

Design and Destinations: Factors Influencing Walking and Total Physical Activity

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Abstract

Do people walk more, or less, depending on the physical character of their residential areas rather than merely their individual characteristics? This paper reports findings for the Twin Cities, Minnesota, about how walking and total physical activity are affected by street pattern, 'pedestrian-oriented' infrastructure and amenities, and mixed use or destinations—in shorthand, design and destinations. The effects of density are dealt with in less depth. Like earlier studies, it finds that walking for specific purposes (i.e. travel or leisure) varies in relation to the physical characteristics of places. However, this study using multiple measures of overall walking and physical activity suggests that socially similar people do the same total amount of physical activity in different kinds of places and that level of activity is, on average, low.

Introduction

Do people walk more, or less, depending on the physical character of their residential areas rather than merely their individual characteristics? If they do walk more when

residing in particular environments, does that mean that they are more physically active, overall? These questions are of great current interest in the public health field where there is much concern about low levels of physical activity and increasing obesity, with

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implications for many health conditions from blood pressure to mental health (Warburtun *et al.*, 2006; Spanier *et al.*, 2006). If walking is a significant part of total physical activity and higher levels of total physical activity are important for health, then increasing walking could have important public health benefits.

Drawing mainly on work from transport and urban design, and focusing on walking for transport rather than exercise, four broad dimensions of the built environment have been proposed as likely correlates of walking and physical activity (PA). It has been suggested that walking is higher in areas with elevated residential and employment densities, more connected street patterns, quality pedestrian infrastructure and amenities such as sidewalks and street trees, and the presence of a variety of destinations (mixed use) (Cervero and Kockelman, 1997; Frank and Pivo, 1994; Handy *et al.*, 2002; Handy, 2003; Saelens *et al.*, 2003). Of course, none of these studies has fully accounted for self-selection into neighbourhoods based on preferences for a built environment that supports walking. The complexities of disentangling significant correlations of the built environment and physical activity from those individuals that comprise the neighbourhood highlight issues of endogeneity, or unmeasured choices, in all such work. In addition, some of these characteristics are difficult to change in existing areas—for example, street patterns. Others are easier and cheaper to retrofit—for example, pedestrian amenities such as street lamps. Transport research has emphasised the importance of destinations—a *trip* is defined as movement between two destinations and so such destinations have been seen as key to movement.

This paper reports findings about how both walking and total physical activity are affected by these factors in residential areas, focusing on three sets of factors: street pattern, 'pedestrian-oriented' infrastructure and

amenities, and mixed use—in shorthand, design and destinations.¹ The effects of density are reported separately (Forsyth *et al.*, 2007b). The study examined associations between physical activity (measured by survey, seven-day travel diary and accelerometer) and the built environment (measured using computer mapping and survey) for 715 participants in 36 environmentally diverse areas in the Twin Cities in Minnesota. It also examined the relative importance of these constructs compared with other social and psychological variables.

Like most earlier studies, we found that walking for specific purposes (i.e. travel or leisure) varies in relation to the physical characteristics of places. However, the contribution of this research is to show that *total* physical activity is similar for similar people in different places. Further, that level of activity is, on average, low. The few associations of the built environment with overall physical activity have unclear policy implications.² Results for specific sub-populations may differ from the larger population, but preliminary analyses show a similar lack of variation (Forsyth *et al.*, 2007a).

The apparent deviation in findings from some earlier work is likely to be due to two factors: a focus in this paper on total physical activity rather than walking for specific purposes; and, methodological innovations in this second generation of work on the relationship between the built environment and physical activity. This study combines a survey, seven-day travel diary and accelerometer measures to assess reliably and objectively total physical activity rather than walking for a specific purpose. It adds objective measures of the built environment to surveys of environmental perceptions and social and psychological characteristics. The study looked at a wider variety of definitions of neighbourhoods than previous studies, such as buffers of different sizes and shapes. The

study also uses a sample design that minimises confounding by socioeconomic characteristics in that similar people in the study live in environmentally different areas, maximising exchangeability (Oakes, 2004). As with previous studies, we were unable to account for the problem of endogeneity, in this case the potential that some measured variables reflect unmeasured choices or characteristics of individuals.

These findings have important implications

- They add further evidence to an emerging proposition that there is a physical activity budget, akin to a travel time budget. People who do more leisure time physical activity do less for other purposes and vice versa (Rodríguez *et al.*, 2006; Krizek *et al.*, 2004).
- It may well reflect the daily mobility of most metropolitan residents who have choices about where and why to be active. Walking outdoors for travel and leisure in one's neighbourhood—the typical focus of studies to date—may have less influence on total physical activity than has been assumed.

The paper first outlines debates about the association between walking, physical activity and features of the built environment; describes study methods; and then provides an overview of select variables from the surveys, travel diaries and accelerometry, comparing these with design and destination features. It concludes with implications for the difficult task of building physical activity into daily life. The finding that regular activity is not normative may require consideration in future intervention approaches. Encouragements beyond merely changing the residential environment may well be needed and are likely to include typical public health strategies such as education campaigns and policy changes (like pricing).

Conceptual Issues

In considering physical activity, it is important to distinguish between walking and other forms of physical activity and between utilitarian walking (primarily for transport) and leisure walking (primarily for exercise). This study drew on a base of research from transport and urban design that indicated that travel walking—measured by survey and diary—was affected by the built environment and particularly by four dimensions: density, street pattern, pedestrian infrastructure and amenities, and mixed use (Cervero and Kockelman, 1997; Crane, 2000; Ewing *et al.*, 2003; Handy *et al.*, 2002; Saelens *et al.*, 2003). Environmental variables affecting leisure walking were less clear. Earlier research mostly relied on self-reported, rather than measured, characterisations of the built environment and thus focused on perceptions. While perceptions are important, one of the motivations behind the flurry of research on this topic is to see if urban planning interventions into the actual physical environment can increase physical activity. Fortunately, new developments in geographical information system (GIS) software and databases enable more sophisticated measurements of these variables at a variety of scales going beyond most earlier work (although see Moudon *et al.*, 2004 for extensive use of GIS; also earlier work by Cervero and Kockelman, 1997; Krizek, 2003a, 2003b; Frank and Pivo, 1994).

In this study, we used the variables listed in Table 1 with detailed protocols for how we measured the variables available on-line.¹ The specific importance of the four categories of variables is outlined in what follows. In the results, we focus on those variables with significant associations with a measure of physical activity and deal only briefly with non-significant variables.

Table 1. Environmental variables measured: over 200 in total

Street pattern—GIS variables

Average census block area
 Median census block area
 Number of access points
 Road length per unit area
 Intersections per unit area (raw intersections, 10-metre, 15-metre buffers)
 Ratio of four-way intersections to all intersections (raw intersections, 10-metre, 15-metre buffers)
 Four-way intersections per unit land area (raw intersections, 10-metre, 15-metre buffers)
 Ratio of three-way intersections to all intersections (raw intersections, 10-metre, 15-metre buffers)
 Connected node ratio
 Median perimeter of block
 Ratio of area within X street distance to area within X distance radius (a ratio of the network buffer to the straight-line buffer)

Pedestrian-oriented design elements—GIS variables

Sidewalk length per unit area
 Sidewalk length divided by road length
 Sidewalk length per length of major road
 Street lights per length of road
 Street trees (trees within an X distance buffer) per length of road
 Percentage of street segments with marked pedestrian crossings at one or both ends
 Percentage of street segments with visible litter, *graffiti* or dumpsters
 Percentage of street segments with traffic calming, broadly defined
 Distance to nearest transit stop
 Transit stop density
 Over 100 additional variables from the Irvine Minnesota Inventory (Day *et al.*, 2006); those that were significant for overall physical activity are discussed in the text.

*Destinations—GIS variables**Percentage of total parcel area in major land uses*

Commercial
 Industrial
 Office
 Parks and recreation
 Residential
 Tax-exempt
 Vacant

 Percentage of land area in night-time uses
 Percentage of land area in social uses
 Percentage of land area in retail uses
 Percentage of land area in industrial and auto-oriented uses
 Proportion of dissimilar land uses among grid cells in an area, formula 1
 Employment per unit land area
 Entropy index
 Herfindahl–Hirschman index, HHI

(Continued)

Table 1. (Continued)*Street pattern—GIS variables*

Retail employment per unit area

Density of employees in major retail sub-categories: general merchandise (old sic 53××)

Density of employees in major retail sub-categories: food stores (54××)

Density of employees in major retail sub-categories: eating and drinking places (58××)

Density of employees in major retail sub-categories: miscellaneous retail (59××)

Distance to nearest employment, bus stop, your job, park, post office, library, elementary school, other school, convenience store, supermarket, vegetable market, bakery, coffee shop, restaurant, laundry, bank, salon, clothing, book store, video store, hardware store, pharmacy, recreation centre, gym (24 measures)

Perceived measures from survey

Street pattern—survey variables (section H; 5 questions)

Pedestrian-oriented design elements—survey variables (sections I, J, L; 17 questions)

Destination—survey variables (sections F, G, O 48 questions)

Notes: a number of these involve several variations so the total number of variables is longer than this list. For example, we looked at over 100 variables using an urban design inventory, but it is listed as one line in this table. Variables were typically measured at 200-metre, 400-metre and, where possible, 800-metre and 1600-metre buffers, both street network and straight-line, as well as for the initial 805*805 square metre focus area. Measures of the distance to the nearest feature were measured in straight-line and street network distances.

Density

Density is the number of items in an area, typically people, houses or workers. Increased density is thought to provide a critical mass of people and places, and a physical sense of community. Density can also increase auto congestion and parking costs, potentially getting people out of their cars if not onto their feet. Transit viability typically increases with density and many people walk to transit. Some consider density to be mainly a proxy variable for characteristics such as income or mixed use and in this study we used employee densities for various retail categories as a mixed use measure (Ewing, 1994; Steiner, 1994; Cervero and Kockelman, 1997; Forsyth *et al.*, 2007b).

Street Pattern or Connectivity

Street pattern is the design or arrangement of streets and blocks; connectivity is “the directness or ease of travel between two points” (Saelens *et al.*, 2003, p. 81; Cervero

and Kockelman, 1997; McNally and Kulkarni, 1999). The two issues are intimately related as small blocks provide potential route options that are typically more direct than large blocks and can allow pedestrians to choose different routes to achieve such ends as maximising efficiency, avoiding boredom or enhancing safety (Ratner *et al.*, 1999). With the advent of widespread use of GIS in the 1990s, street pattern has been more commonly used as a measure of walkability.

Pedestrian-oriented Design Elements: Infrastructure and Amenities

These are the built and planted features that provide pedestrian amenities or that affect pedestrian mobility, safety, interest and comfort. From marked pedestrian crossings and landscaping to street lamps and street trees, these are more open to modification than the basic street pattern.

Pedestrians are exposed to the outdoor elements and walk slowly through the

environment. Amenities can make walking much more enjoyable—for example, street trees for shade and wind protection, bus shelters for waiting, and interesting architecture. They also have unique safety concerns, some of which are affected by design features—for example, street lights or pedestrian crossings.

Measurements of this dimension have been the least developed because data are often incomplete or unavailable. Some studies assume that more ‘traditional’ neighbourhoods with gridded streets possess good pedestrian infrastructure. However, various measures have been developed based on field observations, interviews and GIS-based indicators such as completeness of the sidewalk system (Hess *et al.*, 1999; Moudon and Lee, 2003). This study used interpretation of digital orthophotos, followed by field checking, to construct street tree, street lamp and sidewalk data. It also tested a new urban design inventory (Day *et al.*, 2006; Boarnet *et al.*, 2006).

Many earlier studies that claimed these features increased walking used surveys to ask people if they thought they walked more if there were sidewalks, or else observed people already on trails. Some only looked at travel walking. From these sources, it is difficult to estimate whether such features increased *overall* physical activity. Further, the few studies to examine changes in walking over time with the introduction of a new facility found either no increase in use among walkers—one study (Merom *et al.*, 2003) found cycling increased—or, if there was more use of that specific facility, no increase in overall physical activity (Evenson *et al.* 2005).⁴

Destinations

A key proposition at the base of many transport theories is that people move between activities located in different places. If activities are close enough together to make walking easier, in areas of mixed land uses,

then more people will walk. Mixed use is also thought to provide more visual variety and interest for pedestrians. Assuming that uses have a mixture of opening hours and generate pedestrian traffic, mixed use may well promote informal policing. To date, studies have typically found a number of destinations to be associated with travel walking but far fewer with leisure walking (Hoehner *et al.*, 2005; Lee and Moudon, 2006; Giles-Corti *et al.*, 2005).

However, this raises a number of issues. Is variety enough on its own? Can one key destination make a difference? Are there differences between destinations that have a regional versus a local draw (Handy, 1992)? Once a critical mass of land use variety has been reached, will more mix matter (Krzek, 2003a, 2003b)? There has been a focus on commercial destinations, but schools, faith-based facilities or parks can also be destinations (Audirac 1999).⁵

The measurement of mixed use has been rapidly evolving. As Krizek (2003a, 2003b) outlines, measures have included: simple field-based reports on whether mix is present; density and distance measures including total employment or businesses; density of specific kinds of businesses and jobs, and distances to particular kinds of businesses (see Cervero and Gorham, 1995; Handy, 1992); and entropy and dissimilarity indices that measure overall mix (see Frank and Pivo, 1994; Cervero and Kockelman, 1997). The now fairly wide availability of parcel level land use data and commercial business data allows other measurements based on particular kinds of land uses and businesses (McNally and Kulkarni, 1999, p. 109; Crane and Crepeau, 1998).

Research to Date

Many studies have looked at self-reported walking or physical activity and self-reported environmental contexts. Many studies have examined walking for specific purposes

(such as to the store, for leisure or for travel) or in particular areas (such as in their neighbourhood) without examining total walking or total physical activity.⁶ Most studies from the transport literature have focused on 'trips' that start and end at a different place and do not report recreational walking. Here, we summarise a subset of studies with objective measures of the built environment. In addition, we focus most on those with objective measures of overall physical activity through accelerometer or pedometer, or that use walking or physical activity diaries, rather than recall-based measures. In these studies, there have been mixed findings about the relationship between the environment and overall physical activity.⁷

Lee and Moudon (2006) belong to a new group of researchers adding recreation as well as travel walking to such studies. The researchers asked 438 respondents the frequency of their walking in the past week "(a) to work, (b) to school, (c) to grocery stores, (d) to other retail or service facilities, and (e) for recreation or exercise" (Lee and Moudon, 2006, p. S81). They analysed dozens of environmental variables using GIS. They proposed several variables that facilitate walking, for leisure or for travel, although without an overall measure of total walking or physical activity. Similarly, Hoehner *et al.* (2005) surveyed 1068 residents of Savannah and Saint Louis by phone and audited over 1100 street segments around their homes. While the researchers used the International Physical Activity Questionnaire (IPAQ) that asks about activity across all domains, they did not report overall PA but rather reported PA for transport or leisure. They have some intriguing findings. For example, people in neighbourhoods that were tidy and well maintained were *less* likely to meet recommendations for physical activity through biking and walking for transport (Hoehner *et al.*, 2005, p. 113).

A few recent studies have added to objective measures of the built environment at the neighbourhood level, objective or self-reported measures of overall physical activity or total walking.⁸ Others have combined objective social and built environmental features into neighbourhood types (Nelson *et al.*, 2006). Rodríguez *et al.* (2006) compared two types of neighbourhood and found differences in self-reported walking but not in overall physical activity. Rutt and Coleman (2005) used the behavioural Risk Factor Surveillance System (BRFSS) and GIS-based environmental measures, finding no associations between built environment and physical activity in a sample of 542 mostly Hispanic respondents. The exception was that vigorous PA was higher when people lived further from recreational facilities. Giles-Corti and colleagues (Giles-Corti and Donovan, 2002a, 2002b; Giles-Corti *et al.*, 2005) in a series of studies that looked at traffic, street trees and parks or open space found that some environmental features increased walking, particularly open space.

Those using objective measures of physical activity as well as environmental features are even fewer in number. King *et al.* (2003) found that perceived environment was a strong predictor of physical activity in 158 older, overweight women with activity measured by pedometer over 7 days. However, in a follow-up paper using GIS-based measures of access to various facilities their results were far weaker (King *et al.*, 2005). In addition, they found people living in housing built during 1950–69, according to census data, had *higher* physical activity than those living in older neighbourhoods that were presumably more stereotypically walkable (King *et al.*, 2005). Jago *et al.* (2005) used three days of accelerometry among 210 adolescent boy scouts and the SPACES audit tool to inventory 35 environmental features within 400 metres of each participant's home. Subsequent work added

variables measured using GIS in both a 1-mile and a 400-metre radius from participants' homes (Jago *et al.*, 2006a, pp. 423–424, 426; Jago *et al.*, 2006b). Using a hierarchical model, murder rates within a 1-mile radius were associated with *more* moderate to vigorous PA and proximity to a public recreation centre was negatively associated (Jago *et al.*, 2006b, pp. 234–237). Finally, Frank *et al.* (2005) used accelerometer measures over two days with a sample of 357 adults. The team created a GIS-based walkability index based on net residential density, intersection density and land use mix, measured for a 1-km street network buffer. Logistic regression led them to conclude that

Individuals in the highest walkability quartile were 2.4 times more likely (95 per cent CI: 1.18–4.88) than individuals in the lowest walkability quartile to meet the recommended >30 minutes of moderate physical activity per day (Frank *et al.*, 2005, p. 117).

Thus, studies using objective built environment and physical activity measures have found some associations, but these have not been consistent (Ewing, 2005, p. 69; Kelly-Schwartz *et al.*, 2004; also Ewing *et al.*, 2003). In addition, a study released in 2005 found that at least 3–4 days of accelerometer readings are needed for reliable measurement of habitual physical activity in adults and significantly more for children (Masse *et al.*, 2005). Only the latest generation of studies, such as the one reported in this article, have such data.

Methods

This study focused on residential and mixed use areas in a sector of the Twin Cities metropolitan area reaching from the urban core to the urban edge. This area had particularly rich GIS data. Study or 'focus' areas were selected from inhabited 805-metre grid cells in the area stratified for variation along: street pattern (median block size); and residential

density (gross population density). Each dimension was classified into high/large, medium and low/small. We divided areas into three categories on each dimension—small, medium and large median block size and high, medium, and low densities. High density was defined as greater than 24.7 persons per gross hectare excluding water bodies only; low as less than 12.4 persons per hectare. Small median block size was defined as below 2 hectares which was related to standard block sizes in the area. Large blocks were larger than 3.2 hectares. Study areas were randomly sampled from the extreme types—big blocks/high density; big blocks/low density and so on (see Figures 1 and 2 for study area).

A total of 715 participants were sampled from the 36 focus areas,⁹ with approximately equal numbers in each area.¹⁰ Participant characteristics are described in Table 1 and represent the variables we adjusted for in the final model; 74 per cent of participants were randomly selected and the rest were recruited from the focus areas but not specific randomly sampled addresses.¹¹ Data were also collected for work addresses but are not included in this analysis. To avoid biases due to weather, physical activity measures were staggered from April to November for each area. An innovative feature of this sampling design was that it maximised participant exchangeability, which meant that similar people lived in environmentally different areas (Oakes *et al.*, 2007).

To assess the exchangeability, propensity score matching methods were employed. Propensity score matching methods are one approach designed to reduce heterogeneity between comparison groups. Details of the theory and method can be read elsewhere (Rubin, 1997; D'Agostino, 1998; Rosenbaum, 2005; Rubin and Thomas, 2006). Simply, for this study, the observed covariates which we were interested in matching across exposure categories—in this case, high/low density and large/small block size—were added to

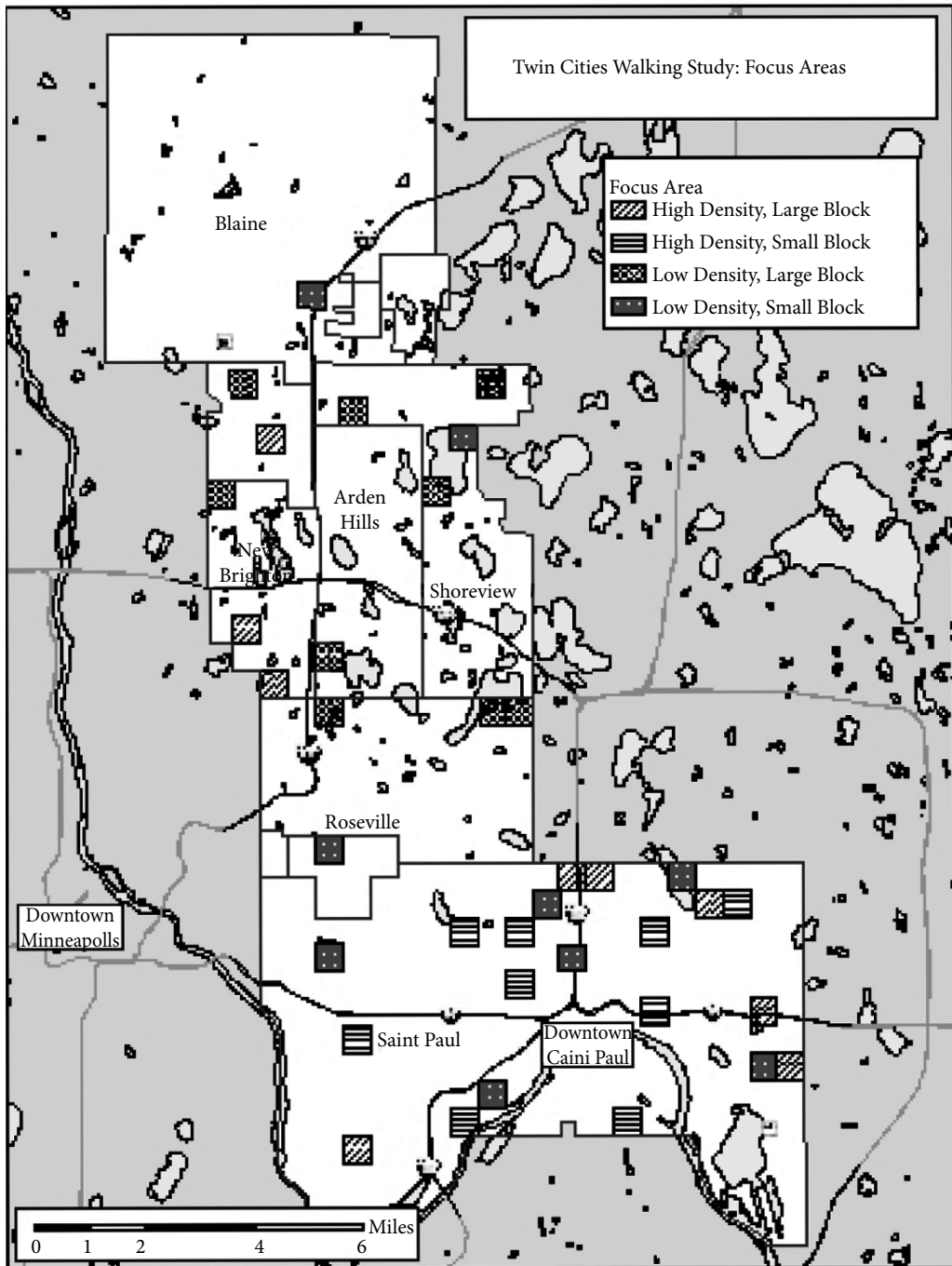


Figure 1. Map of study area



Figure 2. Images of the study area. *Above:* a typical small block, high density area with connected street patterns, mixed use and mixed housing types. *Below:* a large block, low-density area of largely single-family residential uses; such areas often have a few elements of pedestrian infrastructure. There was some variety within types so that, for example, some large block areas were near shops and some small block areas were mostly residential. Across the focus areas, intersections per hectare at the focus area level ranged from 0.1 to 0.9 with far larger ranges at the level of smaller buffers; food store employees per hectare ranged from 0 to 5; and sidewalk length in metres/hectare from 0 to 303.

a logistic regression model estimating the predicted probability of exposure. Covariates added to the model included age, education, marital status, gender, tenure, homeownership and household size. Individuals living in locations with a large block size (high density) were matched on their estimated propensity score to an individual living in a small block size (low density). Examining the overlap, or matching of individuals by exposure category revealed very good overlap, or exchangeability on observed covariates.

The study compared perceived and measured environmental features with self-reported walking and physical activity behaviour (seven-day travel/walking diary and the long form of the IPAQ) and objectively measured total physical activity (accelerometer over seven days). To maximise sample size, missing data were recoded to zero for the IPAQ data as zero values contribute to means and correlations, but not total amounts of PA. However, we also conducted the analysis dropping participants with missing data and the results were similar. (See Table 3 for descriptive statistics

of select physical activity measures.) Environmental features were measured through surveys and GIS-based variables, with GIS data coming from existing databases, orthophoto interpretation and a field-based urban design inventory. As can be seen from Table 1, over 50 variables were measured in addition to the individual urban design measures. All instruments and protocols, except the diary which is a modification of the one developed for the US National Household Travel Survey, are available on-line.¹²

Environmental features can be measured at a variety of scales from the environment close around the person's home to the wider neighbourhood. This paper uses several different geographies: the 36 805*805 square metre focus areas from which participants were sampled; straight-line or crow-flies buffers around the 715 participants at 200 metres and 400 metres and, where available, 800 metres and 1600 metres; buffers along the street network at the same distances, reflecting better the distance in those areas where pedestrians primarily walk along streets;¹³ and,

Table 2. Descriptive statistics of study sample

	<i>Sample size</i>		<i>Means</i>			
	<i>Low density</i>	<i>High density</i>	<i>Low density focus areas</i>	<i>High density focus areas</i>	χ^2	<i>P-value</i>
Males (percentage)	122	125	35.06	35.41	0.01	0.922
White persons (percentage)	317	261	90.57	73.52	34.70	0.000
College degree (percentage)	179	140	51.14	39.44	9.75	0.002
Married (percentage)	231	183	66.00	51.69	14.87	0.000
Own home (percentage)	311	218	89.11	61.58	71.51	0.000
Car Ownership (percentage)	345	314	98.57	88.95	27.72	0.000
					<i>Mean</i>	<i>Median</i>
Age in years	350	352	49.23	44.82	47.02	45.00
Housing tenure in years	319	302	15.61	11.83	13.77	10.00
Overall health (1 is excellent)	350	354	2.22	2.46	2.34	2.00
Household size	346	355	2.66	2.76	2.71	2.00

distances to the nearest feature of a particular type for points or small polygons such as bus stops, stores and parks.

In order to answer the primary research question about the effect of design and destination neighbourhood features on walking and physical activity, several steps were performed. First, we explored which design and destination features were correlated to total physical activity and total, transport, and leisure walking using pairwise correlations at the focus area level. Outcome variables were categorised into three levels of physical activity: none; minimal or low; and moderate (median) or higher (Norris *et al.*, 2006; Slymen *et al.*, 2006). To support and expand on our expected correlational findings, we also used fieldwork from the Irvine Minnesota Inventory to assess associations between pedestrian infrastructure and physical activity. We then used ordinal logistic regressions to determine odds

ratios, adjusted for subject's age, sex, race, education, marital status, homeownership, tenure, overall health, car ownership and total household membership and for clustering by focus area, for only the variables that proved most statistically significant (though modestly so) in the correlations. Finally, we explored crude pairwise correlations to determine the relationship between perceptions of the physical environment and physical activity prior to adding perceptions to the ordinal logistic regression model testing to see if taking into account perceptions modifies the relationship between physical activity and the built environment.

Results

Table 2 displays descriptive characteristics of the study sample by high- and low-density strata. There were no differences between

Table 3. Descriptive statistics of selected physical activity measures

Outcome measures	Sample size		Means			
	Low density	High density	Low density focus areas	High density focus areas	Difference between high and low	P-value
IPAQ transport walking (in MET minutes per week)	356	359	189.8	326.2	-136.4	0.0016
IPAQ leisure walking (MET minutes per week)	356	359	370.8	259.7	111.1	0.0026
IPAQ total physical activity (in MET minutes per week) ^a	356	359	4157.8	4296.7	-138.8	0.69
Travel diary total miles walked per week	354	358	5.7	6.3	-0.57	0.38
Accelerometer, mean total counts per valid day ^b	355	357	224929	222974	1955	0.80
Accelerometer median total counts per valid day ^b	355	357	229975	228171	1804	0.83

^a Total PA on the IPAQ represents all physical activity related to work, transport, leisure and domestic/garden. This does include cycling, walking, running and other movement. Missing values were converted to zero in IPAQ survey for $n = 715$.

^b Accelerometer counts reflect mean or median movement counts per minute.

Note: The recommended amount of 30 minutes of moderate activity 5 days per week is 4 METS (30 minutes * 5 days = 600).

density strata for sex, but statistically significant differences were observed for percentage of White subjects, college educated, married and home and car ownership. Study participants who reside in an area with a low density are more likely to be White, have a college degree, be married, own a home and own a car. They are also older and their home tenure is longer.

As Table 3 demonstrates, differences exist in physical activity measures for those participants residing in low-density compared with high density areas. Those in high-density areas have higher levels of walking for transport, but lower levels of leisure walking. Total physical activity measured by the IPAQ, travel diary total miles walked per week and accelerometer counts, or average number of movements per day, were not statistically different between high- and low-density areas. As is noted in the table, we did not omit participants with missing values for some of the IPAQ questions; this increased *N* for that variable but results were similar.

In Table 4, we report the statistically significant unadjusted Pearson correlations between various GIS-based measures of the built environment and measures of walking and physical activity at the focus area level. While not reported here, there were some statistically significant but modest correlations for environmental variables measured at other geographies. These were relatively few in number and generally up to only 0.10 in value, although a few reached as high as 0.15. These very modest correlations are statistically significant because of the large number of responses. For simplicity, we use the focus area figures in this discussion, but the other geographies did not present a substantially different overall picture.

As can be seen, there are very few correlations with the three measures of total physical activity and these are all negative correlations with measures of retail and commercial uses (both using parcel and Dun and Bradstreet

employment data). In addition, there were no associations with the design variables.

Total walking in mean miles per day is positively correlated with sidewalks, street lights, traffic calming and several of our many measures of connected street patterns (signs vary, but are as expected—i.e. smaller blocks have more total walking). Notably absent were any positive correlations with mixed use—apart from a modest one with miscellaneous retail. Further, in a previous study using the same data, multivariate analysis using ordinal logistic regression and controlling for age, self-reported health, measured body mass index (BMI), ethnicity, education and household income showed that median block size (along with gross population density) were not associated with total walking or total PA (Forsyth *et al.*, 2007b). In the tables presented here, odds ratios paint a similar picture but with intersections per area and sidewalk length per area as opposed to median block size. In that analysis, marginal significance was noted for the association between total walking and total PA and density of food store employees.

Travel walking measured both by survey and diary was positively correlated with social land uses, sidewalks, transit, ~~litter/graffiti~~ and connected street patterns. Leisure walking was negatively correlated with some of the same features: transit, sidewalks, ~~street lights~~, connected street patterns, social land uses, as well as tax exempt land uses.¹⁴

Analyses not shown have small positive correlations between mean and median accelerometer counts of total physical activity and with straight-line and network distances to the nearest video store, hardware store and pharmacy, although not to other destinations.¹⁵ Park distance was negatively correlated with accelerometer readings; however, while the values were significant, they were low.¹⁶ Distance to restaurants had a weak association with total physical activity.

Table 4. Objective built environment features correlated with measures of walking and physical activity at the focus area level, significant (p <0.05)

	<i>Total physical activity</i>			<i>Total walking</i>		<i>Leisure walking</i>		<i>Transportation walking</i>	
	<i>IPAQ (MET minutes/week)^b</i>	<i>Accelerometer mean (total counts/day)^e</i>	<i>Accelerometer median (total counts/day)^e</i>	<i>IPAQ total walking (MET minutes/week)</i>	<i>Travel diary (miles/day)</i>	<i>IPAQ leisure walking (MET minutes/week)</i>	<i>Travel diary (miles/day)</i>	<i>IPAQ (Met minutes/week)</i>	<i>Travel diary (miles/day)</i>
<i>Destinations</i>	—	—	—	—	—	—	—	—	—
Percentage of total parcel area in commercial uses	—	-0.3473	—	—	—	—	—	—	—
Percentage of total parcel area in tax exempt uses	—	—	—	—	—	-0.4214*	—	—	—
Percentage of land area in retail uses	—	-0.3488	—	—	—	—	—	—	—
Retail employment per unit area	—	-0.3384	-0.3305	—	—	—	—	—	—
Density of employees ... general merchandise (SIC53××)	—	-0.3767	-0.3620	—	—	—	—	—	—
Density of employees ... food stores (SIC 54××)	—	-0.3869	-0.3695	—	—	—	—	—	—
Density of employees ... miscellaneous retail (59××)	—	—	—	—	0.3505	—	—	—	—
Percentage of land area, parcels in social land use ^d	—	—	—	—	—	-0.5067	—	0.4166	0.3379
<i>Street pattern</i>	—	—	—	—	—	—	—	—	—
Average census block area	—	—	—	—	-0.3794	—	—	—	—
Number of access points	—	—	—	—	0.3366	-0.3349	—	0.5176	0.5384
Road length per unit area	—	—	—	—	0.4689	—	—	—	0.4794
Intersections per unit area ^a	—	—	—	—	0.4881	—	—	0.4052	0.5279
Four-way intersections per unit land area ^a	—	—	—	—	0.4511	—	—	0.4602	0.5782
Connected node ratio	—	—	—	—	—	-0.3643	—	0.4284	0.4673
Ratio of four-way intersections to all intersections ^a	—	—	—	—	—	—	—	0.4164	0.4698

Ratio of three-way Intersections to all intersections ^a	—	—	—	—	—	—	—	—	-0.4161	-0.4698
<i>Infrastructure/amenities</i>	—	—	—	—	—	—	—	—	—	—
Sidewalk length per unit area	—	—	—	—	0.4510	—	—	—	0.4866	0.6224
Sidewalk length divided by road length	—	—	—	—	0.3449	-0.3318	—	—	0.5282	0.5945
Street lights per length of road	—	—	—	—	0.4874	—	—	—	0.3325	0.5238
Percentage of street segments with visible litter, graffiti, or dumpsters ^c	—	—	—	0.3808	—	—	—	—	—	—
Percentage of street segments with traffic calming	—	—	—	—	0.3629	—	—	—	—	0.3674
Street trees within 15/20 metre buffer/length of road	—	—	—	—	—	0.3757	—	—	—	—
Transit stop density	—	—	—	—	—	-0.4882	-0.3360	—	0.3716	0.4652

^a Where we measured several versions of intersections we only report one here—the raw intersection measure—because more complex measures did not achieve far better results. Note that there were some significant correlations at other geographies—i.e. for straight-line and network buffers at 200, 400, 800 and 1600 metres, but remarkably few and at very low values. Overall, the pattern was quite similar to focus areas.

^b The MET is the metabolic equivalent and 1 MET is the energy expenditure for sitting quietly, so MET minutes are a measure of intensity by duration). The Centers for Disease Control and Prevention (CDC) recommendation of 30 minutes of moderate physical activity (3–6 METS), 5 times per week is approximately 450–900 MET minutes per week (CDC, 2006a, 2006b). The IPAQ, which we used to create these variables, measures physical activity in four domains: job-related; transport; housework, maintenance and caring for family; and recreation, sport and leisure time. Total PA on the IPAQ represents all physical activity related to work, transport, leisure and domestic/garden. This does include cycling, walking, running and other movement. Missing values were converted to zero.

^c This measure came from the Irvine Minnesota Inventory and included the presence of any of the following: speed bump/speed hump/raised crosswalk; or dips (that are intended to slow down traffic); rumble strips or bumps (includes dots, reflectors, raised concrete strips, etc.); curb bulb out/curb extension; traffic circle/roundabout; median; angled/on-street parking (that runs along most or the entire segment—does not have to be on both sides of segment) (Forsyth, 2005, protocol 4.8).

^d Social land uses came from parcel data and included day care centres; medical clinics and offices; theatres; bowling alleys; lodge halls and amusement parks; sport/public assembly facility; (tax) exempt community recreational facilities; library; exempt property owned by board of education; exempt property owned by private schools; churches, etc. public worship (Forsyth, 2005, protocol 5.3).

^e Accelerometer total counts per valid day where counts are movement detected by the device and invalid days are those with < 2 hours of counts above minimum threshold.

Note: dozens of other measures were tested but did not have any significant correlations at the focus area level.

For the perceived environment variables measured via survey, analysed but not shown here, there were statistically significant positive Spearman's correlations between physical activity measured by accelerometer and whether people spoke to others in their neighbourhood, perceptions of crime (three questions), having places to go in walking distance from their home, hills (rare in the study area), nearness to book stores and the participant's job, and access to bicycle and pedestrian paths. Although significant, values were low, with the highest being $r = 0.13$ for closeness to job or school. Again, there were more, unreported, correlations with leisure and travel walking, but they were modest and, as stated in the first paragraph of this paper, it is total physical activity that matters for health. It should be noted that there were dozens of other *survey* variables with no associations with total physical activity measured by accelerometer—dealing with types of residence, access to facilities and services, street design, places for walking and cycling, neighbourhood surroundings, safety from traffic, safety from crime and reasons for moving to the neighbourhood.¹⁷

In comparison, every question about social life was statistically significantly and positively associated with overall PA. Social life was measured as eight questions about how many days in the past month people had waved, said hello, stopped and talked to a neighbour, gone to a neighbour's house, had a neighbour over to socialise, gone somewhere with a neighbour, asked them for help, or sought advice.¹⁸ However, the values were very low, with the highest $r = 0.16$. In addition, the five social cohesion questions (neighbours willing to help, a close-knit neighbourhood, trust in neighbours, neighbours getting along and shared values) did not have any statistically significant correlations.

Adjusted odds ratios from regression models are presented in Table 5. Variables

were selected to represent statistically significant associations with overall physical activity measured by accelerometer and the main environmental variables in Table 3. This analysis tries to explore whether changes in these street pattern, mixed use and pedestrian amenities are likely to change physical activity or whether these associations are less significant after controlling for factors such as age, sex, race, education, marital status, homeownership, tenure, overall health, car ownership and total household members. We used ordinal logistic regression to determine the log odds of travel, leisure or total walking and total movement given the environmental features with the strongest significant association with overall PA or total walking in each category. They are: intersections per unit area; density of employees in food stores (Standard Industrial Classification [SIC] codes 54××); and, sidewalk length per unit area. Density of food store employees is a measure of locally important destinations or land use mix. Given that the mixed use variable was negatively associated, counter to theory, we prepared analyses with and without that variable. However, the overall results were the same.

Controlling for subject characteristics and accounting for clustering at the focus area, there are four marginally statistically significant OR for the three environmental feature types and walking or movement behaviour. In fact, all statistically significant findings are so small as to cause very cautious interpretation. Results indicate that sidewalk length increases the odds of moving from no travel walking to low levels of travel walking by less than 1 per cent. In other words, sidewalk length minimally impacts on whether or not subjects are in a no travel walking category or a low level of travel walking category, or a low-level category to moderate or higher-level category. As the density of food service employees increases, the ordered log odds of total walking and total movement decrease,

Table 5. Adjusted ordinal odds ratios of travel, leisure or total walking and total movement given the number of intersections per area, density of food store employees, and sidewalk length

	<i>Travel walking (n = 605)</i>				<i>Leisure walking (n = 606)</i>			
	<i>OR</i>	<i>SE</i>	<i>95 per cent CI</i>		<i>OR</i>	<i>SE</i>	<i>95 per cent CI</i>	
			<i>Lower</i>	<i>Upper</i>			<i>Lower</i>	<i>Upper</i>
Intersections/area	0.918	0.374	0.413	2.042	0.698	0.231	0.366	1.33
Density of food store employees	0.992	0.006	0.981	1.005	0.990	0.005	0.981	1.000
Sidewalk length/area	1.003	0.001	1.001	1.004	0.999	0.001	0.997	1.001
BIC	1285.392				1378.332			
	<i>Total walking (n = 606)</i>				<i>Total movement (n = 608)</i>			
Intersections/area	0.698	0.234	0.362	1.348	0.485	0.223	0.197	1.193
Density of food store employees	0.980	0.008	0.965	0.995	0.986	0.006	0.974	0.998
Sidewalk length/area	1.001	0.001	1.000	1.003	1.000	0.001	0.998	1.001
BIC	1369.365				1696.575			

Notes: All models employ robust standard errors and account for clustering by focus area. Adjusted for a subject’s age, sex, race, education, marital status, home ownership, tenure, overall health, car ownership, and total household members. ‘Travel walking’ and ‘Leisure walking’ are on the METS scale (IPAQ); ‘Total walking’ is measured in average miles per day (diary); and ‘Total movement’ is the mean total activity per day as recorded on accelerometers.

but again by under 1 per cent. Increased density of food service employees does not substantially impact whether subjects are in a no-walking category or low walking category, or low walking to moderate levels of walking. Other features of design and destination do not significantly impact ordered log odds of travel, leisure, total walking or total movement. Again, the other features of design and destinations did not alter the physical activity measures between categories. We recognise that effect estimates may be imprecise, but even those with statistically significant point estimates are rather close to unity. We also performed these analyses controlling for perceptions of the built environment, including perceptions of crime, interesting places to go within walking distance, difficulty in walking due to hills, time to get to nearby business, job or school, and presence of bicycle or pedestrian trails. Adding the perception variables to the ordinal logistic regression model does

not substantially change the ordered OR or alter the statistical significance with the exception of sidewalk length per unit area and travel walking. After adding perceptions to the model, sidewalk length per unit area’s association with travel walking became significant (OR = 1.00, p-value = 0.004, 95 per centCI: 1.00–1.00), although so small as to ignore its relevance.

Discussion and Limitations

It is certainly possible to design an environment to support transport or leisure walking. It may be possible to increase total walking. However, in terms of overall physical activity, the key public health outcome, there are few statistically significant associations. This could mask the situation that some sub-populations are more sensitive to their residential environments. However, in further work we have analysed a number of additional

groups that differ by ethnicity, education, sex, BMI, work status, car ownership, household type, presence of children and other factors. While preliminary results show differences in walking, total physical activity does not differ (Forsyth *et al.*, 2007a).

One potential limitation of this research is the use of accelerometers. These are motion detectors typically worn on the hip (although other locations are possible) that measure vertical movement and report such motion at one-minute intervals when worn. Such accelerometers have typically been used in more experimental situations and it is only in the past few years that they have been used in larger studies. The science of interpreting accelerometer data is in some flux. Additional work is on-going to analyse how sensitive the findings are to varying approaches to summarising the raw accelerometer data into physical activity variables. The task of reducing raw accelerometer counts per minute to useful data requires a number of decisions that may alter the final summary physical activity data. These decisions may include the choice of a threshold above which activity is considered to be adequately intense to promote health, choices regarding how many hours of wearing per day are required for a 'valid' day, how many 'valid' days of data are required for a participant's data to be included in the analysis, how to deal with consecutive zeros (for example, are these time-periods reflective of non-wearing or sedentary activity?) and how to define bouts of activity. In our analyses, we have eliminated the issue of bouts and thresholds by looking at total counts per day. It can be noted that revising these decisions to various extremes did not alter substantively the interpretation of results herein. More research is needed, however, to validate accelerometer data in observational rather than experimental studies.

We did not control here for self-selection of people who like to walk into environments that support that choice, or for people whose

preference for built environment features self-selected them into certain types of environments. However, if we had controlled for either of these scenarios, it is likely that it would have diminished the results of our study still further. Finally, this is a cross-sectional study examining people in one time-period and one place. It is possible that placing the same people in a different environment, or following them over time, would provide different results.

Certainly, the built environment matters for walking. It is apparent from this study that it is possible to design environments that would be associated with either travel or leisure walking. However, increasing *overall* physical activity is a much bigger challenge.

The policy implications of the research are complex and given such low correlations may actually reflect an unsubstantial practical policy-level application. As Table 1 outlines, this study looked at many measures of design and destinations at many geographies and there were no strong positive correlations between the built environment measures and overall physical activity. The case of mixed use, with statistically significant but negative correlations with total physical activity, is particularly striking.¹⁹ Mixed use or the presence of destinations is often seen in transport planning theories as a key generator of movement (but see Rutt and Coleman, 2005). These findings may indicate how little retail matters in generating *overall* physical activity. Given the reported economic difficulty in supporting local retail within walking distance of homes, this may be an encouraging finding as it is a challenge to add retail (Bartlett, 2003). In related work on density, we found a similar lack of association with overall physical activity using several analytical strategies including both negative binomial and ordinal logistic regressions.

In terms of walking, rather than overall physical activity, several aspects of pedestrian infrastructure were associated with travel and

total walking, and these are comparatively easy to change. However, given the positive associations between walking and street pattern (difficult to change), the results are less encouraging in terms of being able to retrofit existing environments.

Overall, changing the built environment can be difficult. Perhaps the most substantial implication is related to policy-level interventions related to the built environment to increase physical activity. As described, there are limited features that may be altered, but if there is slight to low odds of, for example, altering sidewalk length and increasing physical activity levels of individuals from none to some, is it economically efficient and is there political will? At a population level, however, an increase in physical activity of 1 per cent could have an enormous impact and potentially shift the entire distribution of physical activity in a positive direction. Given the apparently modest effects of the built environment on physical activity, it seems that it may instead be more efficient to change how people relate to their environments through such mechanisms as pricing or education.

One additional interpretation of our findings is that in the US, sedentary behaviour is *common* and both the built and social environments support this. In addition, researchers who work to promote physical activity at the individual level find it difficult to do so for the same reason. The way to alter normative behaviour in societies may lie along an axis moving beyond the work of urban planners and health promoters. The inclusion of sociologists and community-based participatory approaches may underlie the next wave of physical activity promotion efforts.

Notes

1. Results for work areas will be reported later.
2. For example, the study suggests that reducing commercial and retail destinations would

increase overall physical activity but have no effect on total walking. However, this finding was not robust across different measures of physical activity.

3. The GIS measures are available at http://www.designforhealth.net/techassistance/gis_protocols.html. There are a number of versions of the protocols on-line—we used 3.0 and 3.1 for these measures. The survey of the perceived environment is available at www.activelivingresearch.org.
4. While Evenson *et al.* (2005) was survey-based, the pre-/post- research design presumably reduced bias and indicates some additional support for the findings outlined later in this paper. A number of other studies have examined policy and programming interventions, for example, Brownson *et al.* (2004).
5. There are a number of other questions, not dealt with here. Do the destinations need to be in the neighbourhood being examined to promote walking? If not, how can they be measured?
6. Other interesting studies of walking focus on travel walking (Cervero and Duncan 2003; Frank *et al.*, 2006); self-reported *neighbourhood* walking (Li *et al.*, 2005; Handy *et al.*, 2006); walking for particular purposes (Patterson and Chapman, 2004; van Lenthe *et al.*, 2005) or for leisure (Berke *et al.*, 2007).
7. There are a number of studies that use PA recall measures and one objective environmental measure such as distance to a park (for example, Gomez *et al.*, 2004). We have not included these papers.
8. Some have used very large geographical scales, such as the county, to provide background for further work (Doyle *et al.*, 2006) or broad measures of environment such as age of development (Berrigan and Troiano, 2003).
9. The total number of participants was 718, but 3 had invalid addresses.
10. In addition, 20 per cent of participants 147 people, repeated measures for a reliability assessment.
11. Recruitment methods included visiting block clubs, attending fairs, putting up fliers in such places as laundromats and walking the street with fliers. As is explained elsewhere,

- compared with the census, the demographic characteristics of the non-random group reflected those of the focus areas.
12. The survey, GIS measures and urban design inventory are available on-line. The travel diary was a modified version of the National Household Travel Survey that added recreational walking (Twin Cities Walking Study, 2005; Boarnet *et al.*, 2006; Day *et al.*, 2006; Forsyth, 2005).
 13. We used the network analyst in ArcGIS 3.3 that creates a convex hull network buffer. The new network analyst in ArcGIS9.1 uses a different kind of network buffer that leads to slightly different results (see discussion in Forsyth, 2005, Forsyth *et al.*, 2006).
 14. We also examined the association between whether a person had walked at all for leisure or travel as measured by diary. The main differences were a number of negative correlations between various mixed use measures and any leisure walking.
 15. The hardware store variable had significant Pearson correlations with mean accelerometer scores for straight-line and network distances, but only with straight-line distance for median scores.
 16. In ARCGIS version 8.3 and 9.0, it was difficult to measure the distance to the nearest vertex of a polygon. This has been corrected in version 9.2. Thus we approximated distances by creating buffers around parks to see if respondents were within 200, 400, 800 or 1600 metres of the park (Forsyth, 2005). For this analysis, we used a 400 metre buffer.
 17. There were many questions without significant correlations with accelerometer readings including all other questions in the Twin Cities Walking Survey sections E1–6 (types of residence); the remainder of F1–23 (facilities), G1–6 (access to services), H1–5 (street design), the remainder of I 1–5 (places for walking and cycling), J1–6 (neighbourhood surroundings); K1–8 (safety from traffic), the remainder of L1–6 (safety from crime). It was also true for P1–11 (reasons for moving to neighbourhood), as well as C1–5 (social cohesion).
 18. These were from question D1 a–i in the Twin Cities Walking Survey.
 19. In addition, much attention has been paid to developing more complex measures of land

use mix and none of these measures proved statistically significant.

References

- Audirac, I. (1999) Stated preference for pedestrian proximity: an assessment of new urbanist sense of community, *Journal of Planning Education and Research*, 19, pp. 53–66.
- Bartlett, R. (2003) Testing the ‘popsicle test’: realities of retail shopping in new traditional neighbourhood developments, *Urban Studies*, 40(8), pp. 1471–1485.
- Berke, E. M., Koepsell, T. D., Vernez Moudon, A. *et al.* (2007) Association of the built environment with physical activity and obesity in older persons, *American Journal of Public Health*, 97, pp. 486–492.
- Berrigan, D. and Troiano, R. (2003) The association between urban form and physical activity in US adults, *American Journal of Preventive Medicine*, 23, pp. 74–79.
- Boarnet, M., Day, K., Alfonzo, M. *et al.* (2006) The Irvine Minnesota Inventory to measure built environments: reliability tests, *American Journal of Preventive Medicine*, 30(2), pp. 153–259.
- Bourdeaudhuij, I. de, Sallis, J. and Saelens, B. (2003) Environmental correlates of physical activity in a sample of Belgian adults, *American Journal of Health Promotion*, 18(1), pp. 83–92.
- Brownson, R., Baker, E., Boyd, R. *et al.* (2004) A community-based approach to promoting walking in rural areas, *American Journal of Preventive Medicine*, 27, pp. 28–34.
- CDC (Centers for Disease Control and Prevention) (2006a) *Physical activity for everyone: measuring physical activity intensity: metabolic equivalent (MET) level* (<http://www.cdc.gov/nccdph/dnpa/physical/measuring/met.htm>).
- CDC (2006b) *U.S. physical activity statistics: definitions* (<http://www.cdc.gov/nccdph/dnpa/physical/measuring/met.htm>).
- Cervero, R. and Duncan, M. (2003) Walking, bicycling, and urban landscapes: evidence from the San Francisco Bay area, *American Journal of Public Health*, 93(9), pp. 1478–1483.
- Cervero, R. and Gorham, R. (1995) Commuting in transit versus automobile neighborhoods, *Journal of the American Planning Association*, 61, pp. 210–225.

- Cervero, R. and Kockelman, K. (1997) Travel demand and the 3Ds: density, diversity, and design, *Transportation Research Part D*, 2(3), pp. 199–219.
- Cervero, R. and Radisch, C. (1996) Travel choices in pedestrian versus automobile oriented neighborhoods, *Transport Policy*, 3(3), pp. 127–141.
- Committee on Physical Activity, Health, Transportation and Land Use (2005) *Does the built environment influence physical activity: examining the evidence*. Transportation Research Board, Washington, DC.
- Crane, R. (2000) The influence of urban form on travel: an interpretive review, *Journal of Planning Literature*, 15(1), pp. 3–23.
- Crane, R. and Crepeau, R. (1998) Does neighbourhood design influence travel? A behavioral analysis of travel diary and GIS data, *Transportation Research Part D*, 3, pp. 225–238.
- D'Agostino, R. (1998) Tutorial in biostatistics: propensity scores methods for bias reduction in the comparison of a treatment to a non-randomized control group, *Statistics in Medicine*, 17, pp. 2265–2281.
- Day, K., Boarnet, M., Alfonzo, M. and Forsyth, A. (2006) The Irvine Minnesota Inventory to measure built environments: development, *American Journal of Preventive Medicine*, 30(2), pp. 144–152.
- Doyle, S., Kelly-Schwartz, A., Schlossberg, M. and Stockard, J. (2006) Active community environments and health, *Journal of the American Planning Association*, 72(1), pp. 19–32.
- Evenson, K., Herring, A. and Huston, S. (2005) Evaluating change in physical activity with the building of a multi-use trail, *American Journal of Preventive Medicine*, 28(2S2), pp. 177–185.
- Ewing, R. (1994) Characteristics, causes, and effects of sprawl: a literature review, *Environmental and Urban Issues*, 11(2), pp. 1–15.
- Ewing, R. (2005) Can the physical environment determine physical activity levels?, *Exercise and Sport Sciences Reviews*, 33(2), pp. 69–75.
- Ewing, R. and Cervero, R. (2001) Travel and the built environment: a synthesis, *Transportation Research Record*, 1780, pp. 87–113.
- Ewing, R., Schmid, T., Killingsworth, R. et al. (2003) Relationship between urban sprawl and physical activity, obesity, and morbidity, *American Journal of Health Promotion*, 18(1), pp. 47–57.
- Forsyth, A. (2000) Analyzing public space at a metropolitan scale: notes on the potential for using GIS, *Urban Geography*, 21(2), pp. 121–147.
- Forsyth, A. (Ed.) (2005) *Environment and Physical Activity: GIS Protocols*, Version 3.1. Minneapolis, MN: Design Center (http://www.designforhealth.net/techassistance/gis_protocols.html).
- Forsyth, A., Oakes, J. M. and Schmitz, K. H. (2007a) *The built environment and overall physical activity among population subgroups*. Poster presented at the *Active Living Research Annual Conference*, San Diego, February.
- Forsyth, A., Oakes, J. M., Schmitz, K. H. and Hearst, M. (2007b) Does residential density increase walking and other physical activity?, *Urban Studies*, 44(4), pp. 679–697.
- Forsyth, A., Schmitz, K. H., Oakes, M. et al. (2006) Standards for environmental measurement using GIS: toward a protocol for protocols, *Journal of Physical Activity and Health*, 3(S1), pp. 241–257.
- Foster, C., Hillsdon, M. and Thorogood, M. (2005) Environmental perceptions and walking in English adults, *Journal of Epidemiology and Community Health*, 58, pp. 924–928.
- Frank, L. D. and Pivo, G. (1994) Impacts of mixed use and density utilization of three modes of travel: single-occupant vehicle, transit, and walking, *Transportation Research Record*, 1466, pp. 44–52.
- Frank, L. D., Sallis, J. F., Conway, T. et al. (2006) Many pathways from land use to health, *Journal of the American Planning Association*, 72(1), pp. 75–87.
- Frank, L. D., Schmid, T. L., Sallis, J. F. and Chapman, J. (2005) Linking objectively measured physical activity with objectively measured urban form: findings from SMARTAQ, *American Journal of Preventive Medicine*, 28(2S2), pp. 117–125.
- Giles-Corti, B. and Donovan, R. J. (2002a) The relative influence of individual, social and physical environment determinants of physical activity, *Social Science and Medicine*, 54, pp. 1793–1812.
- Giles-Corti, B. and Donovan, R. J. (2002b) Socio-economic status differences in recreational physical activity levels and real and perceived

- access to a supportive physical environment, *Preventive Medicine*, 35, pp. 601–611.
- Giles-Corti, B., Broomhall, M., Knuiiman, M. et al. (2005) Increasing walking: how important is distance to, attractiveness, and size of public open space?, *American Journal of Preventive Medicine*, 28(2S2), pp. 169–176.
- Gomez, J., Johnson, B. A., Selva, M. and Sallis, J. F. (2004) Violent crime and outdoor physical activity among inner-city youth, *Preventive Medicine*, 39, pp. 876–881.
- Grammenos, F., Gregory, K. and Pidgeon, C. (2004) *Applying fused-grid planning in Stratford, Ontario*. Research Highlight, Canadian Mortgage and Housing Corporation, Ottawa.
- Handy, S. (1992) Regional versus local accessibility: neo-traditional development and its implications for non-work travel, *Built Environment*, 18(4), pp. 253–267.
- Handy, S. (1996) Methodologies for exploring the link between urban form and travel behavior, *Transportation Research Record*, 1(2), pp. 151–165.
- Handy, S. (2003) *Critical assessment of the literature on the relationships among transportation, land use, and physical activity*. Draft paper prepared for the TRB and the Institute of Medicine Committee on Physical Activity, Health, Transportation, and Land Use, November.
- Handy, S., Boarnet, M. G., Ewing, R. and Killingsworth, R. E. (2002) How the built environment affects physical activity: views from urban planning, *American Journal of Preventive Medicine*, 23(2S), pp. 64–79.
- Handy, S., Cao, X. and Mokhtarian, P. (2006) Self-Selection in the relationship between the built environment and walking: evidence from northern California, *Journal of the American Planning Association*, 72(1), pp. 55–74.
- Hess, P. M., Moudon, A. V., Snyder, M. C. and Stanilov, K. (1999) Neighborhood site design and pedestrian travel, *Transportation Research Record*, 1674, pp. 9–19.
- Hoehner, C. M., Ramirez, L. B., Elliott, M. B. et al. (2005) Perceived and objective environmental measures and physical activity among urban adults, *American Journal of Preventive Medicine*, 28(2S2), pp. 105–116.
- Humpel, N., Owen, N. and Leslie, E. (2002) Environmental factors associated with adults' participation in physical activity, *American Journal of Preventive Medicine*, 22(3), pp. 188–199.
- Humpel, N., Owen, N., Leslie, E. et al. (2004) Association of location and perceived environmental attributes with walking in neighborhoods, *American Journal of Health Promotion*, 18(3), pp. 239–242.
- Jago, R., Baranowski, T. and Baranowski, J. (2006a) Observed, GIS, and self-reported environmental features and adolescent physical activity, *American Journal of Health Promotion*, 20(6), pp. 422–428.
- Jago, R., Baranowski, T. and Harris, M. (2006b) Relationships between GIS environmental features and adolescent male physical activity: GIS coding differences, *Journal of Physical Activity and Health*, 3, pp. 230–242.
- Jago, R., Baranowski, T., Zakeri, I. and Harris, M. (2005) Observed environmental features and the physical activity of adolescent males, *American Journal of Preventive Medicine*, 29(2), pp. 98–104.
- Kelly-Schwartz, A., Stockard, J., Doyle, S. and Scholssberg, M. (2004) Is sprawl unhealthy?, *Journal of Planning Education and Research*, 24, pp. 184–196.
- King, W. C., Belle, S., Brach, J. S. et al. (2005) Objective measures of neighborhood environment and physical activity in older women, *American Journal of Preventive Medicine*, 28(5), pp. 461–469.
- King, W. C., Brach, J. S., Belle, S. et al. (2003) The relationship between convenience of destinations and walking levels in older women, *American Journal of Health Promotion*, 18(1), pp. 74–82.
- Krizek, K. (2003a) Residential relocation and changes in urban travel: does neighborhood-scale urban form matter?, *Journal of the American Planning Association*, 69(3), pp. 265–281.
- Krizek, K. (2003b) Operationalizing neighborhood accessibility for land use–travel behavior research and regional modeling, *Journal of Planning Education and Research*, 22(3), pp. 270–287.
- Krizek, K., Birnbaum, A. and Levinson, D. (2004) A schematic for focusing on youth in investigations of community design and physical activity, *American Journal of Health Promotion*, 19(1), pp. 33–38.

- Lee, C. and Moudon, A. V. (2006) Correlates of walking for transportation or recreation purposes, *Journal of Physical Activity and Health*, 3(S1), pp. S77–S98.
- Lenthe, F. J. van, Brug, J. and Mackenbach, J. P. (2005) Neighbourhood inequalities in physical inactivity: the role of neighbourhood attractiveness, proximity to local facilities and safety in the Netherlands, *Social Science and Medicine*, 60(4), pp. 763–775.
- Li, F., Fishers, J. K., Brownson, R. and Bosworth, M. (2005) Multilevel modeling of built environment characteristics related to neighborhood walking activity in older adults, *Journal of Epidemiology and Community Health*, 59(5), pp. 558–564.
- Masse, L. C., Fuemmeler, B. F., Anderson, C. B. et al. (2005) Accelerometer data reduction: a comparison of four reduction algorithms on select outcome variables, *Medicine and Science in Sports and Exercise*, 37(11), pp. S544–S554.
- Matthews, C. E., Ainsworth, B. E., Thompson, R. W. and Bassett, D. R. jr (2002) Sources of variance in daily physical activity levels as measured by an accelerometer, *Medicine and Science in Sports and Exercise*, 34(8), pp. 1376–1381.
- McCann, B. A. and Ewing, R. (2003) *Measuring the health effects of sprawl: a national analysis of physical activity, obesity and chronic disease*. Smart Growth America Surface Transportation Policy Project (<http://www.smartgrowthamerica.org/healthreportpr.html>).
- McNally, M. G. and Kulkarni, A. (1999) Assessment of influence of land-use transportation system on travel behavior, *Transportation Research Record*, 1607, pp. 105–115.
- Merom, D., Bauman, A., Vita, P. and Close, G. (2003) An environmental intervention to promote walking and cycling: the impact of a newly constructed rail trail in western Sydney, *Preventive Medicine*, 35, pp. 235–242.
- Moudon, A. V. and Hess, P. (2000) Suburban clusters: the nucleation of multifamily housing in suburban areas of the central Puget Sound, *Journal of the American Planning Association*, 66(3), pp. 243–264.
- Moudon, A. V. and Lee, C. (2003) Walking and bicycling: an evaluation of environmental audit instruments, *American Journal of Health Promotion*, 18(1), pp. 21–37.
- Moudon, A. V., Hess, P., Snyder, M. and Stanilov, K. (1997) *Effects of site design on pedestrian travel in mixed use, medium density environments*. Report WA-RD 431.1, Washington State Department of Transportation, Olympia, WA.
- Moudon, A.V., Lee, C., Cheadle, A. et al. (2004) *Walkable and bikable communities project: a draft report on findings from the walking models*. Urban Form Lab, University of Washington, Seattle, WA.
- Nelson, M. P., Gordon-Larsen, Y., Song, B. and Popkin (2006) Built and social environments: associations with adolescent overweight and activity, *American Journal of Preventive Medicine*, 31(2), pp. 109–117.
- Norris, C. M., Ghali, W. A., Saunders, L. D. et al. (2006) Ordinal regression model and the linear regression model were superior to the logistic regression models, *Journal of Clinical Epidemiology*, 59(5), pp. 448–456.
- Oakes, J. M. (2004) The (mis)estimation of neighborhood effects: causal inference for a practicable social epidemiology, *Social Science and Medicine*, 58, pp. 1929–1952 (with discussion and rejoinder).
- Oakes, J. M., Forsyth, A. and Schmitz, K. H. (2007) *The effect of neighborhood density and street connectivity on walking behavior: the twin cities walking study*. Manuscript.
- Patterson, P. K. and Chapman, N. J. (2004) Urban form and older residents' service use, walking, driving, quality of life, and neighborhood satisfaction, *American Journal of Health Promotion*, 19(1), pp. 45–52.
- Ratner, R. K., Kahn, B. E. and Kahneman, D. (1999) Choosing less-preferred experiences for the sake of variety, *Journal of Consumer Research*, 26, pp. 1–15.
- Rodríguez, D., Khattak, A. and Evenson, N. (2006) Can new urbanism encourage physical activity? Comparing a new urbanist neighborhood with conventional suburbs, *Journal of the American Planning Association*, 72(1), pp. 43–54.
- Rosenbaum, P. R. (2005) Heterogeneity and causality: unit heterogeneity and design sensitivity in observational studies, *The American Statistician*, 59(2), pp. 147–152.
- Rubin, D. B. (1997) Estimating causal effects from large data sets using propensity scores, *Annals of Internal Medicine*, 127(8, Pt 2), pp. 757–763.

- Rubin, D. B. and Thomas, N. (2006) Matching using estimated propensity scores: relating theory to practice, in: D. B. Rubin (Ed.) *Matched Sampling for Causal Effects*. New York: Cambridge University Press.
- Rutt, C. and Coleman, K. (2005) Examining the relationships among built environment, physical activity, and body mass index in El Paso, TX, *Preventive Medicine*, 40, pp. 831–841.
- Saelens, B., Sallis, J. and Frank, L. (2003) Environmental correlates of walking and cycling: findings from the transportation, urban design, and planning literatures, *Annals of Behavioral Medicine*, 25(2), pp. 80–91.
- Sloane, D. C. (2006) From congestion to sprawl: planning and health in historical context, *Journal of the American Planning Association*, 72(1), pp. 10–18.
- Slymen, D. J., Ayala, G. X., Arredondo, E. M. and Elder, J. P. (2006) A demonstration of modeling count data with an application to physical activity, *Epidemiological Perspectives and Innovations*, 3(3), pp. 1–9.
- Song, Y. and Knaap, G.-J. (2004) Measuring urban form, *Journal of the American Planning Association*, 70(2), pp. 210–225.
- Southworth, M. (1997) Walkable communities? An evaluation of neotraditional communities on the urban edge, *Journal of the American Planning Association*, 63(1), pp. 28–44.
- Spanier, P. A., Marshall, S. J. and Faulkner, G. E. (2006) Tackling the obesity pandemic: a call for sedentary behaviour research, *Canadian Journal of Public Health*, 97(3), pp. 255–257.
- Steiner, R. L. (1994) Residential density and travel patterns: review of the literature, *Transportation Research Record*, 1466, pp. 37–43.
- Twin Cities Walking Study (2005) *Twin cities walking survey* (http://www.activelivingresearch.org/index.php/Twin_Cities_Walking_Survey/328).
- Warburton, D. E., Nichol, C. W. and Bredin, S. S. (2006) Health benefits of physical activity: the evidence, *Canadian Medical Association Journal*, 174(6), pp. 801–809.