
Income		
Less than 18,000	n (%)	81 544 (23.6)
18,000 to 30,999	n (%)	88 756 (25.7)
31,000 to 51,999	n (%)	89 795 (26.0)
52,000 to 100,000	n (%)	68 051 (19.7)
Greater than 100,000	n (%)	17 123 (5.0)
Education		
College or University degree	n (%)	117 441 (34.0)
A levels/AS levels or equivalent	n (%)	39 526 (11.5)

O levels/GCSEs or equivalent	n (%)	74 022 (21.4)
CSEs or equivalent	n (%)	19 594 (5.7)
NVQ or HND or HNC or equivalent	n (%)	23 404 (6.8)
Other professional qualifications	n (%)	17 390 (5.0)
None of the above	n (%)	53 892 (15.6)
Employment status		
Paid employment or self-employed	n (%)	210 595 (61.0)
Retired	n (%)	106 508 (30.9)
Unable to work	n (%)	10 782 (3.1)
Unemployed	n (%)	5 339 (1.6)
Home duties/carer/student/volunteer/other	n (%)	12 045 (3.5)
Area deprivation (2001 Townsend index)	Median (IQR)	-2.0 (-3.6 - 0.7)
Residential density (residential address points per 1km street network buffer)	Median (IQR)	2 152 (1 352 – 3 344)
Assessment area		
Manchester	n (%)	11 012 (3.2)
Oxford	n (%)	7 328 (2.1)
Cardiff	n (%)	12 736 (3.7)
Glasgow	n (%)	14 656 (4.2)
Edinburgh	n (%)	11 714 (3.4)
Stoke	n (%)	12 283 (3.6)
Reading	n (%)	18 217 (5.3)
Bury	n (%)	20 192 (5.9)
Newcastle	n (%)	26 432 (7.7)
Leeds	n (%)	30 831 (8.9)
Bristol	n (%)	27 796 (8.1)
Central London	n (%)	8 241 (2.4)
Nottingham	n (%)	20 670 (6.0)
Sheffield	n (%)	20 849 (6.0)
Liverpool	n (%)	25 037 (7.3)
Middlesborough	n (%)	12 954 (3.8)
Hounslow	n (%)	21 321 (6.2)
Croydon	n (%)	21 126 (6.1)
Birmingham	n (%)	20 060 (5.8)
Swansea	n (%)	1 503 (0.4)
Wrexham	n (%)	311 (0.1)

Table 2. Bivariate associations between neighbourhood characteristics

	Availability of parks and other open/green spaces							
	No parks		One or two parks		≥3 parks		Total	
Formal PA facilities	n	%	n	%	n	%	n	%
0	54,536	57.58	25,196	26.60	14,985	15.82	94,717	100.00
1	31,684	46.89	20,888	30.91	14,998	22.20	67,570	100.00
2-3	32,035	37.25	29,423	34.21	24,548	28.54	86,006	100.00
4 or more	24,236	24.99	33,296	34.33	39,444	40.67	96,976	100.00
Total	*142,491*	*41.27*	*108,803*	*31.51*	*93,975*	*27.22*	*345,269*	*100.00*
	Availability of takeaway/fast-food stores							
	No stores		One or two stores		≥3 stores		Total	
Formal PA facilities	n	%	n	%	n	%	n	%
0	66,096	69.78	20,964	22.13	7,657	8.08	94,717	100.00
1	37,621	55.68	19,149	28.34	10,800	15.98	67,570	100.00
2-3	38,499	44.76	26,278	30.55	21,229	24.68	86,006	100.00
4 or more	32,189	33.19	24,639	25.41	40,148	41.40	96,976	100.00
Total	*174,405*	*50.51*	*91,030*	*26.36*	*79,834*	*23.12*	*345,269*	*100.00*

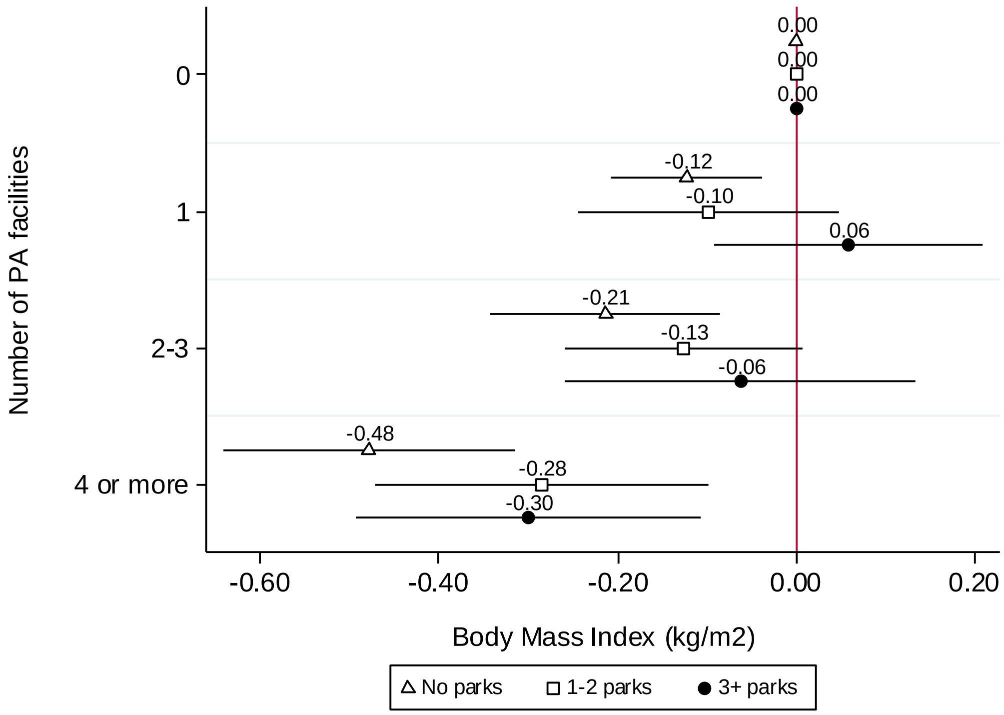

Figure 1. Association between number of formal PA facilities and BMI, stratified by park availability

Figure shows park availability-stratified, fully adjusted mean differences in BMI and associated 95% CIs from multilevel linear regression models. The dashed line at zero represents the reference category (no physical activity facilities with 1km of home). Models are adjusted for age, sex, ethnicity, area deprivation, individual socioeconomic characteristics (income, education, and employment status), residential density, and takeaway store availability.

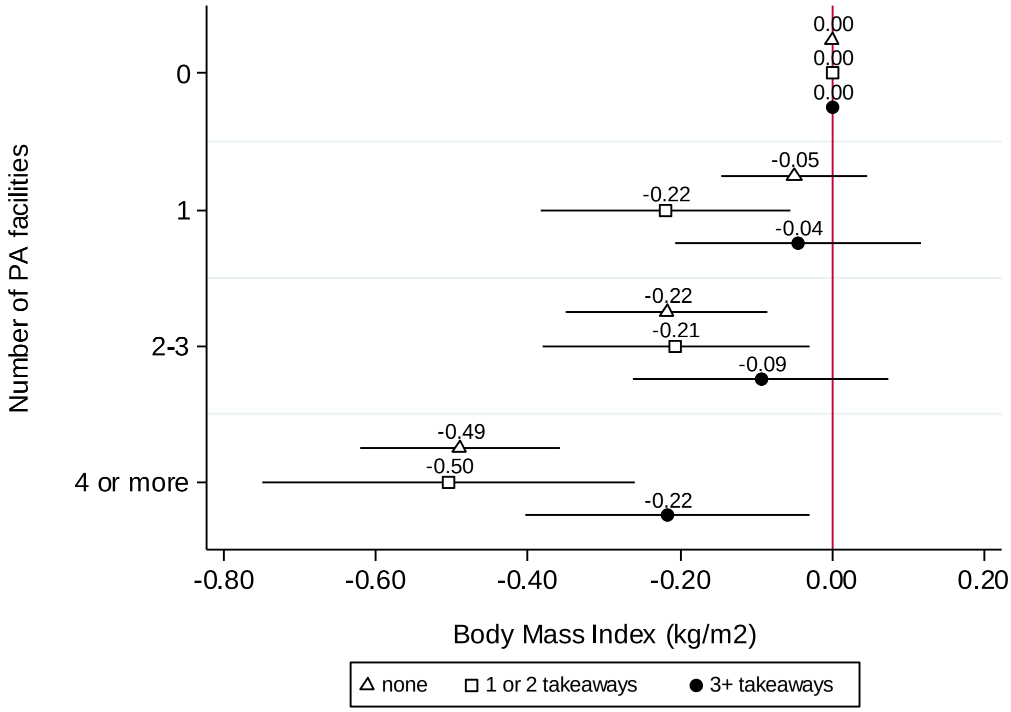

Figure 2. Association between number of formal PA facilities and BMI, stratified by takeaway store availability.

Figure shows takeaway availability-stratified, fully adjusted mean differences in BMI and associated 95% CIs from multilevel linear regression models. The dashed line at zero represents the reference category (no physical activity facilities with 1km of home). Models are adjusted for age, sex, ethnicity, area deprivation, individual socioeconomic characteristics (income, education, and employment status), residential density, and park availability.

Acknowledgements

This research has been conducted using the UK Biobank Resource under Application Number 17380. The authors acknowledge the work of the UK Biobank research team, including those who generated the UK Biobank Urban Morphometric Platform, and thank all the UK Biobank participants. KM was funded by a Commonwealth Scholarship Commission PhD Scholarship (AUCR-2015-40). SC is supported by Health Data Research UK.

Highlights

- Neighbourhoods are multi-dimensional; dimensions may interact to influence health.
- Stronger association of PA facility availability and lower BMI when no local parks.
- Weaker association between PA facilities and BMI when more takeaways near home.
- Formal PA facilities may buffer against a lack of informal, green spaces for PA.
- Benefits of PA facilities may be undermined by unhealthy local food environments.

KM designed the analysis with input from SC and NP. KM undertook the data management, statistical analysis and writing of the manuscript. SC and NP contributed to the interpretation of results and drafting of the manuscript. All authors approved the final submitted version.