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Research paper

Exploring associations between urban green, street design and walking: Results from the Greater London boroughs

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HIGHLIGHTS

- The study examines *salutogenic* environment effects of urban green upon walking.
- The study comprised $N = 15{,}354$ respondents of the London Travel Demand Survey.
- Density of street trees was associated with higher odds of walking.
- Street-level *betweenness* at 400 m was associated with higher odds of walking.
- NDVI and density of street trees were positively associated with *distance walked*.

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ABSTRACT

In recent years, a series of studies have highlighted the positive effects of urban green on individual activity behaviour and health. In this paper, we examine *salutogenic* environment effects of urban green upon walking behaviour and how such effects are mediated by built environment configuration and street-level physical accessibility. The dwelling locations of $N = 15{,}354$ respondents of the London Travel Demand Survey were geocoded and individual walking behaviour was extracted from the travel diary. A 0.5-m resolution normalized difference vegetation (NDVI) index derived from spectral reflectance measurements in remotely sensed colour infrared data was employed as an objective measure of *greenness*, while density of street trees acted as proxy of perceived environmental quality in street corridors. A network model of street-level physical accessibility was developed using spatial Design Network Analysis (sDNA). Logistic regression models reported a significant association of odds of walking with density of street trees and street-level *betweenness* (a measure of street network connectivity), while sensitivity analyses with continuous regression models for participants doing some walking indicated beneficial associations of distance walked with NDVI greenness and street trees. The results illustrate the necessity for targeted intervention strategies in activity-friendly planning via greening and optimized physical design of urban built environments.

1. Introduction

With the alarming increase in the prevalence of obesity and associated chronic cardio-metabolic diseases, *active travel*, has in recent years, emerged as a new mantra for public health promotion (APHA, 2012; Lee & Buchner, 2008; NICE, 2012; WHO, 2002). Walking is the most common form of moderate-intensity physical activity (Pate et al., 1995; USDHHS, 1996). Accumulated epidemiological evidence has highlighted that active travel in the form of walking and cycling can minimize or offset health costs of sedentary lifestyles via increments in individual energy expenditures (Eyler, Brownson, Bacak, & Housemann, 2003; Flint, Cummins, & Sacker, 2014; Jarrett et al., 2012; Sallis, Frank, Saelens, & Kraft, 2004; Warburton, Nicol, & Bredin, 2006).

Constituent components of the built environment have been shown independently to promote walking and influence other physical activity behaviour (Lee & Moudon, 2006; Nagel, Carlson, Bosworth, & Michael, 2008; Owen, Humpel, Leslie, Bauman, & Sallis, 2004; Pikora et al., 2006; Saelens & Handy, 2008; Saelens, Sallis, & Frank, 2003; Suminski, Poston, Petosa, Stevens, & Katzenmoyer, 2005). In their many forms, urban green spaces constitute one of the most important components of the built environment in

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influencing walking, physical activity, health and mortality (Astell-Burt, Mitchell, & Hartig, 2014; De Vries, Verheij, Groenewegen, & Spreeuwenberg, 2003; Giles-Corti & Donovan, 2002; Lee & Maheswaran, 2011; Mitchell & Popham, 2008; Sugiyama, Leslie, Giles-Corti, & Owen, 2008; Takano, Nakamura, & Watanabe, 2002). The planting of trees in urban streetscapes has been practised for many centuries, as manifested in some of the earliest historic plans and paintings of European cities from the Renaissance period. Lawrence (2008) sets out the history of street trees in Europe and America, and their impact on the social and economic activity of the city. Following late 17th century French and Dutch landscape design traditions, street trees have been typically formalized as *allées/avenues and boulevards* of tall, evenly sized trees planted along major thoroughfares; and these continue to constitute an integral part of contemporary urban design practices (Grey & Deneke, 1986; Southworth, 2005). The health-promoting role of street trees has been highlighted in several studies (Lovasi, Quinn, Neckerman, Perzanowski, & Rundle, 2008; Lovasi et al., 2013).

Urban green has been shown to influence walking, physical activity and health outcomes (Hartig, Mitchell, De Vries, & Frumkin, 2014; Webster et al., 2015) and five underlying causal mechanisms have been identified:

- providing facilitative settings that promote physical activity in the form of enhanced walking, green exercise and cycling (Bedimo-Rung, Mowen, & Cohen, 2005; Maas, Verheij, Spreeuwenberg, & Groenewegen, 2008),
- facilitating social contact and fostering a sense of community (Kweon, Sullivan, & Wiley, 1998; Maas, Van Dillen, Verheij, & Groenewegen, 2009),
- providing opportunities for natural healing through recovery from physiological and psychological stress (Grahn & Stigsdotter, 2003; Hartig, Evans, Jamner, Davis, & Gärling, 2003; Ward Thompson et al., 2012; Woo, Tang, Suen, Leung, & Wong, 2009),
- acting as natural sieves, absorbing and diluting urban pollution and thereby ameliorating adverse environmental exposures (Nowak, Crane, & Stevens, 2006) and
- mitigating adverse health impacts of urban heat island effects (Loughner et al., 2012; Shashua-Bar & Hoffman, 2000).

Considerable research effort has begun to be focussed on both understanding the causal mechanisms listed above as well as on the design and configuration of walkable cities (Boer, Zheng, Overton, Ridgeway, & Cohen, 2007; Cerin, Leslie, Toit, Owen, & Frank, 2007; Forsyth, Hearst, Oakes, & Schmitz, 2008; Gómez et al., 2010; King et al., 2003). This agenda is gathering momentum as public health scientists and professionals have discovered a renewed appreciation of the link between health and the built environment. The urgency from the landscape and planning side is influenced, among other factors, by the continuing threat to city eco-systems brought about by densification and, ironically, restrictive growth boundary policies (Moll, 1989 on New York; Pauleit, Ennos, & Golding, 2005 on Sheffiled and Länsstyrelsen, 1996, on Stockholm). A recent survey of cities by the WHO European Healthy Cities Network highlights significant cross-country variability in accessibility to urban green; with almost all residents of the Northern European cities of Brussels, Copenhagen and Glasgow, for example, having access to neighbourhood green space within 15 minutes, but only 47% of the population of the cities of Bratislava and Kiev having the same level of access (Tsourou, 1998). In England, English Nature has stipulated standards for assessing provision of natural green space, termed the Accessible Natural Green space Standard (ANGsT). ANGsT recommends that everyone should have access to natural green space of:

- At least 2 ha within 300 m of their home,
- At least 20 ha within 2 km,
- At least 100 ha within 5 km, and
- At least 500 ha within 10 km.

Traditionally, greening pedestrianization has largely been limited to a small proportion of segments around city centres where pedestrian use outweighs vehicular movement needs. Contemporary landscape design practices continue generally to aim towards the creation of *shared places*, creating provisions for appropriate mixed modes of travel. In the Greater London Authority (GLA), approximately 47% of land area is green with 33% of this being vegetated public space and an additional 14% vegetated private green space and domestic gardens (http://www.gigl.org.uk/our-data-holdings/keyfigures/). The Mayor's London Plan has set standards of accessibility to urban greenery that aim for every Londoner to have a small or local park (less than 20 ha) within 400 m of their home, a district park (20–60 ha) within 1.2 km and a metropolitan scale park (60–400 ha) within 3.2 km (Mayor of London, 2008). A study of the English city of Bristol found that 55% of people live within 300 m of an urban green space with mean distances ranging from 2207 m for young people's type of space, 1758 m for formal, 1082 m for sports, 570 m for natural green, and 481 m for informal green space types (Hillsdon, Jones, & Coombes, 2011).

Recently, The Marmot Review (2010) highlighted the benefits of improving quality and accessibility of green spaces across socio-economic gradients as well as emphasizing the role of well-designed car-free pleasant streets in achieving this. In the UK several studies have highlighted significant spatial inequalities in access to health-promoting physical environments, urban parks and hence health induced by neighbourhood deprivation (CABE, 2010; Mitchell & Popham, 2008; Pearce, Richardson, Mitchell, & Shortt, 2010; Shortt, Rind, Pearce, & Mitchell, 2014).

Notwithstanding the heightened interest and the scientific research and official reports mentioned above, there is still ambiguity in the evidence about the relationship between access to urban greenery and walking and physical activity. This arises primarily as a result of the varied definitions of urban green; diverse methods employed to parameterize them; as well as the problem of causal inference. It is difficult to establish causality as a large proportion of studies focus on parks and open spaces as the unit of analysis in defining 'urban green', thereby conflating their functional roles in delivering a specific health benefit. It is difficult in such studies to conclude whether the health benefits have accrued from their functional roles as 'purely recreational spaces' or from their role more generally as 'salutogenic' environmental spaces'. Furthermore, there have been very few studies of the direct associations between urban greenery and individual-level active travel behaviour that adjust for urban morphology, neighbouhood-level deprivation and other confounding factors. In the absence of such adjustments (statistical controls), it cannot be confidently asserted that any variations in walking behaviour observed between individuals or between sampled neighbourhoods or other spatial units of analysis, is caused by differences in green space access and configuration per se. Where studies use aggregate measures, for example, correlating green space density and walking trips for sampled zones, there are the additional complications of the so called Modifiable Area Unit Problem and Ecological Fallacy. The former means that we cannot be sure whether a measured relationship between greenery and walking is reliable because alternative methods of aggregating will always yield different results. The latter problem means that we cannot reliably make generalised statements about individuals, the fundamental agents of an urban eco-system, on the basis of aggregate data because we are not accounting for possibly causally significant variations of individual patterns within the population in aggregated spatial units.

By using individual data on walking behaviour and predominantly point-based spatial analysis, we can reduce these structural research design problems. The focus of the present study is to capture the salutogenic environment effects of urban greenness operationalized in terms of total green surface area. A Normalized Difference Vegetation Index (NDVI) of greenness acts as a measure of objective greenness while, density of street trees has been used to capture the perception of greenness and quality of street environments. We hypothesize that the presence of urban green and well-designed street layout beneficially influences individual's walking behaviour. We employ the large-scale London Travel Demand Survey data with the objective of assessing independent associations between urban green, density of street trees and individual-level walking behaviour. The study also explores how the above-mentioned associations are mediated by urban morphology, expressed as street-level physical accessibility, as well as by neighbourhood deprivation. Our unique contribution to this field of research is thus made by (a) measuring the associations between greenness and walking at an individual level of analysis; (b) doing this while controlling for socio-economics, accessibility and other factors that can also be expected to influence walking; (c) investigating the effects of accessibility using sensitive network measures of connectivity; and (d) conducting an analysis of both walking/non-walking and degree of walking. To our knowledge, this is the first study to have conducted such a refined study of this nature with a large *N*.

2. Materials and methods

2.1. Study sample

Travel data were obtained from the London Travel Demand Survey (LTDS), an annual household rolling survey conducted by Transport for London over 2005/6–2009/10 to study the travel patterns across 32 London boroughs as well as the area outside Greater London Authority but within the M25 motorway (TFL, 2011). LTDS (2005-2010) comprised 85,650 individuals residing in 37,248 households and achieved a 52.6% response rate. A stratified sampling design was used so that there were 250 participants per borough. Face to face interviews conducted by trained interviewers captured information across key domains of individual participant, their household, trips, trip stages and vehicles. An individual questionnaire captured information on personal socio-demographics and travel behaviour of the interviewee; and a household questionnaire captured information about the individual's household location, structure and basic demographics. The *trip component* included details of trip purposes, modes used, trip start and end times, and the locations of trip origins and destinations while the *stage component* contained information about the origin and destination of individual trip stages. The present study comprised a geocoded sample of $N = 15,354$ (80%) participants of LTDS2009/2010 survey aged 5 and above and residing within the Greater London Authority in 7161 households within 3770 lower super output area neighbourhoods.

The individual, household, trip and trip stage components of LTDS were linked together via unique IDs; and total distance walked by an individual participant was enumerated from the trip stage data by summing up all walk stages.

2.2. Measures of urban greenery and built environment configuration

The study employed two separate measures of urban green to capture the various attributes of urban green environments. Normalized Difference Vegetation Index (NDVI) was employed as an objective measure of general urban greenness. This index has already been validated as a measure of neighbourhood greenness in epidemiological research, showing a strong correlation with expert's ratings (Rhew, Vander Stoep, Kearney, Smith, & Dunbar, 2011). It has been employed in several studies of associations between greenness and walkability and physical activity (Bell, Wilson, & Liu, 2008; Grigsby-Toussaint, Chi, & Fiese, 2011; Liu, Wilson, Qi, & Ying, 2007; Pereira et al., 2013; Troped, Wilson, Matthews, Cromley, & Melly, 2010; Wendel-Vos et al., 2004). The NDVI is an unit-less index calculated from the spectral reflectance measures in satellite data, comparing the amount of energy absorbed by the chlorophyll in the red portion and the amount scattered by the internal structure of the leaves in the near-infrared region. This contrast has been employed as an estimate for vegetation greenness, as indicated by the following formula:

$$\text{NDVI} = \frac{(\text{NIR} - \text{RED})}{(\text{NIR} + +\text{RED})}$$

where RED and NIR stand for the spectral reflectance measurements acquired in the visible (red) and near-infrared regions, respectively. The index ranges between −1 and +1, with higher values reflective of healthy green vegetation and vice versa. Typical NDVI values range from 0.6–0.8 for temperate and tropical rainforest, 0.2–0.3 for shrub and grassland, 0.1–0.2 for bare soil, 0.1–0.0 for barren rock, sand and snow while free-standing water bodies may have very low positive or negative NDVI. A collection of 0.50 m resolution Colour Infrared (CIR) imagery data generated by Blue Sky across the similar temporal scales were merged together (to avoid temporal mismatch and the resulting influence on account of seasonal variability in greenness), with areas of interest extracted and employed in the calculation of NDVI index in Raster Calculator Spatial Analyst, ArcGIS 10.2. The CIR band 2, 630–690 nm, was used as the red region of the electromagnetic spectrum, while band 1, 760–900 nm, acted as the infrared region, so that the formulae used was NDVI = (band 1 − band 2)/(band 1 + band 2). Neighbourhood greenness was calculated in terms of mean and standard deviation in the NDVI values within 0.5 kilometre circular buffers around the LTDS respondent's dwelling (see Fig. 1).

The second measure employed in this study is the density of street trees, as a proxy of perceived urban green and street environment. We posit that as an individual navigates through urban space, the presence of street trees in the constantly updating visual field (longest lines of sight) helps constitute a positive perception of the environment and hence promotes walkability. Trees in urban street corridors are associated with shade, shelter, environmental comfort and general aesthetics. Not only do they define our perception of the quality of street environments, but also to a considerable degree, help form our perception of neighbourhood urban green more generally. The density of street trees was calculated as the number of street trees per sq kilometre within a 1 kilometre street network buffer of each participant's dwelling location. The locations of digitized single-tree canopies were extracted from the Topo-Overlay layer of the UK Map spatial database (http://www.geoinformationgroup.co.uk/products/ukmap).

The impact of urban morphology on walking, physical activity and health can be captured through measures of street-level physical accessibility (Sarkar, Gallacher, & Webster, 2013a, 2013b, 2014a; Sarkar, Webster, & Gallacher, 2014b). In our study, this has been modelled through a sophisticated urban network analysis technique called spatial Design Network Analysis (sDNA) (Chiaradia, Crispin, & Webster, 2012). sDNA can be employed with any standard network database and is able to model 20 localized network accessibility indices (pertaining to network centrality, detour, shape and efficiency, link characteristics, radius-based measures) at user-specified network spatial scales (catchments) and append these measures to individual network links. This

Fig. 1. (a) Indicates the extents of the study area and 0.5 m resolution index of greenery (as captured by NDVI modelled from colour infrared imagery). (b) and (c) Depict the urban green around a specific LTDS dwelling address 'A'. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

allows the analyst to capture behaviourally meaningful subtleties in urban street networks influencing individuals' walking and travel behaviour. In the present study, Ordnance Survey Mastermap Integrated Transport Network (ITN) layer was employed as the base network database to prepare an sDNA physical accessibility model of street links within the study area. In an urban network, geometric distance cost ('angular turning friction through a network') rather than metric distance cost ('linear length of network traversed') has been shown to act as better a predictor of pedestrian movements (Hillier & Iida, 2005). Least angular (geometric) analysis was conducted within a metric catchment area (radius) to measure connectedness at different spatial scales that correspond to different modes of travel (behavioural justification further elaborated below). Network centrality was assessed through *betweenness*, which measures the *through-movement potential* of a street link in that part of the urban network included within the chosen radius. Betweenness is proportional to the estimated count of movements passing through the link from and to all other parts of the network, assuming that journeys in the network follow the shortest angular path between all pairs of segments. The betweenness of a road network link measured within a subset of the network contained within, for example, a 400 m radius centred on that link, represents the degree of through-movement expected along the link on the basis of its connectivity to other parts of the network within a walking distance radius. As such, when compared with betweenness measures (400 m radius) for other links, it can be taken as a relative indicator of the degree of pedestrian through-traffic. The equivalent 3000 m betweenness measures for links can be taken as indicators of relative degrees of through movement of car-born traffic.

Since longer street links generally tend to have more origins and destinations (OD) than shorter street links, thereby supporting more trips; it is customary to account for this using link length-weighted betweenness. In graph notation, link length-weighted sDNA betweenness of x in a graph of *N* links may be defined as:

$$\text{Bt Wl}(x) = \sum_{y \varepsilon N} \sum_{z \varepsilon R_y} L(y)L(z)P(z)OD(y, z, x)$$

where y and z are the geodesic end points; R_y is the set of links within a defined radius from y; $L(y)$ and $L(z)$ are length of links y and z, respectively; P_z is the proportion of link z within the defined radius.

OD is a function defined as:

$$\text{OD} = \begin{cases} 1, & \text{if } x \text{ is on the geodesics from } y \text{ to } z \\ \frac{1}{2}, & \text{if } x \equiv y \not\equiv z \\ \frac{1}{2}, & \text{if } x \equiv z \not\equiv y \\ \frac{1}{2}, & \text{if } x \equiv z \equiv y \\ 0, & \text{otherwise} \end{cases}$$

The notions of metric and geometric costs and betweenness are illustrated in Fig. 2. Betweenness was measured at catchment radii of 400 m (for walk trips) and 3000 m (for longest walk trips), as illustrated in Fig. 3. We chose these radii to correspond to the median distance walked and the top 99 percentile of the walk trips for LTDS 2009/10 (445 m and 2875 m respectively). This corresponds well with other studies (Porta, Romice, Maxwell, Russell, & Baird, 2014). Once calculated, these measures were attributed to the street link closest to a given LTDS participant's dwelling location.

Other measures of built environment quality used comprised access to service destinations, crime, road safety and deprivation measured at the level of lower super output areas (LSOAs). The UK Office of National Statistics defines LSOAs as relatively stable, compact geographical units with reasonable degrees of homogeneity in shape and social composition (Bates, 2006). The *geographical barriers* sub-domain of the English Indices of Multiple Deprivation (EIMD), 2010, which is a composite index of street distances to GP surgery, supermarkets/convenience store, post office and primary school, was employed as a proxy of access to service destinations. The *crime* sub-domain of EIMD, which is a composite index of number of reported violent crimes, theft, burglary and criminal damage per 1000 individuals, was employed as an indicator of public space insecurity that inhibits walking. Road safety was operationalized in terms of number of fatal or major accidents in the LSOA of a respondent's dwelling. The STATS19 accidents database of 2009 was geocoded for this purpose (http://data.gov.uk/dataset/road-accidents-safety-data). The income and employment domains of EIMD were used as indicators of neighbourhood-level deprivation.

2.3. Individual covariates

Self-reported individual-level covariates were extracted from the individual component of LTDS and comprised age, gender, ethnic group, prevalence of disability, household income and access to car. Since we have income at the individual level, the deprivation measure acts as a neighbourhood effect variable rather than an income surrogate.

2.4. Statistical analyses

Walking, expressed as total distance walked in kilometres, was modelled as a two-level outcome (doing some walking vs. not walking) using a cut-off point of 100 m to minimize underreporting in cases of short walk stages. In the second series of models for sensitivity analyses, with a subset of the LTDS participants in the category 'doing some walking', walking was treated as a continuous outcome variable.

Ethnic group was expressed in 20-categories in the original LTDS data and subsequently collapsed into a four level factor (White, Asian, Black, Mixed and others). Prevalence of disability was modelled as a two-level factor expressed in terms of presence or absence of one or more of the eight disability categories. Access to cars was modelled as a three level factor (none, one and more than one). The 10-category imputed household income was banded into a four level factor (<£15,000, £15,000–£35,000, £35,000–£75,000 and >£75,000).

For ease of interpretation of results, the continuous scale NDVI index, betweenness indices at 400 and 3000 m, neighbourhood accessibility to services, crime index, and income and employment deprivation were all transformed into quartiles with the lowest quartile acting as a reference category. Neighbourhood road safety was a three-level factor expressed as zero, one or more than one major/fatal accidents. Standardized *z*-scores were used for density of street trees.

We used a two-part modelling strategy to examine the independent associations between urban green and walking after statistically adjusting for urban morphology and deprivation. In the first part, distance walked was calculated from the LTDS trip-stage database and transformed to a binary outcome variable (cut-off ≥100 m). A series of logistic regression models were fitted on 'doing some walking vs. not walking' to explore the independent associations with neighbourhood-level built environment attributes. For sensitivity analysis, the second part focussed on a subset of LTDS data falling under the category *doing some walking*, with walking being expressed as a continuous variable (total distance walked in kilometres). A series of continuous regression models were

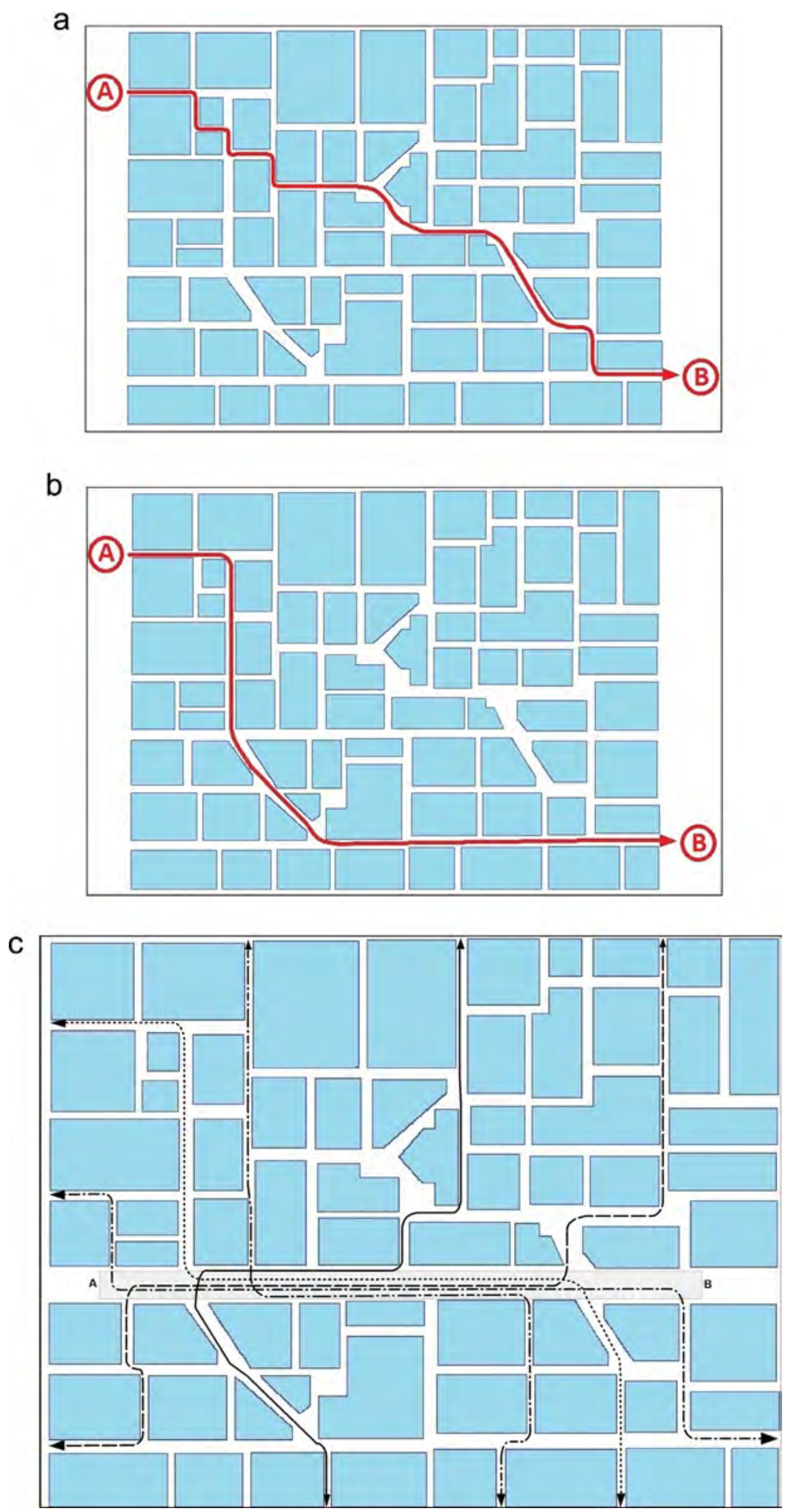

Fig. 2. Street network configurations (a) Route section AB associated with least metric costs and higher geometric and topological costs (b) Route section AB associated with least angular costs (c) Route section AB associated with high path overlap and high through movement potential (betweenness). *Source*: Reproduced from Sarkar et al. (2013a) Health and Place, 19, 33–44.

constructed to examine the relationship between distance walked and neighbourhood-level built environment attributes, including greenery.

Statistical analyses were performed in Stata 11.2 statistical software package. Robust standard errors in Stata 11.2 enabled us to take account of potential LSOA-level clustering.

3. Results

The LTDS (2009/2010) data comprised 37,330 walk stages for 25,614 trips with 49.9% of all trips being *walk only* trips, where the participant walked all the way. The median and top 99% percentile walk distances were 445 and 2875 m, respectively. 56.1%

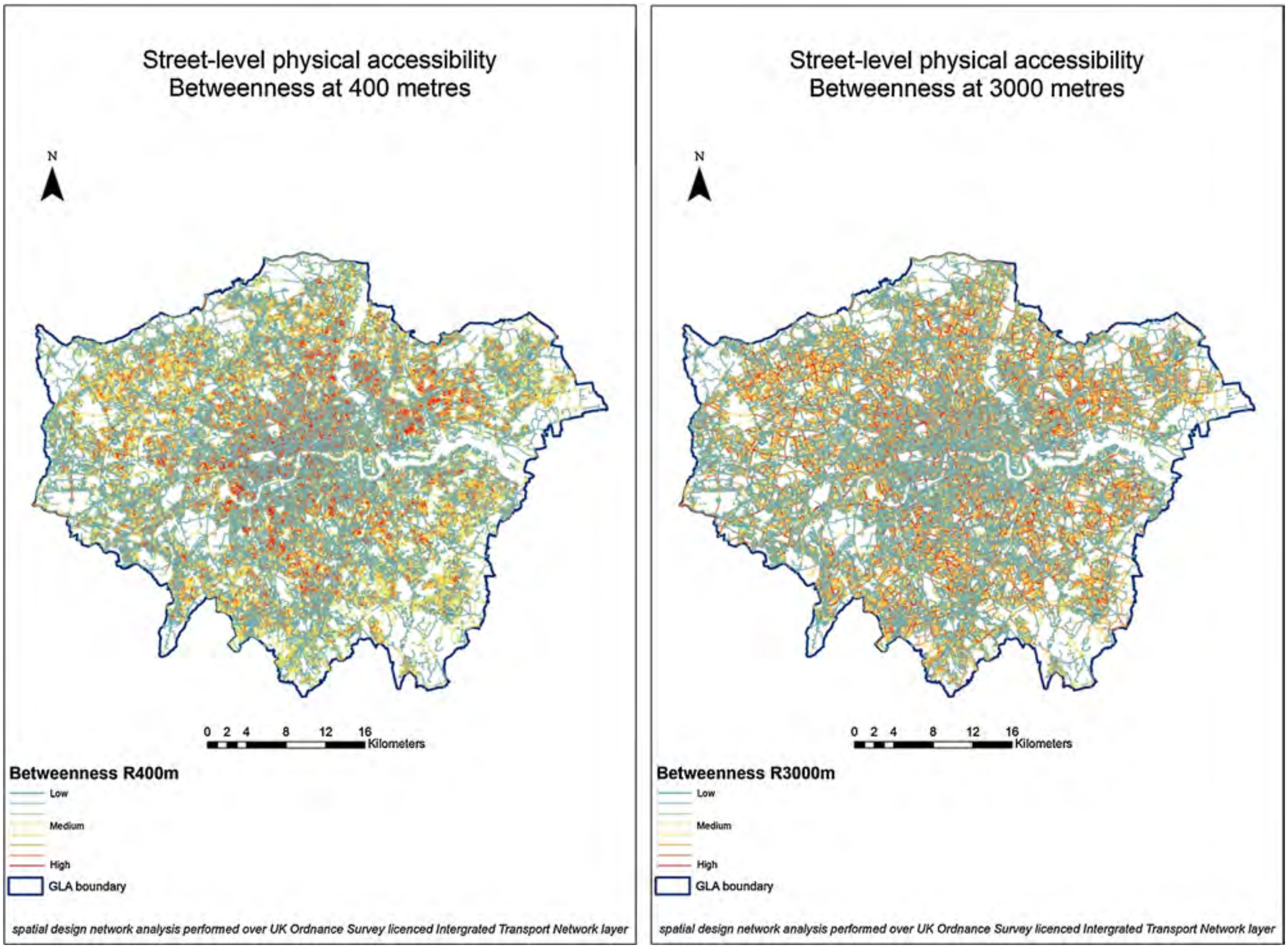

Fig. 3. Street-level betweenness measured at 400 and 3000 m as indices of urban morphology and physical accessibility.

of the study participants did *some walking*. The descriptive statistics of individual-level variables are presented in Table 1. The LTDS (2009/2010) participants had a mean age of 39.4 years (SD = 20.9 years) and walked an average distance of 0.93 km over 21.1 min duration. Females accounted for 52.20% of the cohort while 10.03% of the whole sample had some form of disability. The ethnic make-up comprised 65.90% White, 16.57% Asian, 11.41% Black and 6.12% Mixed and other ethnicity. 28.53% of the households had no access to private car, 42.91% had one car and 25.63% had more than one car. The lowest category of annual household income (less than £15,000) constituted 28.95% of the cohort, while 13.20% fell into the highest income category (greater than £75,000). The mean NDVI was 0.28 (SD = 0.06). Table 2 summarizes the mean distance walked against individual and neighbourhood-level attributes. Data indicate that a smaller proportion of adults walked as compared to children and the mean distance walked was 0.82, 1.20, 1.10, 0.86 and 0.63 km for age groups 5–16, 17–30, 31–42, 43–58 and 59–99 years, respectively. The proportion of females and males doing *some walking* was 57.3% and 54.8%, while the mean distance walked was 0.92 and 0.94 km, respectively. Comparing ethnic groups, a smaller percentage of Whites did *some walking* compared to Black and Asian participants, while their mean distance walked was comparatively higher than the later. As expected, distance walked was much less among participants with disability and participants with access to vehicles. Walking behaviour increases with increasing local-level street betweenness at 400 m as well as with access to service destinations.

Table 1
Descriptive statistics of covariates.

Variable name	Mean (SD)/frequency (%)
Age	39.37 (20.89)
Gender	
Male	47.80%
Female	52.20%
Ethnic group	
White	65.90%
Asian	16.57%
Black	11.41%
Mixed and others	6.12%
Disability	
None	89.97%
Yes	10.03%
Access to cars	
None	28.53%
One	42.91%
>One	25.63%
Household income (£)	
<15k	28.95%
15–35k	30.70%
35–75k	27.15%
>75k	13.20%

The results of logistic regression models associating *doing some walking* and urban green, street design and neighbourhood level factors are presented in Table 3. Model 1 comprises urban green variables adjusted for individual-level factors of age, gender, ethnic group, prevalence of disability, access to vehicles and household income. Variables for urban morphology and accessibility have been added in model 2, while neighbourhood-level deprivation and road safety have been added in model 3. Among the urban green

Table 2
Mean distance walked by individual and neighbourhood-level attributes.

Individual and neighbourhood level attributes	Sample size	Do some walking (%)	Mean (95% CI)
Age			
5–16	2448	62.2	0.82 (0.78, 0.87)
17–30	3423	63.4	1.20 (1.15, 1.25)
31–42	3158	58.1	1.10 (1.05, 1.16)
43–58	3139	50.6	0.86 (0.81, 0.91)
59–99	3186	48.9	0.63 (0.59, 0.67)
Gender			
Male	7338	54.8	0.94 (0.91, 0.98)
Female	8016	57.3	0.92 (0.90, 0.95)
Ethnic group			
White	10,119	55.2	0.96 (0.93, 0.99)
Asian	2544	56.3	0.84 (0.79, 0.89)
Black	1752	57.2	0.86 (0.80, 0.92)
Mixed and others	939	62.3	1.02 (0.94, 1.11)
Disability			
None	13,814	57.9	0.98 (0.96, 1.01)
Yes	1540	39.5	0.49 (0.44, 0.53)
Access to cars			
None	4381	77.1	1.23 (1.19, 1.27)
One	6588	53.2	0.88 (0.84, 0.91)
>One	3935	43.9	0.66 (0.62, 0.70)
Household income			
<15k	4445	56.0	0.84 (0.81, 0.88)
15–35k	4713	56.8	0.92 (0.89, 0.96)
35–75k	4169	56.2	0.99 (0.95, 1.04)
>75k	2027	54.5	1.02 (0.96, 1.09)
Urban morphology and accessibility			
Street-level betweenness 400 m			
Q1—Lowest	3839	55.6	0.92 (0.87, 0.96)
Q2	3839	53.9	0.88 (0.84, 0.93)
Q3	3839	54.5	0.92 (0.88, 0.97)
Q4—Highest	3837	60.3	1.01 (0.96, 1.05)
Street-level betweenness 3000 m			
Q1 – Lowest	3840	56.7	0.94 (0.89, 0.98)
Q2	3839	54.9	0.91 (0.86, 0.95)
Q3	3837	55.8	0.94 (0.90, 0.98)
Q4—Highest	3838	56.9	0.95 (0.91, 0.99)
Lack of access to service destinations			
Q1—Lowest	3848	63.0	1.10 (1.05, 1.14)
Q2	3831	58.6	0.98 (0.93, 1.02)
Q3	3840	53.0	0.82 (0.87, 0.91)
Q4—Highest	3835	49.7	0.79 (0.75, 0.83)
Income deprivation			
Q1—Lowest	3957	54.3	0.96 (0.91, 1.01)
Q2	3932	55.0	0.93 (0.89, 0.97)
Q3	3907	56.1	0.92 (0.88, 0.96)
Q4—Highest	3558	59.3	0.92 (0.88, 0.96)
Employment deprivation			
Q1—Lowest	4925	54.3	0.95 (0.91, 1.00)
Q2	3466	53.9	0.87 (0.83, 0.92)
Q3	3719	58.5	0.96 (0.91, 1.00)
Q4—Highest	3244	58.4	0.94 (0.89, 0.98)
Crime index			
Q1—Lowest	3856	53.2	0.93 (0.88, 0.97)
Q2	3849	56.1	0.92 (0.88, 0.97)
Q3	3888	56.3	0.95 (0.90, 0.99)
Q4—Highest	3761	58.8	0.93 (0.89, 0.97)
Road safety (No. of major/fatal accidents)			
Zero	9629	55.3	0.93 (0.90, 0.96)
One	3745	57.0	0.92 (0.88, 0.97)
>One	1980	58.3	0.96 (0.90, 1.02)

variables, mean NDVI remains non-significant in all three models, while the density of street trees was consistently associated with higher odds of walking (OR = 1.06, 95% CI = 1.03–1.10 in the fully adjusted model). Among the street-level design and accessibility variables, local-scale betweenness at 400 m was beneficially associated with walking. In reference to the lowest quartile, the second and fourth quartile had significantly higher odds of walking (1.15, 0.99–1.32 and 1.29, 1.09–1.53, respectively in model 3). On the contrary, meso-scale betweenness measured at 3000 m was associated with lower odds of falling into the *doing some walking* category (0.86, 0.75–0.99; 0.84, 0.72–0.98; 0.84, 0.71–0.99 for the second, third and fourth quartiles, respectively). Reduced access to service

Table 3
Results of logistic regression models examining association between odds of doing some walking and built environment for $N = 15,354$ participants of LTDS (2009/2010).

Model predictors	Model 1 OR (95% CI) *p*	Model 2 OR (95% CI) *p*	Model 3 OR (95% CI) *p*
Built environment			
Urban green			
Mean NDVI			
Q1 (lowest)—Reference			
Q2	1.04 (0.95, 1.15) $p = 0.38$	1.03 (0.94, 1.13) $p = 0.55$	1.05 (0.95, 1.15) $p = 0.36$
Q3	1.04 (0.94, 1.14) $p = 0.46$	1.02 (0.93, 1.12) $p = 0.71$	1.03 (0.94, 1.13) $p = 0.52$
Q4 (highest)	0.96 (0.87, 1.05) $p = 0.37$	0.95 (0.86, 1.04) $p = 0.26$	0.96 (0.87, 1.06) $p = 0.43$
Density of street trees	1.08 (1.04, 1.12) $p < 0.001$	1.07 (1.04, 1.11) $p < 0.001$	1.06 (1.03, 1.10) $p < 0.001$
Urban morphology and accessibility			
Street design and accessibility			
Street-level betweenness 400 m			
Q1 (lowest)—Reference			
Q2		1.15 (1.00, 1.33) $p = 0.05$	1.15 (0.99, 1.32) $p = 0.06$
Q3		1.13 (0.97, 1.33) $p = 0.11$	1.14 (0.97, 1.33) $p = 0.11$
Q4 (highest)		1.29 (1.09, 1.53) $p < 0.001$	1.29 (1.09, 1.53) $p < 0.001$
Street-level betweenness 3000 m			
Q1 (lowest)—Reference			
Q2		0.86 (0.75, 0.99) $p = 0.04$	0.86 (0.75, 0.99) $p = 0.03$
Q3		0.84 (0.72, 0.98) $p = 0.03$	0.84 (0.72, 0.98) $p = 0.03$
Q4 (highest)		0.84 (0.71, 0.99) $p = 0.03$	0.84 (0.71, 0.99) $p = 0.03$
Lack of access to service destinations			
Q1 (lowest)—Reference			
Q2		0.90 (0.82, 0.99) $p = 0.03$	0.90 (0.81, 0.99) $p = 0.03$
Q3		0.8 (0.73, 0.88) $p < 0.001$	0.80 (0.72, 0.88) $p < 0.001$
Q4 (highest)		0.76 (0.69, 0.84) $p < 0.001$	0.75 (0.67, 0.83) $p < 0.001$
Neighbourhood deprivation			
Income deprivation			
Q1 (lowest)—Reference			
Q2			0.91 (0.8, 1.03) $p = 0.12$
Q3			0.86 (0.73, 1.02) $p = 0.08$
Q4 (highest)			0.97 (0.79, 1.18) $p = 0.74$
Employment deprivation			
Q1 (lowest)—Reference			
Q2			1.00 (0.89, 1.14) $p = 0.95$
Q3			1.08 (0.92, 1.27) $p = 0.35$
Q4 (highest)			0.92 (0.76, 1.11) $p = 0.38$
Crime			
Q1 (lowest)—Reference			
Q2			1.06 (0.96, 1.16) $p = 0.28$
Q3			1.00 (0.9, 1.11) $p = 0.95$
Q4 (highest)			1.00 (0.89, 1.12) $p = 0.94$
Road safety (No. of fatal/major accidents)			
One vs. zero			1.02 (0.94, 1.1) $p = 0.67$
>One vs. zero			1.00 (0.9, 1.11) $p = 0.95$
Individual socio-demographics			
Age			
5–16 years—Reference			
17–30 years	0.88 (0.79, 0.98) $p = 0.03$	0.87 (0.78, 0.98) $p = 0.02$	0.87 (0.78, 0.98) $p = 0.02$
31–42 years	0.76 (0.68, 0.85) $p < 0.001$	0.76 (0.68, 0.85) $p < 0.001$	0.76 (0.68, 0.85) $p < 0.001$
43–58 years	0.64 (0.57, 0.72) $p < 0.001$	0.64 (0.57, 0.72) $p < 0.001$	0.64 (0.57, 0.72) $p < 0.001$
59–99 years	0.58 (0.51, 0.65) $p < 0.001$	0.59 (0.52, 0.66) $p < 0.001$	0.58 (0.51, 0.65) $p < 0.001$
Gender (female vs. male)	1.10 (1.03, 1.18) $p < 0.001$	1.11 (1.03, 1.18) $p < 0.001$	1.10 (1.03, 1.18) $p < 0.001$
Ethnic group			
Asian vs. White	1.01 (0.92, 1.11) $p = 0.88$	1.01 (0.92, 1.1) $p = 0.92$	1.02 (0.92, 1.12) $p = 0.76$
Black vs. White	0.82 (0.74, 0.92) $p < 0.001$	0.81 (0.73, 0.9) $p < 0.001$	0.83 (0.74, 0.92) $p < 0.001$
Mixed & others vs. White	1.04 (0.89, 1.2) $p = 0.64$	1.01 (0.87, 1.17) $p = 0.88$	1.02 (0.88, 1.19) $p = 0.75$
Disability (yes vs. none)	0.47 (0.41, 0.53) $p < 0.001$	0.47 (0.41, 0.53) $p < 0.001$	0.47 (0.41, 0.53) $p < 0.001$
Access to vehicles			
One vs. none	0.40 (0.37, 0.44) $p < 0.001$	0.41 (0.38, 0.45) $p < 0.001$	0.41 (0.38, 0.45) $p < 0.001$
>One vs. none	0.24 (0.22, 0.27) $p < 0.001$	0.26 (0.23, 0.29) $p < 0.001$	0.26 (0.23, 0.28) $p < 0.001$
Household income			
£15–35k vs. >£15k	1.25 (1.14, 1.38) $p < 0.001$	1.25 (1.14, 1.38) $p < 0.001$	1.25 (1.14, 1.37) $p < 0.001$
£35–75k vs. >£15k	1.42 (1.28, 1.58) $p < 0.001$	1.41 (1.27, 1.57) $p < 0.001$	1.40 (1.26, 1.56) $p < 0.001$
>75k vs. >£15k	1.42 (1.25, 1.61) $p < 0.001$	1.41 (1.24, 1.6) $p < 0.001$	1.39 (1.22, 1.58) $p < 0.001$
$-2 \times$ Log likelihood	19,844.6	19,788.9	19,773.3

destinations measured at the LSOA-level was associated with lower odds of walking (0.90, 0.81–0.99; 0.80, 0.72–0.88; 0.75, 0.67–0.83 for the second, third and fourth quartiles, respectively, in reference to the first quartile). In reference to children aged 5–16 years, the odds of doing some walking reduced with the upper age categories (0.87, 0.78–0.98 for 17–30 years, 0.76, 0.68–0.85 for 31–42 years, 0.64, 0.57–0.72 for 43–58 years, and 0.58, 0.51–0.65 for 59–99 years in model 3). In reference to males, females had higher odds of doing some walking (1.10, 1.03–1.18 in fully adjusted model 3).

The results of continuous regression examining relationships between total distance walked and built environment factors are presented in Table 4. In reference to the first quartile, the third and fourth quartiles of mean NDVI are significantly associated with distance walked in our model without urban morphology

Table 4
Results of continuous regression models examining association between distance walked and built environment for $N = 8610$ participants of LTDS (2009/2010).

Model predictors	Model 1 β (95% CI) p	Model 2 β (95% CI) p	Model 3 β (95% CI) p
Built environment			
Urban green			
Mean NDVI			
Q1 (lowest)—Reference			
Q2	0.017 (−0.069, 0.104) $p = 0.691$	0.015 (−0.072, 0.101) $p = 0.735$	0.033 (−0.054, 0.121) $p = 0.457$
Q3	0.093 (0.006, 0.179) $p = 0.036$	0.093 (0.006, 0.18) $p = 0.036$	0.113 (0.024, 0.201) $p = 0.013$
Q4 (highest)	0.077 (−0.008, 0.163) $p = 0.077$	0.08 (−0.006, 0.166) $p = 0.069$	0.106 (0.018, 0.193) $p = 0.018$
Density of street trees	0.056 (0.025, 0.088) $p < 0.001$	0.055 (0.024, 0.086) $p = 0.001$	0.039 (0.007, 0.071) $p = 0.016$
Urban morphology and accessibility			
Street design and accessibility			
Betweenness 400 m			
Q1 (lowest)—Reference			
Q2		0.027 (−0.112, 0.165) $p = 0.705$	0.02 (−0.118, 0.158) $p = 0.778$
Q3		0.075 (−0.075, 0.225) $p = 0.328$	0.073 (−0.077, 0.223) $p = 0.339$
Q4 (highest)		0.045 (−0.114, 0.204) $p = 0.576$	0.045 (−0.114, 0.204) $p = 0.579$
Betweenness 3000 m			
Q1 (lowest)—Reference			
Q2		−0.03 (−0.165, 0.105) $p = 0.662$	−0.035 (−0.17, 0.101) $p = 0.617$
Q3		−0.015 (−0.169, 0.139) $p = 0.847$	−0.016 (−0.17, 0.138) $p = 0.839$
Q4 (highest)		−0.061 (−0.219, 0.098) $p = 0.454$	−0.063 (−0.221, 0.096) $p = 0.438$
Lack of access to service destinations			
Q1 (lowest)—Reference			
Q2		−0.029 (−0.117, 0.06) $p = 0.527$	−0.039 (−0.128, 0.05) $p = 0.394$
Q3		0.018 (−0.071, 0.107) $p = 0.695$	0.002 (−0.087, 0.091) $p = 0.971$
Q4 (highest)		−0.047 (−0.136, 0.042) $p = 0.301$	−0.088 (−0.178, 0.001) $p = 0.054$
Neighbourhood deprivation			
Income deprivation			
Q1 (lowest)—Reference			
Q2			−0.014 (−0.15, 0.122) $p = 0.839$
Q3			−0.084 (−0.242, 0.075) $p = 0.300$
Q4 (highest)			−0.179 (−0.363, 0.005) $p = 0.057$
Employment deprivation			
Q1 (lowest)—Reference			
Q2			−0.071 (−0.206, 0.064) $p = 0.302$
Q3			0.015 (−0.142, 0.171) $p = 0.853$
Q4 (highest)			0.067 (−0.122, 0.257) $p = 0.485$
Crime			
Q1 (lowest)—Reference			
Q2			−0.073 (−0.167, 0.022) $p = 0.132$
Q3			−0.035 (−0.136, 0.067) $p = 0.503$
Q4 (highest)			−0.121 (−0.226, −0.016) $p = 0.024$
Road safety (No. of major/fatal accidents)			
One vs. zero			−0.084 (−0.156, −0.011) $p = 0.024$
>One vs. zero			−0.079 (−0.171, 0.012) $p = 0.088$
Individual socio-demographics			
Age			
5–16 years—Reference			
17–30 years	0.501 (0.415, 0.587) $p < 0.001$	0.501 (0.415, 0.587) $p < 0.001$	0.495 (0.409, 0.582) $p < 0.001$
31–42 years	0.499 (0.407, 0.591) $p < 0.001$	0.498 (0.405, 0.59) $p < 0.001$	0.492 (0.399, 0.584) $p < 0.001$
43–58 years	0.361 (0.265, 0.458) $p < 0.001$	0.361 (0.265, 0.458) $p < 0.001$	0.354 (0.257, 0.45) $p < 0.001$
59–99 years	0.036 (−0.051, 0.124) $p = 0.414$	0.037 (−0.051, 0.124) $p = 0.409$	0.014 (−0.075, 0.102) $p = 0.762$
Gender (female vs. male)	−0.119 (−0.181, −0.057) $p < 0.001$	−0.12 (−0.182, −0.057) $p < 0.001$	−0.122 (−0.184, −0.059) $p < 0.001$
Ethnic group			
Asian vs. White	−0.243 (−0.323, −0.162) $p < 0.001$	−0.245 (−0.326, −0.164) $p < 0.001$	−0.219 (−0.301, −0.137) $p < 0.001$
Black vs. White	−0.237 (−0.326, −0.147) $p < 0.001$	−0.239 (−0.33, −0.149) $p < 0.001$	−0.202 (−0.294, −0.111) $p < 0.001$
Mixed & others vs. White	−0.079 (−0.194, 0.035) $p = 0.174$	−0.082 (−0.197, 0.033) $p = 0.162$	−0.062 (−0.178, 0.053) $p = 0.291$
Disability (yes vs. none)	−0.335 (−0.438, −0.231) $p < 0.001$	−0.335 (−0.439, −0.231) $p < 0.001$	−0.331 (−0.435, −0.226) $p < 0.001$
Access to vehicles			
One vs. none	−0.201 (−0.278, −0.124) $p < 0.001$	−0.199 (−0.276, −0.121) $p < 0.001$	−0.209 (−0.286, −0.131) $p < 0.001$
>One vs. none	−0.421 (−0.516, −0.325) $p < 0.001$	−0.416 (−0.512, −0.32) $p < 0.001$	−0.441 (−0.537, −0.344) $p < 0.001$
Household income			
£15–35k vs. >£15k	0.081 (−0.001, 0.163) $p = 0.053$	0.082 (0, 0.164) $p = 0.051$	0.07 (−0.011, 0.152) $p = 0.091$
£35–75k vs. >£15k	0.213 (0.119, 0.306) $p < 0.001$	0.212 (0.119, 0.306) $p < 0.001$	0.197 (0.103, 0.291) $p < 0.001$
>75k vs. >£15k	0.316 (0.197, 0.435) $p < 0.001$	0.313 (0.194, 0.433) $p < 0.001$	0.281 (0.159, 0.403) $p < 0.001$
Constant	1.514 (1.41, 1.617) $p < 0.001$	1.518 (1.389, 1.646) $p < 0.001$	1.695 (1.543, 1.847) $p < 0.001$

and neighbourhood-level deprivation factors ($\beta = 0.093$, 95% CI = 0.006–0.179 and $\beta = 0.077$, 95% CI = −0.008–0.0163 for Q3 and Q4, respectively). The associations remain robust after adjusting for urban morphology and neighbourhood-level deprivation factors (0.113, 0.024–0.201 and 0.106, 0.018–0.193 for Q3 and Q4, respectively). The density of street trees was positively associated with distance walked, being consistent in all models, subsequent to adjustment for other influences (0.056, 0.025–0.088 for model 1; 0.055, 0.024–0.086 for model 2; 0.039, 0.007–0.071 for model 3). Street-level betweenness remains non-significant with distance walked. Reduced proximity to service destination is inversely associated with distance walked; the association being significant only in the fully adjusted model (−0.088, −0.178 to −0.001 for the highest quartile in reference to the lowest quartile). Among the variables of neighbourhood-level deprivation, the crime subdomain is inversely associated with distance walked (−0.121, −0.226 to −0.016 for the highest quartile in reference to the lowest quartile). The index of road safety is also inversely related to distance walked; in reference to participants' LSOAs with no incidences of major/fatal accidents, having one casualty incident significant reduces distance walked, controlling for other variables (−0.084, −0.156 to −0.011).

4. Discussion

The present study is the first to investigate for a large sample size, the independent associations of the behavioural outcome of *walking* with objectively measured urban green and street-network configuration after adjusting for neighbourhood deprivation and other covariates. Consistent with our hypothesis, both urban green as well as street-level urban design variables are found to be associated with walking, the associations being robust subsequent to adjustments for neighbourhood level deprivation and individual covariates.

Among our principal findings, the density of single street trees within a one kilometre network buffer, local level street connectivity (movement potential measured by betweenness at 400 m), and proximity to service destinations are all independently positively associated with propensity of study participants to walk. A negative association was reported between odds of walking and street level betweenness at 3000 m. Among those walking, the NDVI index of objective greenness and density of single street trees were found to be the only significant determinants of distance walked. Given the size of the sample and the design of the study, which makes it representative of the entire city of London, this is a strong result: *urban design and landscaping is associated with both the propensity to walk and the distance walked*.

4.1. Interpretation

Among urban green variables, our study supports the general hypothesis that streets lined with trees are associated with positive perceptions of greenness and street environmental quality and thereby provide an incentive to walk. Previously, street trees have been found to be associated with lower prevalence of childhood asthma (Lovasi et al., 2008), improved physical activity and weight outcomes (Lovasi et al., 2011, 2013) and enhanced longevity in older adults (Takano et al., 2002). In our present study, the density of street trees within one kilometre street buffer was significant with both the odds of walking as well as the actual distance walked and the relationships were robust after adjusting for other factors that might influence walking behaviour. This is an important finding for the interpretation of indirect associations between greenery and health found in epidemiological studies since it evidences an intermediate stage in the hypothesised causality.

Our findings are consistent with the idea that streetscape greenery is a valued community amenity. This is a strong landscape and urban design doctrine, which our study quantifies in terms of the walking behaviour that it induces. Many studies evidence the value of street trees subjectively from stated preference data (subjects state that they prefer greener environments). Other studies have demonstrated the revealed preference for greenery as measured in the housing market: controlling for other influences on housing price, greenery commands a premium. Street trees have been shown to be a proxy for neighbourhood wealth (Anderson & Cordell, 1988; Tyrväinen & Miettinen, 2000) with a potential to spatially capture well designed neighbourhoods associated with a lower rate of incivilities. Our study quantifies a revealed value for greenery in terms of subject's preparedness to walk. The causal mechanism is presumed to be environmental comfort (shade, shelter etc) and perceptions of greenness, environmental quality, safety, aesthetics and social capital (Kweon et al., 1998; Sullivan, Kuo, & Depooter, 2004).

In the case of NDVI-based objective greenness, in reference to the first quartile there were higher odds of walking among respondents in the second and third quartile of NDVI index, but contrary to our expectations, the results were not significant. However, in our models for sensitivity analyses, higher NDVI (third and fourth quartile) was beneficially associated with distance walked. This implies that amongst those respondents who walk, greenness captured by NDVI is a significant predictors of distance walked. In addition to being an objective measure of greenness, NDVI also manifests some degree of general perceptual greenness, being able to measure the exposure to greenness; for example as viewed through a window. Several previous studies have reported similar beneficial relationship between greenness and physical activity (Almanza, Jerrett, Dunton, Seto, & Ann Pentz, 2012; Grigsby-Toussaint et al., 2011; Tilt, Unfried, & Roca, 2007) as well as associated health outcomes (Bell et al., 2008; Pereira et al., 2012, 2013.,). Two potential mechanisms functioning at physiological and psychosocial levels may explain the reported associations between overall urban green and walking behaviour. First, is a physiological effect. Green is associated with environmental comfort. Studies on genetic biomarkers of stress (salivary cortisol, telomere length) and urban green provide evidence of lower levels of stress in green environments (Ward Thompson et al., 2012; Woo et al., 2009). Urban green thus constitutes therapeutic stress relieving islands in an urbanscape, helping create activity-friendly environments and promoting walking. Our study suggests that people choose to walk when these therapeutic environments are suitably configured. It is not green alone that induces walking. Second is a psychological effect. The intrinsic environmental psychology of a place is a function of the objective and the subjective; the physical nature of the place and the way it is subjectively valued. The latter is a function of values that evolve over time and over a lifetime, via the diversity of landscapes one is exposed to (Cummins, Curtis, Diez-Roux, & Macintyre, 2007; Hale et al., 2011). These experiences interact with the environmental aesthetics of any particular place (Foster, 2009). Urban green may be construed of as helping to create walkable places by fostering aesthetic experiences that connect individuals to places as well as nurturing social capital and a sense of belonging.

Turning to the configuration of the streets that contain the greenery, we find that streets connected by a topological and geometric pattern that raises the chance of through movement from other streets within walking distance tend to be more walked. This is an independent effect to the greenery effect. A higher local level betweenness measured at 400 m was associated with a higher odds of walking. sDNA *betweenness* is an index of centrality and is a proxy of the through movement potential associated with a street link. The choice of 400 m was governed by the median distance walked in the LTDS data as well as the '400 m rule' validated from previous studies (Porta et al., 2014). The beneficial association between local betweenness and propensity to walk further consolidates the long held belief that a spatial scale of 400 m represents the 'sanctuary areas' or the *social urban sphere* that constitutes local walkable neighbourhoods in close proximity to most commercial and service destinations (Appleyard, 1981). Betweenness at a local scale is able to capture positive externalities of aggregated opportunities in the form of attractive destinations as well as the social capital effects of such destinations. On the contrary, the observed negative association of betweenness measured at a spatial scale of 3000 m and propensity to walk may be explained in terms of community severance (Mindell & Karlsen, 2012), combined with a road traffic congestion effect. At a scale of 3000 m, betweenness captures the negative social externality of street morphology, being a proxy of higher traffic density, pollution and reduced perception of safety from traffic.

As expected, reduced proximity to service destinations is associated with lower odds of walking. This supports current wisdom in planning and urban design doctrine: high density, mixed-use urbanism is conducive to walking; and high pedestrian flows, in turn, induce more commerce and destinations in a virtuous cycle. One of the further research questions arising from our findings that street layout and green are independent correlates of walking is to ask what, if any, joint effect do these two dimensions have on walking? This has obvious import in landscape urbanism and design.

Neither betweenness nor index of accessibility are significant in our models for absolute distance walked. It seems that these are important factors influencing an individual's decision to walk but not the distance walked per se. This is another intriguing result to be followed up in subsequent research. The implication is that the availability of accessible destination opportunities induces people to select walking as a mode of travel, but once that decision is made, they have no measurable effect on how far people walk. Green landscape features, on the other hand, do appear to induce people to walk further. This points to distinct roles of different urban design elements in supporting a walkable city. One research question to follow up is to look at the impact of walkable destination opportunities on distance walked within a walkable neighbourhood range, i.e. 400 m. It may be that betweenness (400 m) is positively associated with absolute distance walked within the 400 m range. Indeed, in retrospect, there is no a priori reason to suppose that the density of accessible local opportunities should be associated with absolute distances walked for trips that are not local. Again, this demonstrates the power of sDNA and similar network methodologies, which allows the unravelling of distinct effects at different spatial scales.

The neighbourhood deprivation sub-domains of crime and road safety are inversely associated with distance walked as expected. This is consistent with previous studies (Li, Fisher, Brownson, & Bosworth, 2005) and points to the psychosocial stress associated with crime, neighbourhood decay as well as perceptions of lack of safety from traffic (Koohsari, Karakiewicz, & Kaczynski, 2013). A research question arising here is the interaction of greenery and fear. We are exploring this in another study, not yet published, in the context of optimal size distributions of urban green spaces. Large green spaces can be sources of negative externalities through crime and fear. At the street level, can trees be used to offset externalities of mild crime and fear? At what level of crime/fear do the positive externalities of greenery completely diminish and do they diminish linearly and gradually or suddenly and catastrophically?

Our findings may point towards the significant role of urban networks rather than destinations per se as the *primary activity spaces* promoting walking and physical activity behaviour in cities. This is another potentially important finding, significant enough perhaps to suggest a paradigm change in the way we think about urban greenery. This has potentially profound implications for urban design strategies and the detailed allocation of green investment in urban and landscape designs; suggesting that greater weight should be given to greening routes rather than destination spaces. As an individual navigates in an urban space, the lines of *visual field* are constantly updating and those associated with better perceptions of environmental quality, aesthetics, comfort, physical accessibility and density of attractive destinations act as key predictors of walkability. Further experiments are required to empirically isolate the component contributions of urban network and recreational destinations (such as parks) in promoting walking and physical activity.

4.2. Strengths and limitations

The strengths of the current study include large sample size; detailed and objective measures of urban green and street morphology calculated within buffers of participants' geocoded dwellings; and statistical adjustments for a range of neighbourhood and individual-level covariates. Travel diary data from the LTDS survey enabled geocoding and integration of travel data for a large population size with multiple spatial datasets as well as adjustments for individual-level covariates. Reliance on GIS-based objective measures of greenness and a behavioural model of street-level physical design constituted a robust methodology to examine associations with walking. The application of multispectral very high resolution colour infrared imagery to model the NDVI meant overcoming the common limitations inherent in most studies employing satellite remote sensing data, whose quality is often hindered by low resolution, cloud cover and atmospheric distortions. The 0.50 m resolution Bluesky colour infrared image captured during aerial photography with the Vexcel UltraCamD and the Leica ADS4 has an accuracy of 1 m. Street network modelling with sDNA provides an innovative methodology to study the scalar and network effects of urban design and morphology upon walkability and physical activity. Compared to conventional measure of street connectivity, which is typically fixed in scale, sDNA can dynamically model urban morphometrics (morphological metrics) at multiple spatial scales, thereby capturing the impact of behaviourally-relevant spatial scales upon walkability (Cooper, Fone, & Chiaradia, 2014; Sarkar et al., 2014b). Since sDNA employs street network links as the fundamental unit of analyses, the urban morphometrics computed can be directly appended to each ITN street link which is then connected to a study participant's dwelling location through spatial GIS queries. This enables linkages between urban morphology, walking, health and other behavioural outcomes of respondents living in a geo-coded dwelling.

Limitations of our study include under-reporting of short walking trips in travel diaries. Accelerometry can be employed as a more objective method for collating walking and other physical activity data. Although NDVI constitutes a standardized and objective measure of greenness, nonetheless, at least one small-scale study has highlighted discrepancies between NDVI as an objective measure and individual perceptions of urban greenness (Leslie, Sugiyama, Ierodiaconou, & Kremer, 2010). Further studies might adjust for individually perceived greenness via some survey-based instrument. In the current study the density of street trees can be taken as a proxy for perceived green. Our study uses a cross-sectional design, with attendant limitations imposed on the confidence of causal inferences. Identifying the potential of large *N*, prospective study designs in addressing such limitations, we are currently developing the UK Biobank Urban Morphometric Platform (UKBUMP), a high resolution spatial database of more than 750 individual-level urban morphometrics for half-a-million participants of the flagship UK Biobank Prospective study, spatially distributed across 22 UK cities (Sarkar, Webster, & Gallacher, 2015). The findings from the current study lead us to expect to decipher significant objective correlations between greenery and cardio-vascular and other physical activity-related health.

5. Conclusion

Finally, our research implicitly contributes to the body of evidence pointing to significant health benefits of urban green via walkability and physical activity. From an urban health planner's perspective, striving towards healthy urban design, decisions on siting and optimized morphology (shape, size, intensity) of urban green in synergy with pre-existing urban configuration (both land use as well as street network topology) and social dynamics remains an important challenge. The present study highlights the role of street-level design features (streets lined with trees, high local movement potential at a scale of 400 m) in positively influencing individual decisions to walk. It also evidences the role of greenery density and individual street trees in influencing actual distance walked. Evidence presented in this study will help unravel the influences of the multiple factors affecting individuals' walking and thereby contribute to more targeted retrofitting and intervention strategies in the activity-friendly planning and design of urban built environments and micro-neighbourhoods.

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