Urban nature and physical activity: Investigating associations using self-reported and accelerometer data and the role of household income

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Highlights

- More greenspace was associated with self-reported non-recreational physical activity
- Living by the coast was related to non-recreational, walking and total activity
- Associations were most consistent in the lowest household income quintile
- Relationships were not replicated in a smaller accelerometry subsample

Abstract

Background. Physical inactivity is a major public health concern. Natural, or semi-natural, environments may encourage physical activity, but the influences of socio-economic factors have been under-researched.

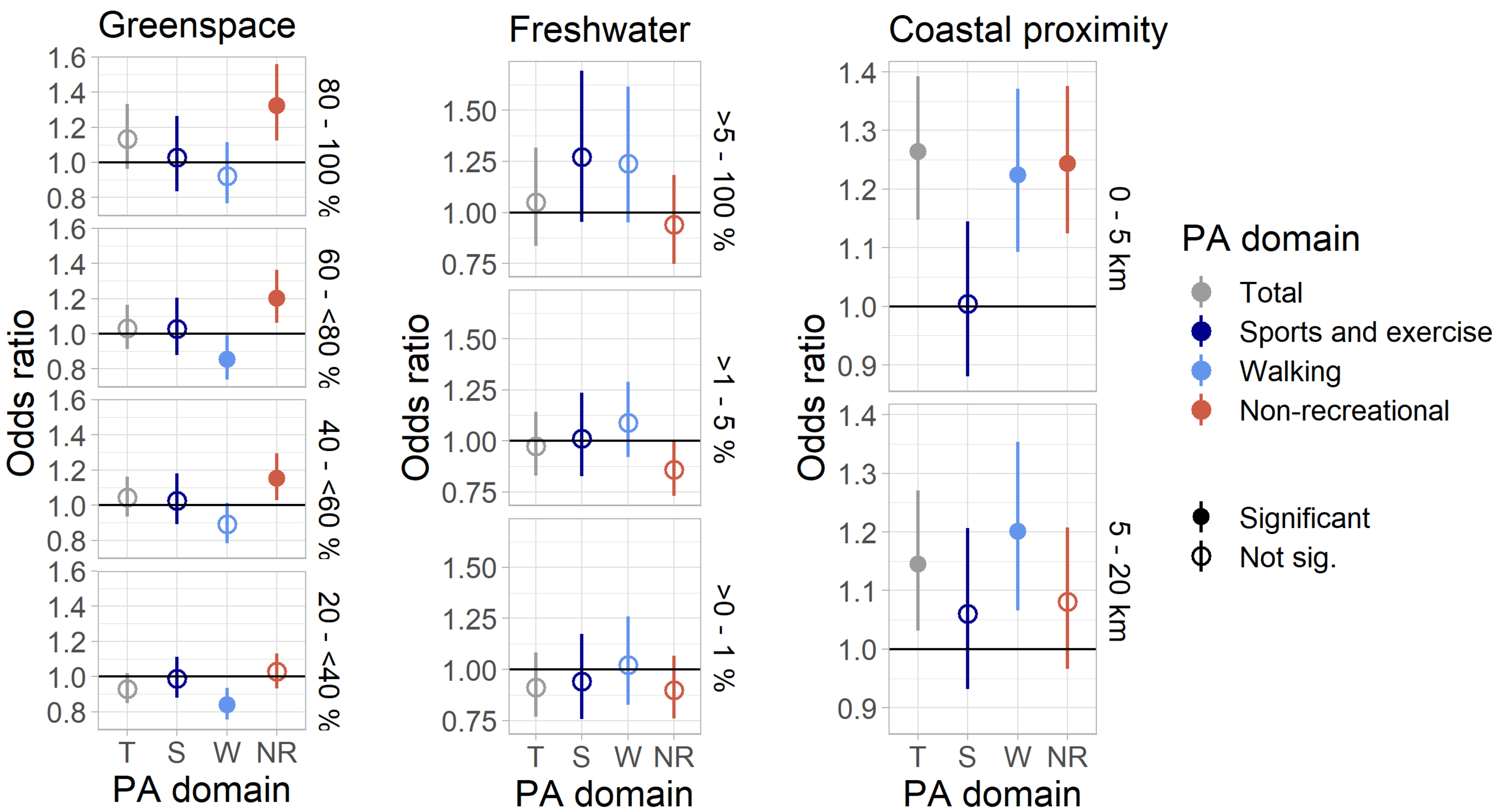
Methods. We explored the associations between meeting physical activity (PA) guidelines and both neighbourhood green (area coverage) and blue (freshwater coverage and coastal proximity) environments for urban adults using data from the Health Survey for England [HSE] (2008/2012). We considered different domains of self-reported PA: walking (n = 18,391), sports and other exercise (n = 18,438), non-recreational (domestic/gardening/occupational; n = 18,446) and all three domains combined (n = 18,447); as well as accelerometer-derived PA data using a subsample (n =1,774). Relationships were stratified by equivalised household income as an indicator of socio-economic status.

Results. After adjusting for covariates, living <5km from the coast was associated with significantly higher odds of meeting UK 2010 guidelines through self-reported total, walking and non-recreational PA (e.g. total PA, <5 km *vs.* >20km, adjusted odds ratio (OR_{adj}) =1.26; 95% confidence interval (CI) = 1.15-1.39) but unrelated to sports and exercise. Greater neighbourhood greenspace, however, was only associated with significantly higher odds of meeting guidelines through non-recreational PA alone (e.g. 80-100% *vs.* <20 % OR_{adj} = 1.32; 95% CI = 1.12–1.56). Although associations were most consistent in the lowest income quintile, income-related results were mixed. Relationships were not replicated in the smaller accelerometry subsample.

Conclusion. Our self-report findings for the differing domains of PA as a function of neighbourhood green and blue space broadly replicated previous research, yet the reasons for the observed differences between PA domains and environments remain unclear. We did not observe any associations between environmental variables and accelerometer-measured PA; further research with larger samples is needed.

Keywords

Physical activity, health inequality, blue space, green space, accelerometer



Graphical abstract

Odds of meeting self-reported physical activity guidelines of 150 mins per week (compared to not meeting them) by LSOA level environmental variables: greenspace area coverage (*vs.* <20 %), freshwater area coverage (*vs.* 0 %) and coastal proximity (*vs.* >20 km) from all domains of PA combined (n = 18,447), sports and exercise (n = 18,438), walking (n = 18,391), and non-recreational activity n = 18,446).

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1. Background

Insufficient physical activity is a risk factor for many physical and mental health conditions. Over 1.5 million deaths were attributed to physical inactivity globally in 2015, an increase of nearly 19% in a decade (Forouzanfar et al., 2016). Characteristics of the built environment, such as street connectivity and the availability of natural and semi-natural spaces (e.g. parks), are associated with physical activity (PA) attainment among urban populations (Dallat et al., 2014; Ferdinand et al., 2012; Saelens and Handy, 2008; Ward Thompson, 2013; White et al., 2014).

Although intuitively appealing, associations between the availability of green infrastructure and the achievement of sufficient PA are mixed. Results of self-reported PA studies are often limited to particular types of green space (Calogiuri and Chroni, 2014) and/or leisure-time PA (Hillsdon et al., 2006; Persson et al., 2019). In a systematic review assessing the association between objectively measured PA and parks, some studies reported positive associations, while others reported no, or mixed, associations (Bancroft et al., 2015). In part, mixed findings may be due to effect modifiers such as dog ownership (White et al., 2018), which are rarely examined.

More consistent associations are found between living close to the coast and greater levels of PA (Gascon et al., 2017). Residents of coastal *vs.* non-coastal neighbourhoods in Australia were more likely to report any leisure-time or transport-related walking (Wilson et al., 2011). In England, adults residing within 1km of the coastline were more likely to report achieving sufficient PA through leisure or transport than adults living further away (White et al., 2014). Nonetheless, these studies relied on relatively simple measures of a single activity, or measures that no longer correspond to PA guidelines. Further, self-reported measures may be subject to greater bias than more 'objective' measures obtained using accelerometers (Hagstromer et al., 2010a; Skender et al., 2016).

Research into the relationship between PA and urban green/blue infrastructure has paid relatively little attention to potential effect modification by socioeconomic variations. Communities who live in greener neighbourhoods and/or by the coast tend to exhibit fewer health inequalities (Mitchell and Popham, 2008; Mitchell et al., 2015; Wheeler et al., 2012). As PA is considered to be one of the key pathways linking urban green/blue spaces and health (Markevych et al., 2017; Pasanen et al., 2019), this would suggest that reduced inequalities in PA in these neighbourhoods may be contributing to these effects (Ball et al., 2007; Dadvand et al., 2016; Hartig et al., 2014; James et al., 2016; Pasanen et al., 2019). However, despite established socioeconomic inequalities in leisure-time PA (Beenackers et al., 2012; Scholes and Mindell, 2012), inequalities vary with different types of PA (Beenackers et al., 2012; Stalsberg and Pedersen, 2018) and it is unclear whether activity inequalities are lessened with greater residential exposure to natural environments.

The aim of the current work was to address some of these evidence gaps using an urban sub-sample of a large cross-sectional dataset, representative of the English population (Health Survey for England

[HSE]). The HSE employs a detailed bespoke physical activity segment, asking respondents to recall all physical activities over the last four weeks, using example images as prompts. Earlier years of the HSE were used to assess the relationship between self-reported PA and local green space. People who lived in greener (urban) areas reported higher levels of PA, which was largely attributed to non-recreational activities such as occupational activities and 'gardening/DIY' (Mytton et al., 2012). A more recent analysis of the HSE replicated earlier evidence that living near the coast was associated with better physical health, and additionally found that this was partially mediated by self-reported land-based PA (predominantly walking). However, no effects of living in "greener" neighbourhoods were found (Pasanen et al., 2019).

The current research extends earlier work in three key ways. First, we determine the relationship between self-reported PA and coastal proximity differentiating by PA domains: sports and formal exercise (e.g. gym, keep fit classes), walking (including both for transport and recreation), non-recreational (including occupational and household DIY/gardening), and all three forms of physical activity combined, updating to the latest guidelines. Second, we explored the potentially moderating role of household income; whether higher levels of PA at the coast are especially present among lower income households. If true, this may help explain the evidence of lower health inequalities in coastal regions (Wheeler et al., 2012). Finally, we looked at a sub-sample who wore accelerometers for a week to see whether more objective indicators support the self-reported patterns.

2. Method

2.1. Data and Sampling

The Health Survey for England (HSE) is an annual cross-sectional survey, designed to be nationally representative of the population living in private households. Data from the 2008 and 2012 waves were pooled. These waves were selected because they included detailed sections on PA. During sampling, addresses were randomly selected from postcode sectors (selected using stratified sampling). All adults, and some children, within selected households were eligible for interview (up to 10) using computer assisted interviewing. Full details can be found in Aresu et al. (2009a) and Bridges et al. (2013) for the 2008 and 2012 HSE surveys respectively. In 2008, a subsample were randomly selected (using addresses) to wear an accelerometer for a week and provide a more objective measure of PA. A maximum of two per household were included and nurses checked for eligibility resulting in 4,507 adults invited.

The current analysis focused on adults (aged 16+; n= 23,388); and, given substantial differences in accessibility to natural environments in urban/rural locations (Cox et al., 2018; Wheeler et al., 2015), only on residents of urban areas (n = 18,447); participants residing in "Village, hamlet and isolated dwellings" and "Town and fringe" settlements were excluded.

Of the 2008 sample, 1,774 urban adults wore the accelerometer for at least 3 days (the minimum amount suggested for reliable estimates of habitual PA (Trost et al., 2005)) and were included in subsequent accelerometer analyses.

2.2. Outcomes

2.2.1. Self-reported physical activity

The HSE uses the bespoke Physical Activity and Sedentary Behaviour Assessment Questionnaire (PASBAQ) (Scholes et al., 2014). Our primary outcome variables were whether or not a person self-reported 150 minutes of moderate-to-vigorous physical activity (MVPA) per week through: (a) sport and exercise (excluding walking); (b) walking (including both for transport and recreation); (c) non-recreational activities alone (domestic and occupational); and (d) all types of PA combined (i.e. a + b + c). The 150 min threshold is in line with current (2010) UK and World Health Organisation (WHO) guidelines for health (Bull and the Expert Working Groups, 2010; World Health Organisation, 2010). The PA questions were almost identical in both waves, with some additional questions in 2012 (Scholes and Mindell, 2012). We chose a binomial outcome because the data were highly right-skewed. This also results in an outcome less sensitive to measurement error and recall bias. Full details of the PASBAQ can be found in Aresu et al. (2009a) and Bridges et al. (2013).

a) *Sports and exercise.* Respondents were asked about common sports and exercises (e.g. swimming, cycling and football), and additionally asked to mention any others they engaged in (e.g. windsurfing). They were asked on how many days in the last 4 weeks they carried out each of these activities for at least 10 minutes and the average duration. The average hours spent per week on sports and exercise were provided in the dataset. Respondents reporting an average of ≥150 minutes per week, in bouts of at least 10 mins, were considered to have achieved the recommended PA guidelines through recreational sports and exercise activity alone. Sport responses were missing for nine respondents; therefore, the modelling sample was 18,438.
b) *Walking.* Participants were asked: if they had completed a walk of at least 10 minutes in the last 4 weeks, on how many days, on how many days they did more than one walk, the average duration, and the walking pace. For those aged ≥65yrs, walking activities at any pace were included as MVPA if the pace was enough to make them "breathe faster, feel warmer or sweat". Only brisk/fast-paced walking were included for other ages in 2012 and for all ages in 2008 (Scholes and Mindell, 2012). Walking purpose was un-specified. The average hours spent per week walking were provided in the dataset. Respondents reporting an average of ≥150 minutes per week, in bouts of at least 10 mins, were considered to have achieved the recommended PA guidelines through walking alone. Walking responses were missing for 56 respondents; therefore, the modelling sample was 18,391.

c) *Non-recreational activity*. For occupational activities (including paid/unpaid work), respondents were asked on how many days they were at work in the past 4 weeks, and the average time spent walking, climbing stairs or ladders, or lifting heavy loads during work. For domestic activities, participants were asked on how many days in the last four weeks they had undertaken typical activities for at least 10 minutes and average duration (Scholes and Mindell, 2012). Only activities of higher intensities were included as MVPA (e.g. spring cleaning, walking with heavy shopping, cleaning windows). Gardening and DIY were asked about in combination, included within a heavy manual work category, we were therefore unable to explore gardening separately; and again only those of at least moderate intensity were included (e.g. digging, moving heavy loads) (NatCen Social Research, 2008; Scholes and Mindell, 2012).

   The average hours spent per week on heavy housework, heavy manual work and occupational activity were each provided in the dataset; and we summed these three variables to provide a measure of non-recreational activity. Where a domain value was missing, the remaining values were included. Respondents reporting an average of ≥150 minutes per week, in bouts of at least 10 mins, were considered to have achieved the recommended PA guidelines through non-recreational activity alone, a potentially important distinction for support funding of recreational services and public places (e.g. (White et al., 2016)). All non-recreational domain responses were missing for one respondent, therefore the modelling sample was 18,446. Individual model results for occupational activity and domestic (heavy housework and heavy manual work) activity are reported in the supplemental materials.

d) *Total activity*. The weekly average duration of MVPA (in bouts of at least 10 min) for all domains were summed. Where respondents reported an average of ≥150 minutes per week they were considered to have achieved the PA guidelines. Where domain values were missing, remaining values were summed to calculate meeting PA guidelines. There were 18,341 respondents with no missing domain values. For one, two, three and four missing there were 86, 12, 7, and 1 respondents, respectively. The domain most often missing was walking (total modelling sample = 18,447).

2.2.2.*Accelerometer – objective measure*

Our secondary outcome measure calculated MVPA in the week following the interview as assessed by accelerometer data. Fully charged ActiGraph acclerometers (model GT1M) were worn on a belt above the hip, placed by a trained interviewer (Aresu et al., 2009a). Participants were asked to remove it while swimming, sleeping, engaging in contact sports, or in the shower/bath; and they received a £20 voucher as a thank you.

The variable average minutes of MVPA per valid day was provided with the dataset (see Aresu et al. (2009b)) with accelerometry cut-offs based on Troiano et al. (2008). As we included participants who had worn the accelerometer for less than one week (≥3 days), we used an average. The threshold corresponding to guidelines was calculated as 150/7 (recommended weekly minutes/days in a week) minutes of MVPA per "valid day" of wearing the Actigraph (wearing for >=600 mins) in bouts of at least 10 minutes.

2.3. Exposure variables

To maintain respondent anonymity, no information regarding home locations is made available in the HSE publically accessible datasets. Following a request by the research team, the data owner (NHS Digital) and manager (National Centre for Social Research, NatCen) used their secure server to append data on green/blue spaces to individuals based on information provided by the research team, before returning the results with area anonymity maintained (Data Sharing Agreement NIC-09479-J9Z4G). Specifically, we sent NatCen details of the amounts of greenspace, freshwater, and coastal proximity of over 32,000 lower-layer super output areas (LSOAs) in England, the smallest neighbourhood unit available. These have an average population of 1,500. NatCen then appended the data for the LSOA in which each respondent lived before returning the enriched, but still anonymised, data to us for analysis.

LSOA greenspace area coverage was based on the Generalised Land Use Database (GLUD) for 2005 (Department for Communities and Local Government, 2007), as also used in (Alcock et al., 2014; Houlden et al., 2017; Mytton et al., 2012). The data include all green spaces, irrespective of accessibility, of at least $5m^2$, excluding domestic gardens. To reduce the probability of identifying the locations of individuals based on cross-tabulations of environmental exposures, only categories of greenspace in bands of 10% were returned, which we collapsed into five bands of 20% (0-20%, 20-40% etc.). Percentage freshwater (minimum feature width = 20 m) coverage of each LSOA was derived from the CEH Land Cover Map 2007 (Morton et al., 2011). Due to the majority of people having little or no freshwater in their LSOA, we derived four categories (0%, >0-1%, >1-5%, >5-100%). Residential coastal proximity was measured from the population-weighted centroid of each LSOA to the nearest coastline (Wheeler et al., 2012), and categorised as <5km, 5–20km and >20km (White et al., 2014).

2.4. Covariates

Equivalised household income was our key moderator and stratification variable. Respondents were asked to report their household income provided in bands shown on a card. A score for each household was calculated based on the number of additional adults (to the (oldest) person with the highest income) and ages of children (NatCen for Social Research, 2008). Household income was then divided by this score to provide the equivalised income by household, a measure of disposable income which accounts for the number and composition of the household (Aresu et al., 2009b).

Following previous research, we also controlled for a range of potential confounding variables at different levels (Anokye et al., 2013; Bauman et al., 2012; Chau et al., 2017; Klompmaker et al., 2018; Richardson et al., 2013; Scholes and Mindell, 2012) including: (a) area-level - neighbourhood deprivation (LSOA IMD; quintiles; most deprived = reference category); (b) household-level - number of children (none = ref.); access to car/van (has access = ref.); (c) individual-level - age (categorised in 20 year intervals; 16–34 = ref.); sex (female = ref.); highest qualification (none/foreign/other = ref.); employment status (in work/education = ref.); marital status (single = ref.); limiting illness (limiting illness = ref.); BMI (normal weight = ref.); smoking (current smoker = ref.); and (d) year of survey (2008 = ref). Further details are presented in Supplementary Table 1. Responses of "Don't know", "Item not applicable" or "Refused" were categorised as "Missing" and included within analyses.

2.5. Analysis

Analyses were carried out in R version 3.6.0 (R Core Team, 2017). We used logistic regression (generalised linear model with a binomial error structure) for both unadjusted models (environmental variables only) and adjusted models with covariates. We fitted several models.

Entire study sample:

- i) Self-reported PA (*sports and exercise, walking, non-recreational and all combined*) dependent on environmental variables (*greenspace coverage, freshwater coverage and coastal proximity*).
- ii) Self-reported PA dependent on environmental variables stratified by household income quintiles.

Accelerometer study sample:

- iii) Reduced-sample objective (accelerometer) PA dependent on environmental variables. Different domains of PA were not available for this measure.
- iv) A sensitivity analysis of iii): Self-reported PA (total) for the same reduced sample.
- v) Objective (accelerometer) PA dependent on the environmental variables, stratified by household income. Due to the reduced sample size, we used income tertiles.

With respect to models (ii & v), a non-significant interaction can obscure important differences if most quintiles show very similar patterns and only one shows a different pattern (especially once sample sizes in quintiles become reduced). We had a clear *a priori* prediction that the effect would be strongest in the lowest income quintile (based on previous research, e.g. (Wheeler et al., 2012)), therefore stratification was conducted irrespective of identifying any interaction term.

The data were weighted using the interview weights and accelerometer interview weights provided in the dataset to account for selection, non-response and population biases (Aresu et al., 2009a), allowing us to generalise the findings to the entire adult population of England. We used the "survey" package in R (Lumley, 2018) which facilitates the analysis of complex survey data, taking into account household clustering and providing cluster-robust standard errors. We were unable to account for LSOA clustering as this was removed by the data providers to preserve anonymity. Model fit was assessed using Cox and Snell's pseudo-R^2 and Akaike's Information Criteria (AIC), which takes into account the number of variables, from the same package (Lumley, 2018; Lumley and Scott, 2015).

2.5.1. Sensitivity analyses and robustness checks

Some of the covariates had missing data with very low sample sizes in this category ("Missing data"). Where N missing <20 (for the full self-reported model sample), these were imputed using the other covariates from the model. These were imputed using the 'mice' package (van Buuren et al., 2019), using logistic regression (car) or polytomous regression (limiting illness and marital status). The results are presented in supplemental materials.

There is a time mismatch between the environmental data (reported in 2005) compared to the health survey data (2008 and 2012). As such, we additionally carried out the self-reported analysis for the year 2008 only, where the mismatch was minimised.

3. Results

3.1. Self-reported PA

3.1.1. Proportion of total PA time by type

We summarise each domain's contribution to total self-reported PA (Fig. 1). Housework, included in non-recreational PA, is clearly an important source of PA. For 13% of respondents, housework made up the entirety of their total PA time, the highest proportion of respondents spending 100% of their PA time on one type (Fig. 1). Occupational activity did not contribute at all to total PA for 70% of respondents, the highest proportion for this duration category. Most respondents also spent no time on DIY/gardening and around 40 – 50 % of respondents spent no time on sports/exercise, walking or occupational PA.

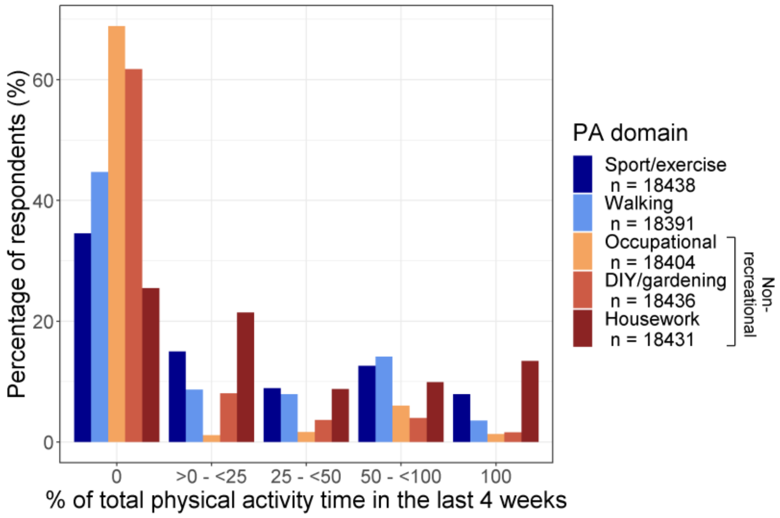

Figure 1 Proportion of total PA time spent on each PA domain. Sports and exercise and walking are displayed in blue and the non-recreational categories (occupational, DIY/gardening and housework) are displayed in shades of orange.

3.1.2. Sample counts

According to the self-reported PA measures: a) 20% met guidelines (≥150mins a week) from sports and exercise PA alone; b) 22 % met guidelines from walking alone; c) 28% met guidelines from non-recreational PA alone; and c) 56% met guidelines from all three domains of activity combined (Table 1). Only 17% of the (urban) sample lived <5km of the coast, the majority had no freshwater in their LSOA (86%), and the largest number lived in LSOAs with <20% greenspace coverage (35%; Table 1).

Table 1 Sample sizes of environmental variables and categories as a function of meeting total self-reported physical activity guidelines. Full counts are in Supplemental Table 1.

	Full model sample		PA[a] guidelines met		PA guidelines not met	
	Unweighted N[b]	Weighted %age	Unweighted N	Weighted %age	Unweighted N	Weighted %age
Self-reported PA						
Total						
Guidelines met	9921	56.30	9921	100.00	0	0.00
Guidelines not met	8526	43.70	0	0.00	8526	100.00
Sports + exercise						
Guidelines met	3260	19.94	3260	100.00	0	0.00
Guidelines not met	15178	80.06	6657	45.41	8521	54.59
Walking						
Guidelines met	3767	21.71	3767	100.00	0	0.00
Guidelines not met	14624	78.29	6138	44.29	8486	55.71
Non-recreational						
Guidelines met	5191	28.23	5191	100.00	0	0.00
Guidelines not met	13255	71.77	4730	39.11	8525	60.89
Environmental variables						
Greenspace coverage						
80 - 100 %	1191	6.08	676	58.75	515	41.25
60 - <80 %	2298	11.86	1266	57.23	1032	42.77
40 - <60 %	3177	16.72	1725	56.78	1452	43.22
20 - <40 %	5554	30.08	2848	54.04	2706	45.96
0 - <20 % (ref)	6227	35.27	3406	57.25	2821	42.75
Freshwater coverage						
>5 - 100 %	493	2.63	268	56.83	225	43.17
>1 - 5 %	1194	6.33	665	56.68	529	43.32
>0 - 1 %	989	5.21	518	55.92	471	44.08
0% (ref)	15771	85.82	8470	56.27	7301	43.73
Coastal proximity						

0 - 5 km	3299	17.11	1804	57.05	1495	42.95
5 - 20 km	2777	14.03	1525	57.92	1252	42.08
>20 km (ref)	12371	68.86	6592	55.78	5779	44.22
Household level covariates						
Household income quintile						
Highest	2922	16.15	1939	67.97	983	32.03
Second highest	2976	16.51	1868	64.13	1108	35.87
Middle	2851	15.23	1594	57.74	1257	42.26
Second lowest	2969	15.27	1425	50.19	1544	49.81
Lowest (ref)	2926	15.46	1315	47.85	1611	52.15
Missing data	3803	21.38	1780	50.87	2023	49.13

[a]PA = Physical activity, [b]N = sample size

3.1.3. Model results

Echoing previous equivocal findings, there was no relationship between the level of area greenspace and the likelihood of meeting PA guidelines through all forms of PA combined, in either the unadjusted or adjusted models (Table 2). However, by breaking total PA down into different components we find that while walking is less likely to take place in greener urban areas (e.g. 60 – 80 % *vs*. <20%; adjusted odds ratio (OR_{adj})= 0.86, 95% confidence interval (CI) = 0.74–0.99), this is counterbalanced by higher levels of non-recreational activity in these areas (e.g. 80–100% *vs.* <20%: OR_{adj} = 1.32, 95% CI = 1.12–1.56). By contrast, there was no relationship between greenspace and the likelihood of meeting PA guidelines through sports and formal exercise.

Although freshwater coverage was unrelated to any of the PA outcomes, the adjusted model suggested that people who lived nearest the coast were significantly more likely to meet guidelines through all domains of PA combined (<5km *vs*. >20km; OR_{adj} =1.26; 95% CI = 1.15-1.39). Breaking this down into the different PA domains, we see that those living <5km vs. >20km from the coast were also more likely to meet guidelines through both walking (OR_{adj}= 1.22, 95% CI= 1.09–1.37) and non-recreational activities (OR_{adj}= 1.24, 95% CI= 1.12–1.38). People who lived 5-20km from the sea were also more likely to meet guidelines through walking alone than those who lived further inland (*vs.* >20km; OR_{adj}= 1.20, 95% CI= 1.07–1.35) which appears to be driving the same picture for total PA (Table 2).

Several covariates replicated earlier findings. For instance, younger, more educated adults and those living in areas of less deprivation tended to be more likely to report meeting PA guidelines, with the exception of non-recreational PA (see Supp. Table 2, 4, 6 & 8 for full details for all covariates). Of most relevance for the current paper, the highest income quintile was associated with significantly higher odds of achieving guidelines from both walking and recreational sports & exercise, but significantly lower odds of achieving guidelines from non-recreational PA than those in the lowest income quintile (Table 2), perhaps reflecting occupations involving less PA. Models explained ~16% of the variation in the outcome variable for total PA (adjusted), ~12 % for sports and exercise and ~7% for non-recreational PA and walking (adjusted).

In Supp. Tables 10-11 we present the breakdown of non-recreational PA into occupational and domestic activities and observe similar relationships for both greenspace and coastal proximity which are positively related to these domains of PA. Freshwater coverage is significantly (negatively) related to occupational activity only.

The environmental predictor coefficients resulting from the sensitivity analysis with imputed data and for the year 2008 were generally in agreement (Supp. Tables 3, 5, 7, 9 & 12). However, the effect sizes were slightly stronger for coastal proximity and weaker for greenspace coverage for the year 2008 alone compared to both 2008 and 2012.

Table 2 Odds ratios (OR) and 95 % confidence intervals (CI) for unadjusted and adjusted models for meeting physical activity guidelines for recreational only (recreational and walking), non-recreational (occupational, DIY and housework) and all self-reported categories combined. Full model results in Supp. Tables 2, 4, 6 & 8. Significance from the model results are also presented

	Total				Sport				Walking				Non-recreational			
	Unadjusted		Adjusted		Unadjusted		Adjusted		Unadjusted		Adjusted		Unadjusted		Adjusted	
Term	OR[a]	95 % CI[b]	OR	95 % CI	OR	95 % CI	OR	95 % CI	OR	95 % CI	OR	95 % CI	OR	95 % CI	OR	95 % CI
Environmental variables																
Greenspace coverage																
80 - 100 %	1.08	0.93 - 1.25	1.13	0.96 - 1.33	0.93	0.77 - 1.14	1.03	0.84 - 1.26	0.84	0.70 - 1.00	0.92	0.77 - 1.11	**1.40*****	**1.20 - 1.63**	**1.32*****	**1.12 - 1.56**
60 - <80 %	1.00	0.90 - 1.12	1.03	0.91 - 1.16	0.92	0.80 - 1.07	1.03	0.88 - 1.20	**0.80****	**0.69 - 0.92**	**0.86***	**0.74 - 0.99**	**1.28*****	**1.13 - 1.44**	**1.20****	**1.06 - 1.36**
40 - <60 %	0.98	0.89 - 1.09	1.04	0.94 - 1.16	0.93	0.81 - 1.06	1.03	0.89 - 1.18	**0.82****	**0.73 - 0.93**	0.89	0.78 - 1.01	**1.20****	**1.07 - 1.34**	**1.15***	**1.03 - 1.30**
20 - <40 %	**0.88****	**0.81 - 0.96**	0.93	0.85 - 1.02	0.90	0.80 - 1.01	0.99	0.88 - 1.11	**0.78*****	**0.70 - 0.86**	**0.84****	**0.75 - 0.94**	1.06	0.96 - 1.16	1.03	0.93 - 1.13
0 - <20 % (ref)																
Freshwater coverage																
>5 - 100 %	1.01	0.81 - 1.26	1.05	0.84 - 1.32	1.28	0.97 - 1.69	1.27	0.95 - 1.69	1.25	0.93 - 1.67	1.24	0.95 - 1.62	0.87	0.70 - 1.09	0.94	0.75 - 1.18
>1 - 5 %	1.00	0.87 - 1.15	0.97	0.83 - 1.14	1.06	0.90 - 1.26	1.01	0.83 - 1.24	1.11	0.94 - 1.31	1.09	0.92 - 1.29	0.86	0.73 - 1.00	0.86	0.73 - 1.01
>0 - 1 %	0.95	0.81 - 1.12	0.91	0.77 - 1.08	1.00	0.81 - 1.24	0.94	0.76 - 1.17	1.08	0.87 - 1.32	1.02	0.83 - 1.26	0.86	0.73-1.02	0.90	0.76-1.07
0% (ref)																
Coastal proximity																
0 - 5 km	1.05	0.96 - 1.15	**1.26*****	**1.15 - 1.39**	**0.85****	**0.75 - 0.96**	1.00	0.88 - 1.15	1.05	0.95 - 1.18	**1.22*****	**1.09 - 1.37**	1.22***	1.11 - 1.34	1.24***	1.12 - 1.38
5 - 20 km	1.10	0.99 - 1.21	**1.15***	**1.03 - 1.27**	1.05	0.93 - 1.20	1.06	0.93 - 1.21	**1.15***	**1.02 - 1.29**	**1.20****	**1.07 - 1.35**	1.07	0.96 - 1.19	1.08	0.97 - 1.21
>20 km (ref)																
Household level covariates																
Household income quintile																
Highest			1.13	0.98 - 1.30		-	**1.50*****	**1.25 - 1.80**			1.18	1.00 - 1.40			**0.73*****	**0.62 - 0.86**
Second highest			1.01	0.88 - 1.16		-	1.18	0.99 - 1.42			0.91	0.77 - 1.08			0.87	0.75 - 1.01
Middle			1.03	0.89 - 1.18		-	1.13	0.94 - 1.36			**0.83***	**0.70 - 0.98**			1.11	0.96 - 1.28
Second lowest			1.00	0.87 - 1.13		-	1.05	0.88 - 1.26			0.94	0.80 - 1.11			1.04	0.91 - 1.20
Lowest (ref)																
Missing data			0.93	0.82 - 1.05		-	1.12	0.94 - 1.34			0.93	0.80 - 1.10			**0.86***	**0.75 - 0.99**
Adjusted for socio-demographics[c]		NO	YES			NO	YES			NO	YES			NO	YES	

Intercept	0.27	-0.49	-1.32	-2.3	-1.19	-1.92	-1.06	-1.74
N[d]	18447	18447	18438	18438	18391	18391	18446	18446
Households	11439	11439	11437	11437	11415	11415	11439	11439
AIC[e]	25279.59	22173.83	18424.3	16256.05	19221.75	17965.3	21919.08	20793.63
Cox & Snell *pseudo*-R^2 (%)	0.13	16	0.12	11.64	0.26	7.29	0.32	6.66

[a] OR= Odds ratio, [b]CI = confidence interval, [c]Adjusted for: area level Index of multiple deprivation (IMD); household level variables, income (presented), children, access to a car/van; individual level variables, age, sex, highest education qualification attained, economic status, relationship status, longstanding illness presence, BMI, cigarette smoking status and year, [d]N = sample size, [e]AIC= Akaike information criterion
* $p<0.05$, **$p<0.01$, ***$p<0.001$

3.1.4. Stratifying by household income

The odds ratios and 95% confidence intervals for models stratified on income are presented in Table 3 and Figure 2 (full results in Supplemental Tables 13-32). The associations between PA and environmental exposures varied by income quintile with some of the most consistent effects, as predicted, among the lowest quintile (Table 3).

For instance, those in the lowest income quintile who lived in the greenest neighbourhoods (80–100% coverage) were significantly more likely to report achieving the guidelines through non-recreational (but not sports or walking) PA (*vs*. <20%: OR_{adj}= 1.88, 95% CI= 1.11–3.20). This pattern for non-recreational PA was also found for those in the lowest income quintile who lived 0-5km (*vs*. <20%) from the coast (OR_{adj}= 1.58, 95% CI= 1.23–2.03). Those within 20km from the coast were more likely to be meeting guidelines from walking and total activity combined than those living further away (e.g. walking, 0-5 km *vs.* >20 km, OR_{adj}=1.41, 95 % CI = 1.03 - 1.91). Living in areas with >5 – 100 % freshwater coverage was also associated with a strong effect, respondents were more likely to achieve guidelines through walking alone (*vs.* 0%, $OR_{adj,=}$ 2.61, 95% CI= 1.62 – 4.20). These data are consistent with other HSE data analysis suggesting that only those in the lowest income quintile show an association between living near the sea and better mental health (Garrett et al., 2019).

In the second lowest income, >5 – 100 % freshwater coverage was associated with meeting PA guidelines through sports and formal exercise. Living 0-5km from the coast was also associated with higher odds of all forms of PA (excluding sports and exercise) in the middle income category. In the second highest income category, living 0-5km was associated with higher odds of meeting guidelines through walking and living 5-20 km was associated with higher odds of meeting guidelines through both recreational and total PA. In other words, living closer to the coast was related to higher odds of some form of PA in three of the five income groups.

For reasons that are less obvious, there was also a greater likelihood of achieving weekly PA through non-recreational PA among those in the middle income quintile living in areas with 60-80% (*vs*. <20%) greenspace, and lower odds of achieving PA through non-recreational PA among those in the highest income quintile living in neighbourhoods with 1-5% (*vs.* 0%) freshwater coverage. Given the large number of tests conducted and coefficients generated, we believe these results should be viewed with caution.

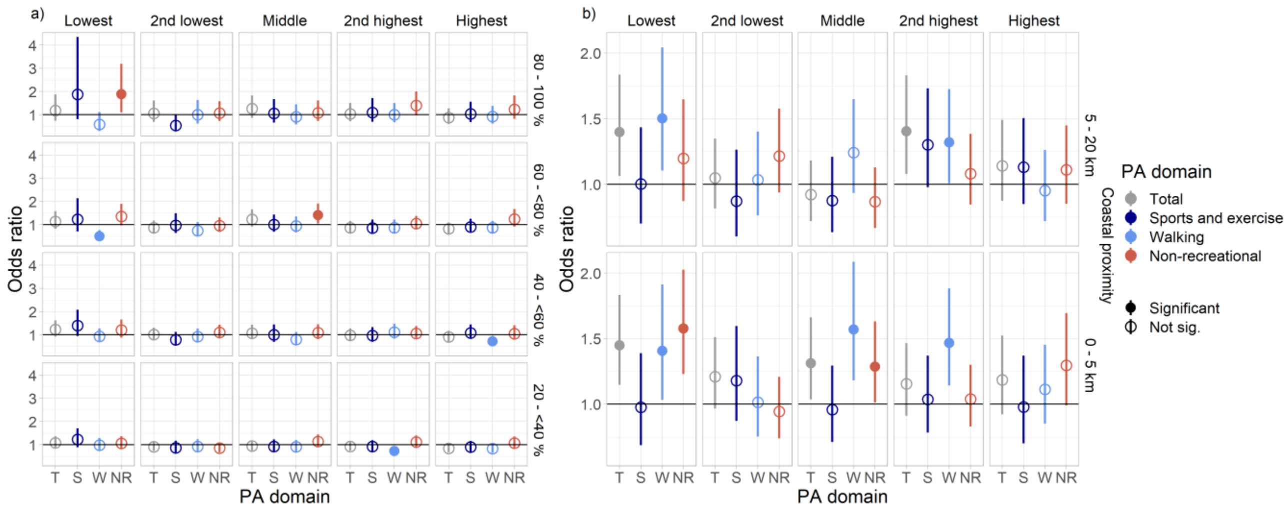

Figure 2 Odds ratio predicting meeting PA guidelines by sports & exercise, walking, non-recreational (domestic and occupational)and total PA by equivalised household income quintiles as a function of a) greenspace coverage (vs. <20 %) and b) coastal proximity (vs. >20km). Significant results are displayed using a filled circle; and non-significant results by a hollow circle.

Table 3 Odds of meeting PA guidelines by household income quintile. As determined using generalised linear modelling with sample weights and accounting for household clustering. Odds ratios are adjusted for all other demographic and socio-economic covariates as in previous adjusted models. Full model results are in Supplementary Tables 13-32.

	Total		Sports and exercise		Walking		Non-recreational	
	OR[a]	95 % CI[b]	OR	95 % CI	OR	95 % CI	OR	95 % CI
Lowest household income								
Environmental variables								
Greenspace coverage								
80 - 100 %	1.18	0.74 - 1.88	1.87	0.80 - 4.36	0.58	0.30 - 1.11	**1.88***	**1.11 - 3.20**
60 - <80 %	1.14	0.82 - 1.58	1.23	0.71 - 2.14	**0.50****	**0.32 - 0.77**	1.36	0.97 - 1.90
40 - <60 %	1.22	0.92 - 1.62	1.40	0.94 - 2.08	0.93	0.68 - 1.27	1.20	0.87 - 1.65
20 - <40 %	1.08	0.86 - 1.36	1.23	0.89 - 1.71	0.97	0.74 - 1.29	1.05	0.82 - 1.36
0 - <20 % (ref)								
Freshwater coverage								
>5 - 100 %	1.33	0.76 - 2.33	1.30	0.64 - 2.64	**2.61*****	**1.62 - 4.20**	1.00	0.55 - 1.83
>1 - 5 %	1.23	0.77 - 1.96	1.50	0.82 - 2.72	1.57	0.89 - 2.76	1.26	0.81 - 1.97
>0 - 1 %	1.01	0.58 - 1.76	0.84	0.39 - 1.83	1.49	0.71 - 3.13	0.65	0.39 - 1.07
0% (ref)						-		
Coastal proximity						-		
<5 km	**1.45****	**1.15 - 1.83**	0.98	0.69 - 1.39	**1.41***	**1.03 - 1.91**	**1.58*****	**1.23 - 2.03**
5 - 20 km	**1.40***	**1.06 - 1.83**	1.00	0.70 - 1.43	**1.50****	**1.10 - 2.04**	1.20	0.87 - 1.65
>20 km (ref)								
Intercept	-0.58		-2.8		-2.16		-1.75	
N[c]	2926		2923		2913		2926	
Households	1947		1946		1944		1947	
AIC[d]	3440.35		2134.97		2565.15		3086.57	
Cox & Snell *pseudo*-R^2 (%)	21.47		14.67		13.74		9.21	
Second lowest								

Environmental variables								
Greenspace coverage								
80 - 100 %	1.05	0.69 - 1.61	0.53	0.28 - 1.02	1.00	0.61 - 1.63	1.07	0.72 - 1.58
60 - <80 %	0.87	0.64 - 1.17	0.97	0.64 - 1.49	0.74	0.49 - 1.12	0.95	0.69 - 1.31
40 - <60 %	1.00	0.77 - 1.31	0.78	0.54 - 1.13	0.92	0.66 - 1.27	1.10	0.84 - 1.43
20 - <40 %	0.91	0.72 - 1.14	0.86	0.63 - 1.17	0.92	0.69 - 1.23	0.85	0.67 - 1.09
0 - <20 % (ref)				-				
Freshwater coverage				-				
>5 - 100 %	1.33	0.77 - 2.27	**2.39****	**1.31 - 4.35**	0.99	0.46 - 2.11	0.85	0.50 - 1.45
>1 - 5 %	0.89	0.62 - 1.28	1.11	0.71 - 1.73	0.87	0.53 - 1.42	0.85	0.60 - 1.22
>0 - 1 %	1.09	0.74 - 1.60	1.45	0.84 - 2.52	1.14	0.71 - 1.83	1.24	0.81 - 1.91
0% (ref)				-				
Coastal proximity				-				
<5 km	1.21	0.97 - 1.51	1.18	0.87 - 1.60	1.01	0.75 - 1.37	0.95	0.74 - 1.21
5 - 20 km	1.05	0.81 - 1.35	0.87	0.60 - 1.26	1.03	0.76 - 1.40	1.21	0.94 - 1.58
>20 km (ref)								
Intercept	-0.79		-2.64		-2.24		-1.76	
N	2969		2969		2966		2969	
Households	1839		1839		1838		1839	
AIC	3626.08		2223.06		2702.73		3359.16	
Cox & Snell *pseudo*-R^2	17.73		12.71		7.05		9.83	
Middle								
Environmental variables								
Greenspace coverage								
80 - 100 %	1.26	0.87 - 1.83	1.05	0.66 - 1.67	0.91	0.57 - 1.45	1.08	0.73 - 1.61
60 - <80 %	1.24	0.92 - 1.67	1.00	0.70 - 1.43	0.95	0.67 - 1.35	**1.42****	**1.05 - 1.91**
40 - <60 %	1.07	0.80 - 1.42	0.99	0.68 - 1.44	0.79	0.55 - 1.12	1.08	0.80 - 1.45
20 - <40 %	0.94	0.75 - 1.19	0.92	0.68 - 1.23	0.91	0.69 - 1.20	1.13	0.89 - 1.44
0 - <20 % (ref)				-				

Freshwater coverage				-				
>5 - 100 %	0.85	0.46 - 1.56	0.88	0.42 - 1.84	1.55	0.89 - 2.69	0.96	0.53 - 1.73
>1 - 5 %	0.80	0.54 - 1.17	0.77	0.45 - 1.30	0.80	0.52 - 1.21	0.74	0.50 - 1.09
>0 - 1 %	0.71	0.44 - 1.13	0.65	0.34 - 1.25	1.18	0.66 - 2.11	0.70	0.47 - 1.06
0% (ref)				-				
Coastal proximity				-				
<5 km	**1.31***	**1.04 - 1.66**	0.96	0.71 - 1.29	**1.57****	**1.18 - 2.08**	**1.29***	**1.01 - 1.63**
5 - 20 km	0.92	0.72 - 1.18	0.87	0.63 - 1.21	1.24	0.93 - 1.65	0.87	0.67 - 1.13
>20 km (ref)								
Intercept	-0.63		-1.94		-2.32		-1.35	
N	2851		2850		2844		2851	
Households	1730		1730		1727		1730	
AIC	3591.88		2605.07		2682.89		3481.13	
Cox & Snell *pseudo*-R^2 (%)	12.61		9.04		6.28		8.30	
Second highest								
Environmental variables								
Greenspace coverage								
80 - 100 %	1.04	0.72 - 1.50	1.09	0.69 - 1.71	1.01	0.67 - 1.50	1.39	0.97 - 2.00
60 - <80 %	0.87	0.65 - 1.16	0.86	0.61 - 1.22	0.87	0.62 - 1.22	1.05	0.79 - 1.38
40 - <60 %	0.97	0.74 - 1.27	0.96	0.69 - 1.32	1.11	0.83 - 1.47	1.05	0.81 - 1.37
20 - <40 %	0.92	0.73 - 1.16	0.92	0.71 - 1.19	**0.73***	**0.56 - 0.94**	1.11	0.88 - 1.39
0 - <20 % (ref)								
Freshwater coverage								
>5 - 100 %	1.20	0.63 - 2.27	1.16	0.52 - 2.58	0.89	0.47 - 1.67	0.80	0.41 - 1.55
>1 - 5 %	1.28	0.89 - 1.84	1.14	0.73 - 1.77	1.26	0.87 - 1.82	0.96	0.67 - 1.37
>0 - 1 %	1.31	0.86 - 1.98	0.99	0.65 - 1.52	1.01	0.61 - 1.68	1.19	0.84 - 1.69
0% (ref)								
Coastal proximity								
<5 km	*1.16*	0.91 - 1.46	1.04	0.78 - 1.37	**1.47****	**1.14 - 1.88**	1.04	0.83 - 1.30

5 - 20 km	**1.40***	**1.08 - 1.83**	1.30	0.98 - 1.73	**1.32***	**1.01 - 1.72**	1.08	0.84 - 1.38
>20 km (ref)								
Intercept	0.04		-1.62		-1.38		-1.52	
N	2965		2975		2974		2976	
Households	1744		1746		1745		1746	
AIC	3675.84		2996.09		3175.6		3631.87	
Cox & Snell *pseudo*-R^2 (%)	8.92		9.74		5.09		5.2	
Highest								
Environmental variables								
Greenspace coverage								
80 - 100 %	0.87	0.60 - 1.28	1.03	0.68 - 1.56	0.92	0.62 - 1.38	1.23	0.82 - 1.83
60 - <80 %	0.82	0.62 - 1.10	0.90	0.65 - 1.25	0.86	0.64 - 1.17	1.24	0.91 - 1.68
40 - <60 %	0.91	0.70 - 1.17	1.08	0.81 - 1.44	**0.71***	**0.53 - 0.95**	1.05	0.78 - 1.40
20 - <40 %	0.85	0.67 - 1.06	0.90	0.69 - 1.16	0.83	0.65 - 1.05	1.07	0.85 - 1.36
0 - <20 % (ref)								
Freshwater coverage								
>5 - 100 %	1.03	0.61 - 1.75	1.39	0.77 - 2.52	0.79	0.45 - 1.40	1.38	0.78 - 2.44
>1 - 5 %	0.80	0.57 - 1.11	0.82	0.56 - 1.21	1.21	0.84 - 1.75	**0.63***	**0.41 - 0.94**
>0 - 1 %	0.79	0.55 - 1.12	0.91	0.60 - 1.38	0.98	0.66 - 1.46	0.91	0.63 - 1.33
0% (ref)								
Coastal proximity								
<5 km	1.19	0.92 - 1.52	0.98	0.70 - 1.37	1.11	0.85 - 1.45	1.30	0.99 - 1.69
5 - 20 km	1.14	0.87 - 1.49	1.13	0.85 - 1.50	0.95	0.72 - 1.26	1.11	0.85 - 1.45
>20 km (ref)								
Intercept	0.23		-2.39		-1.43		-0.57	
N	2922		2922		2916		2922	
Households	1823		1823		1820		1823	
AIC	3476.92		3260.68		3457.08		3416.98	

Cox & Snell *pseudo*-R^2 (%)	8.78	9.52	5.43	4.21

*p<0.05, **p<0.01, ***p<0.001

[a]OR = odds ratio, [b]CI = confidence interval, [c]N = sample size, [d]AIC = Akaike information criterion

Adjusted for: area level Index of multiple deprivation (IMD); household level variables, income (presented), children, access to a car/van; individual level variables, age, sex, highest education qualification attained, economic status, relationship status, longstanding illness presence, BMI, cigarette smoking status and year.

3.2. Accelerometer data

The correlation between accelerometer measures of average minutes per day of MVPA and at least moderate average self-report minutes per day was within the range of those reported by Skender et al. (2016) (Spearman's rank correlation, ρ =0.32, p<0.001). However, they are not for the same periods of time as the accelerometer was worn for the week after the interview.

3.2.1. Sample counts

As accelerometer data did not differentiate between different domains of PA, only the total weekly PA (average) was explored. Although 59% of the accelerometer sub-sample self-reported meeting PA guidelines, only 17% (n=270) met guidelines according to the accelerometry data (Supp. Table 33).

3.2.2. Model results

Neighbourhood greenspace was not significantly related to meeting total PA guidelines using accelerometry data (Table 4). However, area greenspace coverage of 60-80 % was significantly associated with increased odds of self-reporting meeting PA guidelines in the same subsample (*vs.* <20 % OR_{adj} = 1.67; 95 % CI = 1.10 – 2.54). The point estimate for 80 – 100% was in the same direction but not statistically significant. Neither neighbourhood freshwater coverage of coastal proximity were related to either accelerometer or self-reported PA for this sample. Coastal proximity was significantly related to total self-reported PA in the full sample. This suggests that the reduced accelerometer sub-sample was not representative of the overall sample and/or did not have sufficient power to detect effects. Some covariates were significantly related to meeting PA according to the objective measure (Table 4; Supp. Tables 34-35).

Table 4 Unadjusted and adjusted model results for predicting meeting objective physical activity guidelines (≥150 moderate to vigorous physical activity mins per week) compared to not meeting them (<150 moderate to vigorous physical activity mins per week) and self-reported physical activity for the same sample

	Accelerometer Physical Activity				Self-reported Physical Activity (total)			
	Unadjusted		Adjusted		Unadjusted		Adjusted	
term	OR[a]	95 % CI[b]	OR	95 % CI	OR	95 % CI	OR	95 % CI
Environmental variables								
Greenspace coverage								
80 - 100 %	0.60	0.31 - 1.17	0.85	0.42 - 1.72	1.19	0.75 - 1.88	1.37	0.82 - 2.28
60 - <80 %	0.97	0.60 - 1.57	0.92	0.55 - 1.53	**1.69****	**1.15 - 2.49**	**1.67***	**1.10 - 2.54**
40 - <60 %	0.77	0.47 - 1.27	0.85	0.51 - 1.43	0.89	0.63 - 1.24	0.96	0.67 - 1.36
20 - <40 %	0.73	0.49 - 1.08	0.80	0.53 - 1.23	0.86	0.65 - 1.15	0.89	0.65 - 1.21
0 - <20 % (ref)								
Freshwater coverage								
>5 - 100 %	1.25	0.43 - 3.64	1.17	0.42 - 3.21	1.42	0.68 - 2.97	1.54	0.76 - 3.11
>1 - 5 %	1.38	0.73 - 2.61	1.02	0.50 - 2.09	1.06	0.68 - 1.66	0.91	0.55 - 1.51
>0 - 1 %	1.44	0.71 - 2.92	1.24	0.60 - 2.56	0.98	0.56 - 1.72	0.97	0.53 - 1.78
0% (ref)								
Coastal proximity								
0 - 5 km	1.01	0.69 - 1.47	1.20	0.78 - 1.84	1.10	0.83 - 1.45	1.27	0.93 - 1.75
5 - 20 km	0.83	0.51 - 1.33	0.85	0.51 - 1.41	0.84	0.60 - 1.17	0.84	0.58 - 1.20
>20 km (ref)								
Intercept	-1.47		-2.2		0.35		-0.49	
N[c]	1774		1774		1774		1774	
Households	1382		1382		1382		1382	
AIC[d]	1615.76		1519.58		2402.24		2262.62	
Cox & Snell *pseudo*-R^2 (%)	0.53		10.4		1.20		13.18	

*p<0.05, **p<0.01, ***p<0.001

[a]OR = odds ratio, [b]CI = confidence interval, [c]N = sample size, [d]AIC = Akaike information criterion

3.2.3. By household income

Here we explored coastal proximity only as results for the earlier analyses were most consistent for this environmental variable. However, there were no significant relationships found between coastal proximity and meeting PA levels for any of the household income tertiles. The confidence intervals are typically wide in comparison to the self-report results using the full sample and the sample sizes are smaller (Table 5; Supp. Tables 36 - 38).

Table 5 Adjusted model results predicting meeting PA guidelines according to the objective measure by household income tertile.

Household income quintile		All objective		
	Coastal proximity	OR[a]	95 % CI[b]	Unweighted count
Lowest				
	0 - 5 km	0.80	0.27 - 2.35	102
	5 - 20 km	1.89	0.80 - 4.49	53
	>20 km (ref)			285
Middle				
	0 - 5 km	0.98	0.47 - 2.02	114
	5 - 20 km	0.98	0.48 - 2.03	82
	>20 km (ref)			312
Highest				
	0 - 5 km	1.28	0.62 - 2.62	97
	5 - 20 km	0.49	0.21 - 1.14	74
	>20 km (ref)			374

[a]OR = odds ratio, [b]CI = confidence interval

4. Discussion

4.1. Summary of findings

4.1.1. Research question 1 – neighbourhood green/blue space and physical activity by domain

Those in neighbourhoods with more greenspace were more likely to meet weekly physical activity (PA) guidelines of 150 minutes than those in the least green neighbourhoods through engagement in non-recreational PA (including occupational and gardening/DIY); while we generally found no relationship between greenspace coverage and sports and exercise and a negative relationship between greenspace coverage and walking PA. This partially replicates earlier greenspace findings using the HSE (Mytton et al., 2012), although the overall relationship between total PA and greenspace found previously was not evident in our results. However, Mytton et al. (2012) also found associations between greenspace and both self-reported occupational and domestic manual (DIY and gardening) PA (at 5 x 30 min sessions/week), but not with sports, walking or their bespoke measure of greenspace leisure. There were no significant relationships between freshwater area coverage and PA in any of the domains in contrast with previous research in France (Karusisi et al., 2012) .

Nevertheless, we did find that people who lived closest to the coast (<5km) were more likely to self-report meeting PA guidelines than those who lived >20km. Those living in the intermediate range (5-20km) showed an attenuated, but still significant effect. This supports previous research (White et al., 2014) that used a different dataset (the UK Monitor of Engagement with the Natural Environment [MENE]), and earlier guidelines. We extended previous research by exploring different domains of PA and found that those living <5km were more likely to achieve the guidelines through both walking and non-recreational PA alone; whereas those living 5-20km from the coast were only more likely (*vs*. >20km) to meet guidelines through walking PA alone. Overall, the findings largely support the contention that living near urban green spaces is associated with non-recreational PA while living near the coast, is associated with multiple domains of PA, including walking.

The pattern of relationships between a range of covariates and PA outcomes were similar to previous research. For example, there was a greater likelihood of reporting meeting the 2010 UK Guidelines if the respondents were male, younger, more educated and without limiting illness. This provides some confidence in the quality of the self-reported data, and thus the current findings in respect to both green and blue spaces.

4.1.2. Research question 2 – neighbourhood blue/green space and physical activity by income

Further extending previous work, we find varying relationships between coastal proximity and meeting PA guidelines by household income. The strongest pattern was for those in the lowest income quintile, possibly helping to account for lower health inequalities among England coastal residents (Wheeler et al., 2012). We also found varying relationships by PA domain, with those in the lowest incomes and living closest to the coast more likely to meet PA guidelines through non-recreational activity alone compared to those living further away. We also found a strong relationship between freshwater coverage and walking for those in the lowest household income.

Neighbourhood greenspace was typically not related to meeting PA guidelines. However, for those in the lowest household income quintile, the highest level of greenspace was significantly associated with higher odds of meeting PA guidelines through non-recreational activity. This was also the case in the middle income quintile, although with a reduced effect size.

4.1.3. Research question 3 – neighbourhood blue/green space and objectively measured physical activity

The analysis of accelerometry data from a sub-sample found lower levels of PA as compared to self-report methods, which replicates previous work (Joint Health Surveys Unit and NatCen, 2009). Our results are higher here, 17 % compared to 4-6 % previously, as we use updated guidelines. Nevertheless, we found no relationship between coastal proximity or area level freshwater/greenspace and likelihood of meeting weekly PA guidelines.

4.2. Explanation of results

4.2.1. Research question 1 – neighbourhood blue/green space and physical activity by domain

Although private gardens were not included in our measure of 'greenspace', greener (and less dense) urban areas are also more likely to have greater garden provision (Dennis and James, 2017). This may contribute to our finding that the odds of achieving PA guidelines through non-recreational activity alone was higher in greener urban areas as gardening was included in our measure (see also Mytton et al. (2012)). In support of this, Maas et al. (2008) found a link between greenspace coverage and time spent on gardening; and gardening has been related to PA in the USA, Japan and England, UK (Bail et al., 2018; de Bell et al., 2020; Machida, 2019; Park et al., 2008). Results breaking down the non-recreational PA into occupational and domestic activities also show a strong association between increasing greenspace coverage and occupational activity. This likely reflects that people who live in city centres (with less green space) are less likely to engage in manual labour occupations than those on urban fringes where levels of greenspace are higher (Dennis and James, 2017).

Replicating several earlier cross-sectional (Hillsdon et al., 2006; Maas et al., 2008) and longitudinal studies (Persson et al., 2019), a positive relationship with greenspace was not replicated for either sports and exercise or walking. As Maas et al. (2008) argued, areas with more greenspace may discourage some forms of PA, such as walking and cycling, due to less infrastructure and greater distances to shops and other facilities.

Sports and exercise were not found to be related to any of the environmental variables. Although this domain includes activities typically conducted outdoors such as running and cycling, it also includes activities typically carried out indoors such as going to the gym and keep fit classes. There may be reduced provision of such indoor facilities in less dense areas. For example, in Norwich, England, Panter et al. (2008) found that most gyms were located in the city centre. As such, it may be that there are inverse relationships between green space coverage and outdoor PA and indoor PA facilities, which resulted in no detectable overall relationship in this analysis.

With respect to coastal blue spaces and walking, there is evidence that people enjoy being in these locations more than non-aquatic settings (MacKerron and Mourato, 2013; White et al., 2013), and are more willing to repeat exercise in them (White et al., 2015). Once there, they also tend to spend longer engaging in PA than in non-aquatic settings (Elliott et al., 2015), which would help people accumulate the duration needed to meet guidelines.

The relationship between non-recreational PA and coastal proximity is less easily explained. Coastal residents may be more likely to have physical occupations, such as fishing. However, this seems unlikely to be the full explanation given the numbers of people employed in the fishing industry nationally (a total of 5,900 fishers in England in 2012 (Marine Management Organisation, 2013)). Mytton et al. (2012), also using the HSE, found a relationship between greenspace and non-recreational activities, which we extend to coastal proximity and some of the mechanisms may be the same. Our assertion that there may be the opportunity for occupations with more physical activity nearer the coast is supported by the finding that the strongest relationship between non-recreational activity and coastal proximity is for those in the lowest incomes who are more likely to be performing manual occupations.

4.2.2. Research question 2 – neighbourhood blue/green space and physical activity by income

Those in the lowest household incomes are perhaps most likely to be undertaking PA whilst at work. Manual workers have been found to be more likely to achieve PA guidelines (Poortinga, 2006). Those living both closest to the coast and 5 – 20 km in this income quintile were also more likely to meet PA guidelines through walking activity compared to those living further away. The results across the remaining household income quintiles were mixed. There were significant relationships detected between PA and coastal proximity in both the middle and second highest income quintiles at different proximities.

Why this pattern should only exist for those in the lowest, middle and second-highest income quintiles, as opposed to all quintiles, is less clear. For those in the lowest income quintile, where there may be financial resource limitations, proximity to facilities for physical activity, such as coast paths, may be of greater importance than for those in other quintiles.

4.2.3. Research question 3 – neighbourhood blue/green space and objectively measured physical activity

We find a discrepancy between physical activity attainment measured through self-reporting compared to the accelerometer. Of those who self-reported meeting PA guidelines, 23% met PA guidelines according to accelerometry data, while nearly 8% of respondents who met guidelines using accelerometry data did not self-report meeting them. Correlations between objective and questionnaire-based methods exhibit considerable variation (Hagstromer et al., 2010b; Skender et al., 2016). We consider that the potential effect of self-selection bias for self-reported activity is minimal as the survey is designed to be nationally representative and we had few missing data values for the outcome variable. There were no missing variables for total PA, 56 for walking, 9 for sports and exercise and one for non-recreational. Although some level of over-reporting of PA is considered likely, the PASBAQ used here is associated with lower over-reporting levels than the more familiar IPAQ (Scholes et al., 2016).

The accelerometer thresholds used by the HSE were developed by Troiano et al. (2008) by combining results from several studies (Brage et al., 2003; Freedson et al., 1998; Leenders et al., 2001; Troiano et al., 2008; Yngve et al., 2003), which generally assessed energy expenditure in young (under 30) and healthy adults. The actual energy expenditure associated with these cut-offs are likely to vary with individual fitness level (Ozemek et al., 2013). Further, they may be underestimating energy expenditure for those with chronic health conditions in particular (Dibben et al., 2019) and may not accurately reflect the energy expended walking or running uphill (Aresu et al., 2009b). These may account for some of the discrepancy between accelerometer and self-reported PA measures.

The results from the self-reported measure suggest there is a relationship between coastal proximity and physical activity, which was not replicated by accelerometer-measured PA. One possible explanation of this difference might be that respondents were asked to remove the accelerometer during water-based activities and thus these activities are therefore not recorded by those most likely to engage in them (i.e. coastal/freshwater residents). Although possible, this is unlikely given the very low number of even coastal residents who engage in these type of activities on a regular basis in the UK (Elliott et al., 2018; Pasanen et al., 2019). An alternative explanation might be that coastal residents (and those living near freshwater) are more likely to 'over-report' their levels of PA, and that any bias is particularly strong among those in the lowest income quintile.

However, perhaps more tellingly, self-reported PA among the accelerometer sub-sample was also not related to coastal proximity, whereas it was in the full model sample. This suggests that the reduced sub-sample was either not representative of the overall sample (Roth and Mindell, 2013) and/or had insufficient power to detect effects. Supporting these possibilities, there were also no significant effects on self-reported PA of covariates such as gender, education and area deprivation which were seen in the overall sample. The UK Biobank (https://www.ukbiobank.ac.uk) may represent a resource for further research on this question, with a larger sample size of accelerometer collected PA data, although it is not representative of the whole population (Smith et al., 2019).

4.3. Strengths and limitations

The current study had a number of strengths including the large sample size from a representative national survey and the inclusion of a range of covariates. It is also a strength that we considered a range of different relationships and find that these vary by environment, PA domain and household income. Further, despite the lack of a detectable association, it is also a strength that we attempted to replicate the relationship using accelerometer data as a more objective measure of PA. However, despite these strengths the study also has several limitations.

The most obvious is the cross-sectional nature of the data, therefore we are unable to identify causality in these associations; for example, it may be that more physically active people tend to move home to be closer to green/blue spaces. More longitudinal research that tracks people's levels of PA before and after a home relocation to a more or less green/blue area, as has been done for mental health (e.g. (Alcock et al., 2014)), is needed. Further, although the date of interview and region of residence were recorded during the survey, these data are not made available to researchers for reasons of confidentiality. We can therefore not account for seasonal or regional variance (or regional clustering) in the data (Cepeda et al., 2018; Schepps et al., 2018) which have been documented for PA (Scholes and Mindell, 2012), recreational visits to natural environments (Boyd et al., 2018) and the relationship between coastal proximity and self-reported PA (White et al., 2014).

A third limitation was that, due to confidentiality requirements, our measures of greenspace, freshwater coverage and coastal proximity were based on LSOA coverage or weighted centroid distance rather than distance buffers from people's homes, potentially leading to errors in exposure estimation. There was also a lack of information on the quality, accessibility, or actual use of these spaces (Flowers et al., 2016). Improved area metrics may refine our estimates further. We also recognise a time mismatch between when the environmental variables were derived (2005/2007) and the earliest physical activity data used (2008), potentially introducing some error. However, such data have been used in previous work (Alcock et al., 2014; Garrett et al., 2019; Pasanen et al., 2019); and we ran a sensitivity analysis for the year 2008 only (the closest in time to the land cover measures), which resulted in very similar findings.

Fourth, accelerometers do not record cycling movements accurately (due to a lack of up-and-down motion) and participants were told to remove them while doing any water-sports. These are clear limitations when investigating the role of coastal proximity. Cycling may be a relatively important activity in blue spaces compared to other types of natural environment (Jansen et al., 2017), though as noted above the number of people engaging in watersports is relatively small (Elliott et al., 2018). With the rise in wearable technology, people are becoming more familiar with such devices and such data collection methods are likely to become more widespread in the future, enabling larger samples of more objective PA.

5. **Conclusion**

Our findings replicate and extend previous research in several ways. Contrary to intuition, we did not find people more likely to be reporting meeting recommended PA guidelines through the predominantly recreational activities of sports and exercise and walking in greener neighbourhoods; rather, replicating a previous analysis of HSE data, greener areas were associated with a greater likelihood of meeting activity guidelines through non-recreational activity including gardening and occupational activity. The self-report data also replicated earlier findings that people who lived near coastal waters were more likely to meet guidelines via walking, supporting the idea that these places are particularly good at encouraging this kind of PA. There was also some indication that the effects were most robust among the lowest income quintile, but the findings were mixed and further studies are needed to clarify the effects. Importantly, the self-report findings were not replicated using the accelerometer data. The small sample size may be a key reason, as this sample did not replicate the self-report data either. Further research could capitalise on the growing use of wearable technology although such results may generate their own biases if the sample is not representative.

Supplemental materials

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CRediT authorship contribution statement

JKG: Conceptualisation; Methodology; Formal analysis; Writing – original draft; Writing – review and editing; Visualisation. **MPW**: Conceptualisation; Methodology; Data Curation; Writing – original draft; Writing – review and editing. **LRE**: Methodology; Writing – original draft; Writing – review and editing. **BWW**: Methodology; Data Curation; Writing – review and editing; Project administration**. LEF**: Writing – review and editing; Funding acquisition.

Declaration of competing interest

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

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