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RESEARCH

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Examining the interaction of fast-food outlet exposure and income on diet and obesity: evidence from 51,361 UK Biobank participants

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Abstract

Background: Household income (as a marker of socioeconomic position) and neighbourhood fast-food outlet exposure may be related to diet and body weight, which are key risk factors for non-communicable diseases. However, the research evidence is equivocal. Moreover, understanding the double burden of these factors is a matter of public health importance. The purpose of this study was to test associations of neighbourhood fast-food outlet exposure and household income, in relation to frequency of consumption of processed meat and multiple measures of adiposity, and to examine possible interactions.

Methods: We employed an observational, cross-sectional study design. In a cohort of 51,361 adults aged 38–72 years in Greater London, UK, we jointly classified participants based on household income (£/year, four groups) and GIS-derived neighbourhood fast-food outlet proportion (counts of fast-food outlets as a percentage of all food outlets, quartiles). Multivariable regression models estimated main effects and interactions (additive and multiplicative) of household income and fast-food outlet proportion on odds of self-reported frequent processed meat consumption (> 1/week), measured BMI (kg/m^2), body fat (%), and odds of obesity (BMI ≥ 30).

Results: Income and fast-food proportion were independently, systematically associated with BMI, body fat, obesity and frequent processed meat consumption. Odds of obesity were greater for lowest income participants compared to highest (OR = 1.54, 95% CI: 1.41, 1.69) and for those most-exposed to fast-food outlets compared to least-exposed (OR = 1.51, 95% CI: 1.40, 1.64). In jointly classified models, lowest income and highest fast-food outlet proportion in combination were associated with greater odds of obesity (OR = 2.43, 95% CI: 2.09, 2.84), with relative excess risk due to interaction (RERI = 0.03). Results were similar for frequent processed meat consumption models. There was no evidence of interaction on a multiplicative scale between fast-food outlet proportion and household income on each of BMI (P = 0.230), obesity (P = 0.054) and frequent processed meat consumption (P = 0.725).

Conclusions: Our study demonstrated independent associations of neighbourhood fast-food outlet exposure and household income, in relation to diet and multiple objective measures of adiposity, in a large sample of UK adults. Moreover, we provide evidence of the double burden of low income and an unhealthy neighbourhood food environment, furthering our understanding of how these factors contribute jointly to social inequalities in health.

Keywords: Fast-food outlet exposure, Household income, Adiposity, Processed meat consumption, Interaction, UK biobank

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Background

Unhealthy diet and high body weight are key modifiable risk factors for non-communicable diseases (NCDs) such as cardiovascular disease, type-2 diabetes and some cancers. According to the WHO's Global Burden of Disease study, dietary risks and high body weight are two of the top three contributors to the number of years suffered with disability and morbidity in the UK [1]. Food-related ill health in the UK, driven by unhealthy diet, contributes to 10% of the combined mortality and morbidity burden [2]. Processed meat consumption, in particular, is associated with higher incidence of type-2 diabetes, coronary heart disease [3–5], and certain cancers [6].

Social inequalities in diet and obesity are established across markers of socioeconomic position (SEP) such as education, income (including *household* income [7]) and occupation [8], and may be contributing to recognised inequalities in NCD risk [9, 10]. Explanations include having less knowledge about healthy eating and fewer cooking skills [11, 12], and less time for cooking at home among socially disadvantaged groups [13]. Low-income groups, in particular, are also more price-sensitive [14], spending less on food overall and per calorie than other social groups [15].

In addition to individual-level socioeconomic determinants, neighbourhood food environments are also potentially important influences on diet and weight [16, 17], although the research evidence remains equivocal [18, 19]. Neighbourhoods where the mix of food retailing is biased towards a high proportion of fast-food outlets may be especially influential [20–22] – where fast-food might be perceived as the easier choice and therefore used more, and where greater fast-food access is not simply a function of greater access to all types of food outlet [23]. As a result, recent studies have increasingly situated fast-food access within the wider context of overall neighbourhood food retailing through adopting relative as opposed to absolute measures of exposure [24–30]. Easier access to fast-food outlets may facilitate the consumption of energy dense, nutrient poor fast foods [31, 32], which have been linked prospectively to excess weight gain [33], and associated with other cardio-metabolic risk factors [34]. Despite some fast-food outlets selling 'healthier' foods than others, at a population level, visits to and use of fast-food outlets has been linked to weight gain over time [35], and consumption of a less healthy diet and greater odds of obesity [36], respectively.

Fast-food access may also contribute to established social inequalities in fast-food consumption and weight [37]. Deprived neighbourhoods have generally greater numbers of fast-food outlets [16, 38], and there is evidence that the influence of neighbourhood environments vary by educational attainment as a marker of SEP [39]. However, there has been little research on the interaction between fast-food access and household income, which may hold implications for diet and weight via different mechanisms. Low-income consumers, in particular, may be disproportionately affected by the presence of fast-food outlets [14], which serve large portions of energy-dense, calorific foods at low prices [40].

With mounting evidence of the adverse influence of fast-food outlets on health and the abundance of fast-food outlets in deprived areas, the proliferation of these outlets has become a public health concern. Policies are now in place in many regions of the UK to stem growth in this retail sector [41], while in the US, a moratorium was placed on the opening of new fast-food outlets in South Los Angeles, for example [42]. At the same time, more empirical research is needed to better understand the magnitude of influence of fast-food outlets on health and their contribution to social inequalities.

Using a large sample from the UK Biobank, the aim of this study was to establish the independent and combined associations (including interactions) of each of neighbourhood fast-food access and household income, with processed meat consumption and multiple measures of adiposity.

Methods

Study sample

UK Biobank is a cross-sectional, observational cohort study, which recruited 502,656 people between 2006 and 2010. Those registered with the National Health Service and living within 25 miles of the 22 UK assessment centres were invited to participate in the study. The UK Biobank study design has been reported in detail previously [43]. UK Biobank received ethical approval from the North West Multi-centre Research Ethics Committee (MREC), the Community Health Index Advisory Group (CHIAG) and the Patient Information Advisory Group (PIAG).

Exposure – Neighbourhood fast-food outlet proportion and household income

For participants attending the three UK Biobank Greater London assessment centres of Barts, Hounslow and Croydon (n = 68,850) [44], neighbourhood food outlet exposure metrics were derived in 2014 using 2012 UKMap data courtesy of The GeoInformation Group [44]. UKMap data are collected for Greater London via field survey, are updated twice per year, and have a stated spatial accuracy of ±1 m. Numbers of outlets by type were summed within a 1 mile straight-line radius (circular) 'neighbourhood' buffer of participants' geocoded home street address, a distance equating to a 15-min walk for an average adult and previously linked to actual food shopping behaviours [45]. Fast-food outlets were described in UKMap data as 'take-away' outlets, defined as outlets selling food and/or drink for consumption off the premises (excluding general and convenience stores, coffee shops and supermarkets). We expressed the number of neighbourhood fast-food outlets as a proportion (%) of all neighbourhood food outlets (sum of counts of fast-food outlets, supermarkets, restaurants, convenience stores, cafes, and specialist stores). Household income (£/year) was self-reported by UK Biobank participants using the following income brackets: <£31,000, £31,000-£51,999, £52,000-£100,000, >£100,000.

Outcomes – Processed meat consumption and adiposity

Participants completed a dietary screener, which included questions on the consumption frequency of a limited range of foods from major food groups, as part of a questionnaire relating to their general lifestyle during baseline visits to UK Biobank assessment centres. Processed meat consumption (defined by UK Biobank as consumption of foods such as bacon, ham, sausage, meat pies, kebabs, burgers, chicken nuggets) served as our primary dietary outcome, as a proxy for fast-food consumption, because this type of food is commonly available in fast-food outlets [32, 46, 47]. Processed meat consumption frequency was measured by UK Biobank as follows: "How often [do you] eat processed meats…?", with six possible response options from "Never" to "Once or more daily". For this analysis, frequencies were dichotomised, with those reporting more than once per week defined as frequent processed meat consumers. Consumption of fast-food approximately once per week has been associated with cardio-metabolic risk [6], akin to the risk associated with frequent processed meat consumption [3–6], as well as with increased body weight over time [33]. Nearly a quarter of UK adults consume fast-foods at home at least weekly [48]. Body mass index (BMI, kg/m^2) was calculated from measured height and weight, with participants having a BMI ≥ 30 classified as obese. Body fat (%) was measured using bioelectrical impedance analysis, with the Tanita BC418MA body composition analyser (Tanita, Amsterdam).

Statistical analysis

We used multivariable linear and binomial logistic regression models to examine associations of proportion of fast-food outlets in the home neighbourhood and household income, in relation to BMI, percentage body fat, odds of frequent processed meat consumption and obesity. We also calculated adjusted risk ratios (RRs) for obesity and processed meat consumption outcomes, which are presented in Additional files. We tested for interaction of fast-food outlet proportion (quartiles) and household income (four groups) on a multiplicative scale using an F-test for linear models and a likelihood ratio test for logistic models.

We also tested for interaction on an additive scale using relative excess risk due to interaction (RERI). Following STROBE reporting guidelines [49] we estimated the separate and combined associations of neighbourhood fast-food outlet proportion and household income on the odds of being obese, and of frequent processed meat consumption using binomial logistic regressions with a single reference category. RERI was calculated using odds ratios (ORs) as follows:

$$\mathrm{RERI} = \mathrm{OR}_{11} - \mathrm{OR}_{10} - \mathrm{OR}_{01} + 1$$

where ORs are for being obese or a frequent consumer of processed meat, for those with lowest incomes and most-exposed to fast-food outlets (OR_{11}), those with lowest incomes and least-exposed (OR_{10}) and those with highest incomes and most-exposed (OR_{01}) [49, 50]. RERI scores > 0 suggest positive interaction, or a greater risk due to interaction than would be attributable to the additive effects of each of these factors in isolation [49].

Adjusted models included the following covariates, also reported in the UK Biobank lifestyle questionnaire: age, sex, ethnicity, smoking status, number of household residents, highest educational attainment (five categories), UK Biobank assessment centre attended, and the sum of counts of supermarkets, restaurants, convenience stores, cafes and specialist stores within 1 mile Euclidean (straight-line) radius buffers of home address. To establish independent associations, both household income and fast-food proportion models were mutually adjusted.

This was a complete case analysis, with the Greater London UK Biobank sample restricted to those with complete data across all outcomes and covariates of interest (Additional file 1). Exclusions resulted in final sample sizes for BMI, processed meat consumption and percentage body fat models of 51,361, 51,090 and 50,766, respectively. Analytic samples remained representative of the UK Biobank participants attending assessment centres in Greater London across key variables (Additional file 2). Participant data were collected 2006–2010 and analysed in 2016 using Stata 14 (StataCorp LP., Texas).

Results

Sample characteristics

Descriptive statistics, overall and stratified by quartiles of neighbourhood fast-food outlet proportion, are shown in Table 1 (and also stratified by household income in Additional file 3). The sample had a mean age of 56 years (aged 38–72 years overall), with 44% of participants' men and approximately 80% identifying their ethnicity as white. Mean BMI and body fat were 26.9 kg/m^2 and 30.8% respectively, with 21.8% obese, and 27.7% of the sample consuming processed meat more than once per week. Fast-food outlets constituted 18.4% of neighbourhood food

Table 1 Characteristics of participants in the UK Biobank sample, UK ($n = 51,361$), overall and stratified by quartiles of fast-food outlet proportion

	Quartiles of fast-food outlet proportion				
	Q1 (0–13%)	Q2 (13–17%)	Q3 (17–24%)	Q4 (24–45%)	All
Age, years	56.5 (8.2)	55.7 (8.2)	55.6 (8.2)	56.0 (8.2)	56.0 (8.2)
Men (no. (%))	5552 (43.2)	5621 (43.8)	5709 (44.5)	5643 (43.9)	22,525 (43.9)
Ethnicity (no. (%))					
White	11,430 (89.0)	10,496 (81.8)	9601 (74.8)	9405 (73.2)	40,932 (79.7)
Asian or Asian British	359 (2.8)	966 (7.5)	1322 (10.3)	1187 (9.2)	3834 (7.5)
Black or Black British	350 (2.7)	612 (4.8)	1028 (8.0)	1369 (10.7)	3359 (6.5)
Other	351 (2.7)	402 (3.1)	483 (3.8)	448 (3.5)	1684 (3.3)
Don't know or Prefer not to say	84 (0.6)	96 (0.7)	124 (1.0)	102 (0.8)	406 (0.8)
Household income, £/year (no. (%))					
< 31,000	3379 (26.3)	3859 (30.1)	4563 (35.5)	4798 (37.4)	16,599 (32.3)
31,000 – 51,999	2396 (18.7)	2657 (20.7)	2756 (21.5)	2881 (22.4)	10,690 (20.8)
52,000 – 100,000	3057 (23.8)	3034 (23.6)	2563 (20.0)	2415 (18.8)	11,069 (21.6)
> 100,000	2409 (18.8)	1504 (11.7)	876 (6.8)	591 (4.6)	5380 (10.5)
Don't know or Prefer not to say	1606 (12.5)	1779 (13.9)	2083 (16.2)	2155 (16.8)	7623 (14.8)
Highest education (no. (%))					
Compulsory (≤11 y of education) or Other[a]	2074 (16.1)	2703 (21.1)	3675 (28.6)	4286 (33.4)	12,738 (24.8)
Further (12–13 y of education)	1680 (13.1)	1779 (13.9)	2039 (15.9)	2224 (17.3)	7722 (15.0)
Higher (> 13 y of education)	8956 (69.7)	8151 (63.5)	6865 (53.5)	6085 (47.4)	30,057 (58.5)
Prefer not to say	137 (1.1)	200 (1.6)	262 (2.0)	245 (1.9)	844 (1.6)
Current or ex-smoker (no. (%))	6304 (49.1)	6109 (47.6)	5759 (44.8)	5587 (43.5)	23,759 (46.3)
Anthropometric and Diet Outcomes					
BMI, kg/m^2	26.1 (4.5)	26.6 (4.8)	27.3 (5.0)	27.6 (5.0)	26.9 (4.9)
Body Fat, %	29.8 (8.3)	30.4 (8.4)	31.3 (8.7)	32.0 (8.7)	30.8 (8.6)
Obese, BMI ≥ 30 (no. (%))	2102 (16.4)	2564 (20.0)	3136 (24.4)	3401 (26.5)	11,203 (21.8)
Frequent processed meat consumption[e]	3239 (25.2)	3464 (27.0)	3647 (28.4)	3885 (30.3)	14,235 (27.7)
Food Environment Exposures[b]					
Fast-food outlets	35.7 (30.3)	46.5 (30.2)	40.1 (27.2)	34.5 (16.9)	39.2 (27.1)
Other food outlets[c]	400.6 (422.0)	266.1 (177.0)	161.6 (114.7)	84.9 (46.5)	228.3 (265.0)
Fast-food outlet proportion, %[d]	9.1 (2.9)	15.0 (1.2)	20.1 (2.1)	29.4 (3.5)	18.4 (7.9)

Data are mean (standard deviation) unless otherwise stated; percentages represent column percentage | [a] Those reporting 'Other' education will include those with no and non-British qualifications | [b] Counts of food outlets within 1 mile Euclidean (straight line) radius buffers of home address | [c] Sum of counts of Supermarkets, Restaurants, Convenience stores, Cafes and Specialist stores | [d] Fast-food outlets expressed as a proportion of the sum of counts of Fast-food outlets, Supermarkets, Restaurants, Convenience Stores, Cafes and Specialist stores | [e] Frequent consumption was defined as more than once per week; processed meat includes bacon, ham, sausages, meat pies, kebabs, burgers, chicken nuggets

retail on average, corresponding to a mean of 39.2 fast-food outlets. There were systematic differences in demographic and other variables across fast-food exposure groups. In particular, participants in higher exposure groups were less likely to be white, reported lower incomes and fewer educational qualifications. For the quarter of participants most-exposed to fast-food outlets, 24–45% of neighbourhood food vendors were fast-food outlets. Participants with greatest fast-food exposure tended to have higher BMI, higher intake of processed meat and were more likely to be obese.

Associations of neighbourhood fast-food outlet proportion with BMI, obesity and frequent processed meat consumption

Greater BMI, percentage body fat, odds of obesity, and frequent processed meat consumption, were each positively associated with a higher proportion of fast-food outlets in neighbourhoods. In the unadjusted model 1, those with the highest proportion of fast-food outlets (Q4) were 1.54 kg/m^2 heavier (95% CI: 1.42, 1.66; $p < 0.001$) than those with the lowest proportion (Table 2), and had 2.17% higher (95% CI: 1.96, 2.38; $p < 0.001$) body fat (Additional file 4). Adjusting for additional individual-level demographic (model 2), socioeconomic (model 3) and other neighbourhood-level covariates (model 4) attenuated this association. However, those with the highest proportion of fast-food outlets remained on average 0.99 kg/m^2 heavier (95% CI: 0.85, 1.14; $p < 0.001$) than those with the lowest proportion (Table 2) and had 1.37% higher (95% CI: 1.17, 1.56; $p < 0.001$) body fat (Additional file 4) in our most adjusted models, and with a dose-response association at least across the first three quartiles.

In our unadjusted binomial logistic regression model (Table 2), those with the highest proportion of fast-food outlets had 1.84 (95% CI: 1.73, 1.96) greater odds of being obese than not being obese. These associations were attenuated but remained significant after adjustment for potential confounders (models 2–4); in model 4 those with the highest proportion of fast-food outlets had 1.51 (95% CI: 1.40, 1.64) greater odds of being obese, again with a dose-response association at least across the first three quartiles.

Those with the highest proportion of fast-food outlets had 1.28 (95% CI: 1.19, 1.38) greater odds of being frequent processed meat consumers, relative to those with the lowest proportion. Corresponding risk ratios (RRs) for risk of obesity and frequent processed meat consumption related to fast-food proportion were similar in magnitude and again showed evidence of a dose-response association, and are shown in Additional file 5.

Associations of household income with BMI, obesity and frequent processed meat consumption

Greater BMI, percentage body fat, odds of obesity, and frequent processed meat consumption, were each systematically associated with lower household income. In unadjusted models, those with lowest household incomes (<£31,000) were 1.73 kg/m^2 heavier (95% CI: 1.58, 1.88; $p < 0.001$) than those with highest incomes (Table 3); had 3.78% higher (95% CI: 3.52, 4.05; $p < 0.001$) body fat (Additional file 6); and had 2.29 (95% CI: 2.10, 2.49) greater odds of being obese. Significant associations were not observed with processed meat consumption.

Additional covariate adjustment attenuated these associations; however, they remained significant. In our maximally-adjusted models, those with lowest incomes were 0.68 kg/m^2 heavier (95% CI: 0.52, 0.84; $p < 0.001$), had 0.83% higher body fat, had 1.54 (95% CI: 1.41, 1.69) greater odds of being obese, and 1.25 (95% CI: 1.15, 1.35) greater odds of frequent processed meat consumption, compared to those with highest incomes. There was no evidence of interaction on a multiplicative scale between

Table 2 Associations of quartiles of fast-food outlet proportion with body mass index (estimated using a multivariable linear regression model, $n = 51,361$), obesity (estimated using a binomial logistic regression model $n = 51,361$), and frequent consumption of processed meat (estimated using a binomial logistic regression model, $n = 51,090$) in the Greater London UK Biobank sample

		Model 1[a]		Model 2[b]		Model 3[c]		Model 4[d]	
	Quartile[e]	β	95% CI	β	95% CI	β	95% CI	β	95% CI
Difference in BMI (kg/m^2)	Q1 (0.0–12.7%)	ref		ref		ref		ref	
	Q2 (12.7–16.9%)	0.53**	0.41, 0.65	0.48**	0.36, 0.59	0.37**	0.25, 0.49	0.35**	0.23, 0.47
	Q3 (16.9–23.7%)	1.21**	1.09, 1.33	1.04**	0.93, 1.16	0.83**	0.70, 0.95	0.80**	0.67, 0.93
	Q4 (23.7–44.6%)	1.54**	1.42, 1.66	1.30**	1.18; 1.42	1.03**	0.89; 1.17	0.99**	0.85, 1.14
		Model 1[a]		Model 2[b]		Model 3[c]		Model 4[d]	
		OR	95% CI	OR	95% CI	OR	95% CI	OR	95% CI
Odds of obesity (BMI ≥ 30 kg/m^2)	Q1 (0.0–12.7%)	ref		ref		ref		ref	
	Q2 (12.7–16.9%)	1.28**	1.20, 1.36	1.26**	1.18, 1.34	1.20**	1.12, 1.28	1.19**	1.11, 1.27
	Q3 (16.9–23.7%)	1.65**	1.55, 1.76	1.57**	1.48, 1.67	1.43**	1.34, 1.53	1.42**	1.32, 1.52
	Q4 (23.7–44.6%)	1.84**	1.73, 1.96	1.70**	1.60, 1.81	1.53**	1.43, 1.65	1.51**	1.40, 1.64
		Model 1[a]		Model 2[f]		Model 3[c]		Model 4[d]	
		OR	95% CI	OR	95% CI	OR	95% CI	OR	95% CI
Odds of frequent consumption of processed meat[g] (> once per week)	Q1 (0.0–12.7%)	ref		ref		ref		ref	
	Q2 (12.7–16.9%)	1.10*	1.04, 1.16	1.15**	1.08, 1.22	1.10*	1.04, 1.17	1.10*	1.03, 1.16
	Q3 (16.9–23.7%)	1.18**	1.12, 1.25	1.29**	1.22, 1.36	1.19**	1.12, 1.27	1.18**	1.11, 1.26
	Q4 (23.7–44.6%)	1.29**	1.22, 1.37	1.45**	1.36, 1.53	1.30**	1.22, 1.39	1.28**	1.19, 1.38

*$p < 0.05$; ** $p < 0.001$ | [a] Model 1 is an unadjusted model | [b] Model 2 adjusts for age, sex, ethnicity, smoking status | [c] Model 3 additionally adjusts for household income, number in household, highest educational attainment and UK Biobank assessment centre attended | [d] Model 4 additionally adjusts for sum of counts of Supermarkets, Restaurants, Convenience stores, Cafes and Specialist Stores within 1 mile Euclidean (straight line) radius buffers of home address | [e] Q1 = quartile with lowest fast-food outlet proportion in home neighbourhood (min-max %) – Q4 = quartile with greatest fast-food outlet proportion in home neighbourhood (min-max %) | [f] Model 2 adjusts for age, sex, ethnicity | [g] Includes bacon, ham, sausages, meat pies, kebabs, burgers, chicken nuggets

Table 3 Associations of household income with body mass index (estimated using a multivariable linear regression model, $n = 51,361$), obesity (estimated using a binomial logistic regression model, $n = 51,361$), and frequent consumption of processed meat (estimated using a binomial logistic regression model, $n = 51,090$) in the Greater London UK Biobank sample

	Household Income (£/year)	Model 1[a]		Model 2[b]		Model 3[c]		Model 4[d]	
		β	95% CI	β	95% CI	β	95% CI	β	95% CI
Difference in BMI (kg/m²)	> 100,000	ref		ref		ref		ref	
	52,000–100,000	0.71**	0.55, 0.87	0.60**	0.45, 0.76	0.44**	0.29, 0.60	0.33**	0.17, 0.48
	31,000–51,999	1.17**	1.01, 1.33	0.95**	0.80, 1.11	0.67**	0.51, 0.83	0.51**	0.35, 0.67
	< 31,000	1.73**	1.58, 1.88	1.36**	1.21, 1.51	0.85**	0.69, 1.01	0.68**	0.52, 0.84
		Model 1[a]		Model 2[b]		Model 3[c]		Model 4[d]	
		OR	95% CI	OR	95% CI	OR	95% CI	OR	95% CI
Odds of obesity (BMI ≥ 30 kg/m²)	> 100,000	ref		ref		ref		ref	
	52,000–100,000	1.42**	1.29, 1.56	1.37**	1.24, 1.50	1.29**	1.17, 1.41	1.22**	1.11, 1.34
	31,000–51,999	1.70**	1.55, 1.86	1.57**	1.43, 1.72	1.41**	1.28, 1.54	1.32**	1.20, 1.45
	< 31,000	2.29**	2.10, 2.49	2.02**	1.84, 2.20	1.66**	1.51, 1.82	1.54**	1.41, 1.69
		Model 1[a]		Model 2[e]		Model 3[c]		Model 4[d]	
		OR	95% CI	OR	95% CI	OR	95% CI	OR	95% CI
Odds of frequent consumption of processed meat[f] (> once per week)	> 100,000	ref		ref		ref		ref	
	52,000–100,000	1.08*	1.00, 1.16	1.17**	1.09, 1.27	1.13*	1.05, 1.22	1.10*	1.02, 1.19
	31,000–51,999	1.01	0.94, 1.09	1.24**	1.15, 1.34	1.19**	1.10, 1.29	1.14*	1.06, 1.24
	< 31,000	1.01	0.94, 1.08	1.38**	1.28, 1.49	1.30**	1.20, 1.41	1.25**	1.15, 1.35

Measure of interaction (fast-food exposure*household income with difference in BMI) on a multiplicative scale based on an F-test, $P = 0.230$ | * $p < 0.05$; ** $p < 0.001$ | [a] Model 1 adjusts for number in household | [b] Model 2 additionally adjusts for age, sex, ethnicity, smoking status | [c] Model 3 additionally adjusts for highest educational attainment and UK Biobank assessment centre attended | [d] Model 4 additionally adjusts for fast-food outlet proportion and the sum of counts of Supermarkets, Restaurants, Convenience stores, Cafes and Specialist Stores within 1 mile Euclidean (straight line) radius buffers of home address | [e] Model 2 adjusts for age, sex, ethnicity | [f] Includes bacon, ham, sausages, meat pies, kebabs, burgers, chicken nuggets

fast-food outlet proportion and household income on BMI ($P = 0.230$). Corresponding RRs for risk of obesity and frequent processed meat consumption related to household income are shown in Additional file 7.

Combined associations of neighbourhood fast-food outlet proportion and household income with each of obesity and frequent processed meat consumption

There was no evidence of interaction on a multiplicative scale between fast-food outlet proportion and household income on obesity ($P = 0.054$) and frequent processed meat consumption ($P = 0.725$). We observed evidence of interaction on an additive scale using RERI, which for obesity was 0.03 and for frequent processed meat consumption was 0.18. This demonstrated that greater odds of obesity and frequent processed meat consumption were associated with highest fast-food exposure and lowest household income in combination, in excess of the odds associated with either highest fast-food outlet exposure or lowest household income in isolation. Table 4 shows adjusted binomial logistic regression results for each combination of fast-food exposure quartile and level of household income on odds of obesity. Those with the highest proportion of fast-food outlets and lowest income had 2.43 (95% CI: 2.09, 2.84) greater odds of being obese, relative to those with the lowest proportion of fast-food outlets and highest household incomes.

Table 5 shows adjusted binomial logistic regression results for each combination of fast-food outlet proportion quartile and level of household income on odds of frequent processed meat consumption. Those with the highest proportion of fast-food outlets and lowest income had 1.46 (95% CI: 1.29, 1.65) greater odds of consuming processed meats frequently, relative to those with the lowest proportion of fast-food outlets and highest household incomes.

Discussion

In a large UK adult sample, our results showed clear, consistent associations between neighbourhood fast-food outlet proportion and processed meat consumption, as well as proportion in relation to multiple objective measures of adiposity (body mass index and body fat percentage), including odds of obesity, and with some evidence of dose-response observed. We also showed independent associations between household income and each of these outcomes. We found no evidence of multiplicative interaction, suggesting that associations between fast-food proportion and our outcomes were not significantly

Table 4 Additive interaction between quartiles of fast-food outlet proportion and household income on the odds of being obese (BMI ≥ 30 kg/m^2), modelled using a binomial logistic regression model in the UK Biobank sample, UK (n = 51,361)

	Quartiles of fast-food outlet proportion[a]								Fast-food outlet exposure (Q4) within household income strata
	Q1 (0–13%)		Q2 (13–17%)		Q3 (17–24%)		Q4 (24–45%)		
Household Income (£/year)	Obese/ not obese (n)	OR (95% CI)	Obese/ not obese (n)	OR (95% CI)	Obese/ not obese (n)	OR (95% CI)	Obese/ not obese (n)	OR (95% CI)	
> 100,000	264/2145	ref[b]	206/1298	1.30 (1.07, 1.59); P = 0.008[c]	143/733	1.60 (1.27, 2.00); P < 0.001[c]	104/487	1.73 (1.34, 2.23); P < 0.001[c]	1.53 (1.12, 2.08) P = 0.008[d]
52,000–100,000	433/2624	1.27 (1.08, 1.50); P = 0.004[c]	475/2559	1.44 (1.22, 1.69); P < 0.001[c]	494/2069	1.81 (1.53, 2.13); P < 0.001[c]	581/1834	2.26 (1.91, 2.66); P < 0.001[c]	1.69 (1.43, 2.02) P < 0.001[d]
31,000–51,999	389/2007	1.42 (1.20, 1.69); P < 0.001[c]	495/2162	1.64 (1.39, 1.93); P < 0.001[c]	605/2151	1.95 (1.66, 2.29); P < 0.001[c]	724/2157	2.20 (1.87, 2.58); P < 0.001[c]	1.51 (1.27, 1.80) P < 0.001[d]
< 31,000	687/26922	1.67 (1.43, 1.95); P < 0.001[c]	957/2902	2.05 (1.76, 2.39); P < 0.001[c]	1271/ 3292	2.30 (1.98, 2.68); P < 0.001[c]	1401/3397	2.43 (2.09, 2.84); P < 0.001[c]	1.56 (1.37, 1.78) P < 0.001[d]
Household income (< £31,000/year) within takeaway exposure strata		1.58 (1.34, 1.88) P < 0.001[e]		1.36 (1.15, 1.65) P = 0.001[e]		1.49 (1.21, 1.82) P < 0.001[e]		1.53 (1.22, 1.93) P < 0.001[e]	

Measure of interaction (fast-food exposure*household income with odds of obesity) on a multiplicative scale based on a likelihood ratio test, P = 0.054 | Measure of interaction on an additive scale for Q4 fast-food exposure and household income < £31,000 (RERI) = 0.03. RERI scores > 0 suggest positive interaction and departure from additivity | ORs are adjusted for age, sex, ethnicity smoking status, number in household, highest education attainment, UK Biobank assessment centre attended, and the sum of counts of Supermarkets, Restaurants, Convenience stores, Cafes and Specialist Stores within 1 mile Euclidean (straight line) radius buffers of home address | [a] Q1 = quartile with lowest fast-food outlet proportion in home neighbourhood (min – max %) – Q4 = quartile with greatest fast-food outlet proportion in home neighbourhood (% range) | [b] Single reference group; those exposed to the highest proportion of fast-food outlets and with the highest household income | [c] ORs and p values relative to single reference group (ref) | [d] ORs and P values relative to those who were least exposed to fast-food outlets within strata of household income | [e] ORs and P values relative to those with the highest household incomes within strata of fast-food outlet exposure

different across household income groups. However, we demonstrated the magnitude of obesity and frequent processed meat consumption odds within population--subgroups, including the marginally excess odds (evidence of additive interaction) associated with both highest fast-food outlet proportion and lowest income for these outcomes. This double burden of individual-level disadvantage and neighbourhood-level imbalance towards fast-food retail, holds clear implications for public health and understanding the generation and persistence of social inequalities in diet, health and NCD risk [9, 10].

Broadly, we were able to demonstrate a clear relationship between neighbourhood fast-food outlet exposure, diet and body weight, thereby making an important contribution to an equivocal evidence base. Where comparisons can be drawn, the relationships we observed with fast-food exposure were consistent with those of recent research, for the outcomes of unhealthy diet [19, 20, 31, 39, 51], and obesity [18, 19, 24, 28, 30, 31, 39], especially those using a relative measure of fast-food access [20, 24, 25, 28, 30]. A previous UK study observed for those most-exposed to fast-food outlets (relative to those least-exposed) a 0.97 kg/m^2 difference in BMI (our study, $\beta = 0.99$ kg/m^2) and an odds of 2.15 for obesity (our study, OR = 1.51) [31]. Another showed consistent associations, of a 0.90 kg/m^2 difference in BMI across combined home and work neighbourhood fast-food exposure [39]. While a recent study that also used UK Biobank data found comparatively weaker and less consistent associations between fast-food access and multiple measures of adiposity [52], these differences may be explained to some extent by methodological dissimilarities [53]. Mason et al. used an absolute measure of street network proximity to the nearest fast-food outlet, precluding adjustment for wider food environment context, as facilitated through our use of a relative measure of fast-food density. It has been suggested that methodological inconsistencies might explain divergent findings across other recent studies [18, 19, 54–56], examples of which may include: use of proximity as opposed to density; different delineations of neighbourhood extent; use of area- as opposed to person-based exposure measures; and multiple possible aspects of inaccuracy in underpinning food outlet data [57]. Elsewhere, only one previous study has attempted to establish the magnitude of the combined associations of neighbourhood fast-food access and individual-level SEP, with unhealthy diet and adiposity. That study found highest fast-food exposure combined with lowest education to result in a 3.12 greater odds of obesity, relative to those least-exposed and most-educated [39]. In our study, the combination of highest fast-food exposure and lowest income was associated with a 2.43 greater odds of obesity, and a 1.46 greater odds of frequent processed meat consumption, relative to those least-exposed and with highest incomes.

In this sub-group (those most exposed and with lowest incomes) we also observed marginally excess odds of

Table 5 Additive interaction between quartiles of fast-food outlet proportion and household income on the odds of frequent processed meat consumption[a] (more than once per week), modelled using a binomial logistic regression model in the Greater London UK Biobank sample, UK ($n = 51{,}090$)

	Quartiles of fast-food outlet proportion[b]								Fast-food outlet exposure (Q4) within household income strata
	Q1 (0–13%)		Q2 (13–17%)		Q3 (17–24%)		Q4 (24–45%)		
Household Income (£/year)	More than once/once or less (n)	OR (95% CI)	More than once/once or less (n)	OR (95% CI)	More than once/once or less (n)	OR (95% CI)	More than once/once or less (n)	OR (95% CI)	
> 100,000	653/1756	ref [c]	401/1103	0.95 (0.82, 1.10); $P = 0.495$[d]	253/623	1.06 (0.89, 1.27); $P = 0.502$[d]	177/414	1.11 (0.90, 1.37); $P = 0.335$[d]	1.19 (0.93, 1.54) $P = 0.158$[e]
52,000–100,000	782/2274	0.98 (0.86, 1.11); $P = 0.742$[d]	860/2172	1.13 (1.00, 1.29); $P = 0.047$[d]	788/1769	1.22 (1.07, 1.39); $P = 0.003$[d]	790/1622	1.34 (1.17, 1.54); $P < 0.001$[d]	1.39 (1.20, 1.62) $P < 0.001$[e]
31,000–51,999	593/1798	1.06 (0.92, 1.21); $P = 0.418$[d]	695/1960	1.12 (0.99, 1.28); $P = 0.079$[d]	785/1963	1.25 (1.10, 1.42); $P = 0.001$[d]	902/1975	1.41 (1.24, 1.61); $P < 0.001$[d]	1.31 (1.12, 1.54) $P = 0.001$[e]
< 31,000	842/2526	1.17 (1.03, 1.33); $P = 0.015$[d]	1036/2799	1.29 (1.14, 1.46); $P < 0.001$[d]	1277/3253	1.38 (1.22, 1.55); $P < 0.001$[d]	1423/3350	1.46 (1.29, 1.65); $P < 0.001$[d]	1.29 (1.13, 1.46) $P < 0.001$[e]
Household income (< £31,000/year) within takeaway exposure strata		1.11 (0.97, 1.28) $P = 0.117$[f]		1.27 (1.09, 1.48) $P = 0.002$[f]		1.30 (1.09, 1.56) $P = 0.003$[f]		1.45 (1.18, 1.78) $P < 0.001$[f]	

Measure of interaction (fast-food exposure*household income with odds of processed meat consumption) on a multiplicative scale based on a likelihood ratio test, $P = 0.725$ | Measure of interaction on an additive scale for Q4 fast-food exposure and household income < £31,000 (RERI) = 0.18. RERI scores > 0 suggest positive interaction and departure from additivity | ORs are adjusted for age, sex, ethnicity smoking status, number in household, highest education attainment, UK Biobank assessment centre attended, and the sum of counts of Supermarkets, Restaurants, Convenience stores, Cafes and Specialist Stores within 1 mile Euclidean (straight line) radius buffers of home address | [a] Includes bacon, ham, sausages, meat pies, kebabs, burgers, chicken nuggets | [b] Q1 = quartile with lowest fast-food outlet proportion in home neighbourhood (min – max %) – Q4 = quartile with greatest fast-food outlet proportion in home neighbourhood (% range) | [c] Single reference group; those exposed to the highest proportion of fast-food outlets and with the highest household income | [d] ORs and *p* values relative to single reference group (ref) | [e] ORs and *P* values relative to those who were least exposed to fast-food outlets within strata of household income | [f] ORs and *P* values relative to those with the highest household incomes within strata of fast-food outlet exposure

both obesity and frequent processed meat consumption, over and above the additive effects of each risk factor in isolation, which is evidence of additive interaction. We observed no evidence of a differential impact of fast-food exposure across household income levels (multiplicative interaction), in contrast to a US study, which showed that neighbourhood fast-food access was only related to BMI among low income adults [58]. However, the relative merits of assessing interaction on additive vs multiplicative scales has long been the subject of epidemiological debate. While analysis of multiplicative interactions is more commonplace, it has been suggested that additive interaction bears particular relevance to public health, for which a key concern is the risk of disease in the proportion of the population for whom the risk factors occur together [59, 60].

Implications for public health

These results suggest that those experiencing a double of burden of lowest SEP and greatest fast-food exposure, are especially at risk of frequently consuming processed meats and being obese. The mechanisms underpinning these relationships are likely to include the low cost [40] and perceived value for money of fast food [61], appealing to the price sensitivity of low-income consumers [14], and thereby influencing how and how frequently these outlets are used. We argue that this compounding of individual-level disadvantage by neighbourhood-level high proportion of fast-food outlets, is implicated in social inequalities in diet, health and NCD risk [9, 10].

In this context, the greater number of fast-food outlets commonly found in deprived areas [16], and the relative concentration of fast-food outlets in these areas over the last decade in developed countries [38], is cause for deepening public health concern [16, 62]. However, our findings highlight the potential for upstream, neighbourhood-level dietary public health interventions. Not only to improve population-level diet and health [63], but those of at risk population sub-groups in particular [64, 65], which may contribute to the levelling of social inequalities in health. Such interventions, which include exclusion zones around schools or other planning regulations designed to reduce clustering and proliferation of new fast-food businesses, have already begun to be implemented across the US and the UK [41, 42, 66], including boroughs of Greater London where this research took place [67]. For example, these restrictions form an important part of the Mayor of London's *London Plan* [68], which includes a focus on healthy food environments in general, and access to hot food takeaways specifically, up to the year 2041.

Limitations and strengths

Our study has a number of limitations, foremost of which is the cross-sectional, observational study design, limiting causal inference. We employed a theoretically- and behaviourally-relevant definition of residential 'neighbourhood' [45], which also has precedent for use [31, 39] however which may not match the neighbourhood perceptions or align with the food purchasing behaviours of individuals in this study, and which may have resulted in exposure misclassification. While residential location constitutes an important daily anchor point [69], ensuring relevance of assessing neighbourhood food outlet exposure around this location, we could not assess exposure to the food environment within wider activity spaces [70]. That said, research has shown that magnitude of non-residential neighbourhood food outlet exposure is unrelated to that of residential exposure [71, 72], resulting in random error (not bias) that would have likely served to attenuate our parameter estimates towards the null [73]. UK Biobank data was collected 2006–2010, with neighbourhood food exposure metrics derived from 2012 UKMap data [44]. This resulted in temporal mismatch, although grouping exposure estimates into quarters is likely to have reduced the impact of misclassification. Further misclassification may have emerged from use of UKMap data, which is of unknown completeness, including how this may vary geographically.

We used frequency of processed meat consumption as a proxy for fast-food intake, however, while fast-food outlets are likely to be an important source of these types of foods, such processed foods could be obtained from non-fast-food outlets [74]. Moreover, UK Biobank had only limited detail of dietary intakes, with no information on total diet, energy intake or portion sizes of food and drink consumed. Thus we could estimate only frequency of processed meat consumption, but not total amount. We used household income as our marker of socioeconomic status, in lieu of other markers including educational attainment and occupational social class, which are both imperfectly correlated with income [75]. Our results may be sensitive to the selection of income as our marker of SEP, however, given that findings were consistent with those of a similar study that used education as a marker of socioeconomic status [39], this appears unlikely. Finally, participants in our analytic sample were located in Greater London. While this may influence generalisability, once again the present results were consistent with those we have reported previously from elsewhere in the UK [31, 39].

These limitations are balanced by a number of strengths. First, the large sample size, allied with socioeconomic heterogeneity, allowed robust sub-group analyses. Second, neighbourhood fast-food outlet access was well-characterised, including accounting for fast-food outlets in the context of wider neighbourhood-level food outlet access [53]. Third, we used two objective measures of adiposity, alongside a dietary outcome, demonstrating consistent and complementary associations. Lastly, our study satisfies a number of Bradford Hill criteria, which are useful for inferring causality – in this case, neighbourhood 'effects' - from a cross-sectional study design, including: *consistency* (across multiple epidemiologic studies in different locations and populations, and perhaps to the greatest extent with studies that also employed a relative measure of fast-food exposure), *biological gradient* (evidence of dose-response, especially for adiposity models), and *plausibility* (of a cause-and-effect relationship) [76].

Conclusions

Our study demonstrated independent associations between each of income and neighbourhood fast-food exposure, with diet and two objectively measured adiposity outcomes, in a large sample of UK adults. Moreover, we provide evidence of the double burden of low income and an unhealthy neighbourhood food environment, resulting in an additive interaction and an excess and substantially greater likelihood of unhealthy diet and obesity. Although further work is necessary, these findings support emerging guidelines regarding the regulation of neighbourhood fast-food access for the promotion of population health.

Additional files

Additional file 1: Flow diagram for UK Biobank sample restriction, for body weight-, processed meat consumption- and percentage body fat-based analyses reported in this study. (DOCX 37 kb)

Additional file 2: UK Biobank participants attending Greater London assessment centres (Barts, Croydon, Hounslow; $n = 68,850$) and UK Biobank analytic sample ($n = 51,361$) demographic comparisons. (DOCX 20 kb)

Additional file 3: Characteristics of participants in the UK Biobank sample, UK ($n = 51,361$), overall and stratified by household income. (DOCX 24 kb)

Additional file 4: Associations of quartiles of fast-food outlet proportion with body fat percentage (estimated using a multivariable linear regression model, $n = 50,766$) in the Greater London UK Biobank sample. (DOCX 20 kb)

Additional file 5: Adjusted risk ratios (RRs) describing the associations of quartiles of fast-food outlet proportion with body mass index (estimated using a multivariable linear regression model, $n = 51,361$), obesity (estimated using a binomial logistic regression model $n = 51,361$), and frequent consumption of processed meat (estimated using a binomial logistic regression model, $n = 51,090$) in the Greater London UK Biobank sample. (DOCX 22 kb)

Additional file 6: Associations of household income with body fat percentage (estimated using a multivariable linear regression model, $n = 50,766$) in the Greater London UK Biobank sample. (DOCX 20 kb)

Additional file 7: Adjusted risk ratios (RRs) describing the associations of household income with body mass index (estimated using a multivariable linear regression model, $n = 51,361$), obesity (estimated using a binomial logistic regression model, $n = 51,361$), and frequent consumption of processed meat (estimated using a binomial logistic regression model, $n = 51,090$) in the Greater London UK Biobank sample. (DOCX 22 kb)

Abbreviations
BMI: Body mass index; CHIAG: Community Health Index Advisory Group; MREC: Multi-centre Research Ethics Committee; NCD: Non-communicable disease; OR: Odds ratio; PIAG: Patient Information Advisory Group; Q: Quartile; RERI: Relative excess risk due to interaction; RR: Risk ratio; SEP: Socioeconomic position; STROBE: STrengthening the Reporting of Observational studies in Epidemiology; UK: United Kingdom; US: United States; WHO: World Health Organization

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Availability of data and materials
The dataset used and analysed during the current study are available from UK Biobank (www.ukbiobank.ac.uk) upon application.

Authors' contributions
The study analysis was designed by TB and PM. CS and CW were responsible for collecting food outlet data and developing food environment metrics in consultation with TB and PM. TB and PM analysed the data and wrote the paper together with contributions from CS and CW. All authors read and approved the final manuscript.

Ethics approval and consent to participate
UK Biobank received ethical approval from the North West Multi-centre Research Ethics Committee (MREC), the Community Health Index Advisory Group (CHIAG) and the Patient Information Advisory Group (PIAG).

Consent for publication
Not applicable.

Competing interests
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