Defining Mixed-Use: Which Land Uses Promote Walking?

by

Megan Lewis McConville

A Master's Project submitted to the faculty
of the University of North Carolina at Chapel Hill
in partial fulfillment of the requirements
for the degree of Master of City and Regional Planning
in the Department of City and Regional Planning.

Chapel Hill

2009

Approved by:

__________________________ __________________________

READER (optional) ADVISOR

Abstract

A growing body of literature finds that mixed-use development can affect trip frequency, trip length and mode choice. Though researchers have explored the general impacts of this type of development on travel, few have examined which specific land uses should be mixed to achieve transportation-related goals. This Master's Project addresses this gap in the literature, focusing on the influence of mixed land uses on utilitarian walking. Built environment data was related to utilitarian walking and total walking for individuals (n=251) in Montgomery County, Maryland. For a variety of land uses, exposure measures included the distance from participants' homes to the closest instance of each land use (presence), the number of instances of each land use within ½ and ¼ mile buffers of homes (intensity), and the number of different land uses present within ½ and ¼ mile buffers of homes (diversity). Distances to bus stops, fast food restaurants, grocery stores, Metro stations, offices, physical activity uses, recreational facilities, restaurants, social uses and sports facilities were negatively associated with transportation walking (OR .01-.90). The intensities of bus stops, grocery stores, offices, and retail stores were positively correlated with utilitarian walking (OR 1.04-5.51). Furthermore, a dose-response relationship between land use diversity and walking for transport was detected. Results suggest that planners, policymakers and developers can encourage physical activity and promote walking as a travel mode choice through the careful design of mixed-use developments.

Table of Contents

Introduction

"Mixed-use development" has become something of a buzzword in planning and policy circles. This type of development, which integrates residential, office, commercial, recreational and other compatible land uses in a given area, has been touted as a remedy for a wide spectrum of community dysfunctions, from the obesity epidemic to the erosion of social capital. Most notably, researchers have observed the influence of mixed-use development on travel behavior. A growing body of literature has shown that mixed land uses can affect trip frequency, trip length and travel mode choice. However, though researchers have explored the general impacts of mixed-use development on travel, few have examined which particular land uses should be mixed to achieve transportation-related goals, and how they should be combined. This Master's Project attempts to respond to that deficiency in the literature, specifically focusing on the influence of mixed land uses on walking. Using detailed built environment and travel data from Montgomery County, Maryland, this paper examines the relationships between particular land uses and utilitarian walking.

With the growing popularity of New Urbanism and other forms of neo-traditional development that incorporate mixed land uses, it is becoming increasingly important to define "mixed-use." Planners, policymakers and developers who advocate mixed-use development are often pursuing the overall policy goal of reducing vehicle miles traveled. They believe that bringing origins and destinations closer to each other will allow people to drive less and walk, cycle and use transit more. However, without guidance indicating which uses are most effective at reaching transportation-related goals, decision makers are operating blindly. In fact, if they do not have the knowledge necessary to implement mixed-use development properly, sustainable transportation goals could even be counteracted. As Crane (1996) pointed out, residents of areas with high retail accessibility might shop more often and drive more miles overall, since lower transportation costs stimulate travel. Fortunately, a better understanding of the composition of mixed-use development will increase the chances that it has its intended effects, and will ensure that land use combinations that do effectively reduce auto dependence are included in future neighborhoods.

The walking mode was selected as a focus for several reasons. Previous research has found significant associations between mixed-use development and walking. It makes sense that pedestrians, who are more exposed to their surroundings, would be more sensitive to the built environment than auto travelers. Mixed-use development is thought to provide more visual variety and interest for walkers (Forsyth et al, 2008). Additionally, it brings destinations closer together, and pedestrians would seem to be particularly responsive to this increased accessibility (Joh et al, 2008). Moreover, walking trips are shorter and therefore easier to relate to the built environment in a given area. In contrast, transit or driving trips would require separate analyses of the origin and the destination, and associations between travel behavior and the built environment may be less clear.

This paper focuses specifically on walking for transportation, as opposed to walking for leisure or recreation. Utilitarian walking is done with a destination or purpose in mind (other than getting exercise). This distinction is drawn because prior research has suggested that transport walking and leisure walking are influenced by different environmental factors (Hoehner et al, 2005). Mixed-use environs have been shown to affect travel walking, but their influence on leisure walking is less clear (Forsyth et al, 2008; Lovasi et al, 2008; Lund, 2003; McCormack et al, 2008; Owen et al, 2007). Transportation walking is also of particular interest because it has the potential to replace automobile trips.

The following research question is posed in this study: *Which land uses should be mixed with residential uses to encourage utilitarian walking, and with approximately what intensity and how much diversity?* Intensity refers to the amount of a specified land use in a given area, while diversity refers to the number of land use types.

The next section of this paper reviews the relevant literature related to mixed-use development and walking, and then lists the three hypotheses. Subsequently, the study's methods are outlined, including descriptions of the sample, the variables and the statistical analysis. Results are discussed in the next section, followed by a discussion analyzing findings. Finally, recommendations are provided for planners and policymakers. In addition, to situate the study's results in a broader context, a supplementary analysis of the relationship between mixed-use development and total walking is included in the Appendix.

Literature Review

Mixed-Use Development and Walking

Experts in both the planning and public health fields have identified associations between mixed-use development and utilitarian walking. For instance, Saelens et al (2003) found that respondents reporting proximity and ease of access to non-residential land uses in their neighborhoods walked more for errands, and Frank et al (2008) observed that land use mix at the places of residence and employment significantly increased walking in comparison to driving for work tours. However, the literature addressing the influence of mixed land uses on transportation walking is still fairly undeveloped in comparison with the research describing the effects of mixed uses on walking in general. For that reason, and because this review focuses primarily on the treatment of land use exposures, works analyzing all types of walking will be included here.

The studies referenced above are representative of much of this body of literature, in that they focused on the effects of mixed-use development in general, rather than on the influences of specific land uses. Often, independent variables are simple dichotomous indicators of the existence of mixed uses (Badland et al, 2008; Ball et al, 2001; Boer et al, 2007; Guo et al, 2007; Joh et al, 2008), or, more general still, indices combining a mixed-use measure with other land use descriptors (Cervero & Duncan, 2003; Craig et al, 2002; Frank et al, 2005; Frank et al, 2007; Owen et al, 2007). While establishing an overall connection between land use mixing and walking behavior is important, it provides little concrete guidance to planners and developers who are looking to implement mixed-use development.

For instance, Owen et al (2007) scored neighborhoods on their degree of land use mixing and combine that measure into a composite walkability index which also includes three other environmental variables. Though the authors found positive associations between the walkability index and transport-related walking, these results are of limited use to practitioners, who cannot distinguish the particular features of the built environment with which walking for transport is actually related. As Crane & Crepeau (1998) pointed out, combining environmental characteristics makes conclusions about the influences of individual features impossible to isolate.

Some experts narrow their concept of mixed-use development to include broad land use categories, such as residential and commercial (Cao et al, 2006; Cerin et al, 2007; Crane & Crepeau, 1998). For example, Cerin et al (2007) characterized land uses in general classes including residential, commercial/industrial and recreational, and concluded that some of these categories were significant correlates of walking for transport. However, as with the aforementioned land use indices, it would be difficult for a planning practitioner to apply this information. Though a policymaker may know that residents of districts designated commercial/industrial engage in more transport-related walking than residents of other districts, the actual properties of this land use category are so vague as to be impossible to replicate. In fact, Cerin et al (2007) acknowledged that an analysis of broad land use categories can provide only limited information on specific destinations that influence travel choices.

Additionally, using broad land use categories may produce conflicting results. For instance, retail land uses have been found to have varying effects on pedestrian behavior. Cervero & Kockelman (1997) observed that mixed-use environs with retail services significantly induced walking, and Lund (2003) found a positive association between access to local shops and destination walking. At the same time, Crane & Crepeau (1998) discovered that the proportion of land devoted to commercial uses had no effect on the choice between walking and driving. These diverging findings suggest that additional research is needed. Specifically, this disagreement could be due to the fact that researchers are combining dissimilar land uses into the overly general classification of "retail." For instance, chain grocery stores, bakeries, clothing boutiques and hardware stores could influence walking behavior in very different ways. Broad land use categories may not prove to be significant predictors of walking if they include particular uses that are not themselves associated with walking. Giles-Corti (2005) and Cerin et al (2007) echoed this idea, finding that, in explaining walking for transport, the type and mix of commercial destinations may be more important than their mere presence. Accordingly, explorations of the impacts of specific kinds of retail on walking may help clear this ambiguity.

Specific Land Uses and Walking

A few studies have noted that the explanatory power of measures of access to destinations can increase with their specificity. For instance, Cerin et al (2007) found that the proximity of commercial destinations was positively associated with walking for transport, but certain destinations were more important than others. Food shops were significant contributors to transport-related walking, while car and home-related commercial destinations did not predict it (Cerin et al, 2007). Kitamura et al (1997) found no relationship between non-motorized travel and a mixed-use dummy variable, but did find correlations with accessibility indicators for specific land uses, such as rail stations, bus stops and parks. Rajamani et al (2003) concurred with previous findings that capturing the degree of land use mix may not suffice and that including the actual uses is crucial. Consequently, their study utilized both composite indices and disaggregate measures such as distances to parks and bus stops.

McCormack et al (2008) recently responded to the emerging need for land use specificity by examining the impacts of a variety of particular uses on walking. They found that access to bus stops, transit stations, convenience stores, newsstands, shopping malls and public mail boxes within 400 meters of homes, and schools, transit stations, newsstands, convenience stores and shopping malls within 1500 meters of homes, were positively associated with regular transport-related walking. These precise findings are useful to planners seeking to increase walking by implementing mixed-use development.

A handful of other studies have explored the association between walking and parks, food shops, retail stores, recreational destinations, schools and transit stops (Cerin et al, 2007; Forsyth et al, 2008; Giles-Corti & Donovan, 2002; Giles-Corti & Donovan, 2003; Handy & Clifton, 2001; Lovasi et al, 2008; Kitamura et al, 1997; Wen et al, 2007). However, scholars have produced disparate findings, signaling the need for further research. Furthermore, only half of the abovementioned studies were conducted in the United States. The U.S. obviously has a unique spatial environment, transportation infrastructure and culture, and additional investigations specific to this context need to be conducted. In addition, there is little research on restaurants, libraries, banks, sports facilities, offices and other land uses that have an intuitive connection with walking behavior.

Increasing the specificity of land uses does have the potential to invite problems into a study. Expanding analyses to include multiple land use variables could lead to multicollinearity problems that contaminate model estimation (Cervero & Duncan, 2003). Also, extremely specific land uses may not have strong enough effects to predict walking, a possibility which could limit the usefulness of considering these uses in isolation. Some of the studies that have included detailed land uses have found no significant relationships (Forsyth et al, 2008; Lovasi et al, 2008). For instance, Forsyth et al (2008), looking at such detailed land uses as vegetable markets, bakeries, coffee shops, laundromats and salons, observed no correlations with walking.

In summary, the majority of studies examining the association between mixed-use development and walking utilize broad land use measures that are of limited usefulness to planning practitioners. Those focusing on more detailed land use categories have produced conflicting results and have omitted important land uses that may encourage utilitarian walking. Clearly, further exploration of the relationships between specific land uses and walking for transportation is needed.

Land Use Intensity and Walking

Few studies have examined how land use intensity relates to walking. Some of the work that has considered intensity has utilized general measures. For example, in the work of Cervero & Kockelman (1997), intensity emerged as a particularly strong predictor of non-personal vehicle travel (transit or non-motorized modes) for non-work purposes. Their analysis was carried out using factor analysis, combining various per-developed-acre intensity and density measures into a general intensity factor.

Other studies examining the impacts of land use intensity have only included one or two uses. Crane & Crepeau (1998), operationalizing intensity as the proportion of land in the household's census tract that was residential or commercial, found no significant relationships with the decision between driving and walking. Wells et al (2008), on the other hand, observed a negative relationship between commercial intensity and walking. Measuring retail and office intensity as a service jobs-to-population ratio and a jobs-to-resident ratio, they found that increases in these intensities were associated with fewer steps per week. Rajamani et al (2003) also found intensity to be a significant predictor. Using ratios of acreage in a given land use type to the number of housing units in the neighborhood, they showed that the ratio of park area per housing unit was positively associated with walking for recreation.

Forsyth et al (2008) undertook a more thorough examination of intensity, considering a number of detailed land uses. In most cases, they found no relationship between walking and the percentage of total parcel area devoted to the use. Exceptions were significant associations between the density of employees in miscellaneous retail and total walking, between the percentage of land area in social uses and transport and leisure walking, and between transit stop density and transport and leisure walking. Lovasi et al (2008) also considered the intensities of eleven specific land uses, quantified as the count of each destination type within a one kilometer buffer. Similar to Forsyth et al (2008), they showed that these were not significant predictors of walking for exercise.

This review demonstrates that the existing research on intensity and walking is limited and has uncertain implications. Further work is needed to better understand the relationship between walking and the intensities of the specific land uses expected to influence it.

Land Use Diversity and Walking

Likewise, there has been little research on the influence of land use diversity on walking. McCormack et al (2008) saw a dose-response effect of diversity on walking, finding that each additional destination within 400 and 1500 meters resulted in an additional 12 and 11 minutes spent walking for transport per two week period, respectively. Also, for each additional utilitarian destination within 1500 meters, walking for transport increased by 10 minutes per two week period.

Hoehner et al (2005) also discovered a relationship between the number of destinations and transportation physical activity (including both walking and bicycling). For both perceived and objective land-use measures, transportation physical activity was positively associated with having more destinations within walking distance of one’s home. People in the highest quartile for the number of nonresidential destinations were two to three times more likely to engage in transportation physical activity or meet physicians’ recommendations through transportation physical activity than those in the lowest quartile.

Boer et al (2007) looked specifically at business diversity. They found a positive relationship between the number of business types in a neighborhood and increased walking, but there was an upper limit to this effect. Increasing business diversity beyond four types of establishments did not further increase walking.

In summary, several studies have concluded that a higher number of land uses encourages more walking, but this body of research is still small. The influence of land use diversity on walking deserves further attention. Key questions yet to be answered include whether the number of uses has a linear effect on walking and whether there is a critical mass of land use variety needed to attract pedestrians.

Quantifying Land Use Mixing

In addition to the gaps identified above, prior research associating mixed-use development and walking is plagued by a lack of consistent, proven methods for quantifying land uses. As Boarnet & Crane (2001) point out, land use mixing is "more than a simple feature of the built environment that can either be readily described or easily replicated." Many studies use coarse or subjective built environment variables that may not be statistically significant due to measurement problems (in contrast to the often-continuous nature of control variables like incomes and travel distances, which enjoy a predictive advantage) (Cervero & Kockelman, 1997).

As described above, some analyses use measures that are so general as to impede their usefulness to planning practitioners seeking to apply the research. For instance, Cervero (1996) uses a dichotomous yes-no variable indicating the existence of non-residential uses in the study area.

Additionally, some of the measures utilized are potentially indirect proxies for land use mix, which could distort findings. For example, density of retail and service employment, a commonly used indicator of mixed uses, shows the number of jobs within a given area but not necessarily the number of establishments (Boarnet & Crane, 2001). Boarnet & Crane (2001) find the percentage of land in certain uses to be more accurate.

In other cases, the data has been so manipulated that it no longer reflects the built environment characteristic intended. Entropy and dissimilarity indices, which quantify the degree to which land uses are evenly distributed within a given area, are one example. Evenness is not necessarily a positive quality, nor is unevenness automatically a barrier to walking. For instance, a neighborhood containing an uneven combination of two shops and 30 houses may be very attractive to pedestrians.

Finally, many of the studies reviewed measure land use at an aggregate census tract or block group level (Boarnet & Crane, 2001; Boer et al, 2007; Cervero & Duncan, 2003; Cervero & Kockelman, 1997), which can obscure important information about the proportion of non-residential to residential uses within walking distance, the degree of clustering or dispersal of uses, and the level of accessibility to pedestrians. These aggregate descriptions of urban form co-opt useful conclusions about their relationships with travel (Handy, 1996).

To sum up, some associations between specific land uses and walking are emerging from the current literature, but this particular line of research is still nascent. Further developments in this area would be extremely useful to planning practitioners as they consider including mixed-use projects in their communities. Additionally, the literature has produced little guidance on the effects of land use intensity and diversity on walking. Building on this limited research would also be helpful to planners, who need to know how uses should be mixed as well as which ones to combine. Finally, this literature review underscores the importance of measurement. The methods used to operationalize land uses greatly impact the applicability of a study's results. Land use variables that distort or hide the built environment characteristic they represent are less useful to planners and policymakers than straightforward and precise measures.

This paper attempts to respond to the abovementioned gaps in the urban planning and public health literature in several ways. First, it builds on the prior research suggesting that some specific land uses – including grocery stores, convenience stores, drug stores, parks, transit stops, schools and post offices – are associated with transport walking, while others are not. This study aims to develop those findings and test the influence of other land uses that can reasonably be expected to predict utilitarian walking, such as stores carrying lower-order goods and smaller-sized items that consumers purchase on a regular basis as well as restaurants and other entertainment-related land uses. Accordingly, the first hypothesis is: *Proximity to "functional" destinations – bus stops, grocery stores, libraries, Metro stops, non-fast food restaurants, recreation centers, retail stores, and schools – is related to walking for transport.* As distances to these destinations increases, transportation walking is expected to decrease.

This study explores not only which land uses should be mixed with residential development, but how they should be mixed. Specifically, it examines the influences of intensity and diversity on walking for transport. Thus, the second hypothesis is: *The intensity of the land uses related to utilitarian walking is itself positively related to utilitarian walking.* As intensity increases, transportation walking is expected to increase. However, this relationship may be nonlinear. For example, the number of retail shops in a neighborhood may be associated with increased walking to a point, after which additional shops could reduce pedestrian-friendliness. The third hypothesis is: *Greater diversity of uses is related to increased walking for transport.* As diversity increases, transportation walking is expected to increase. This relationship may also show nonlinearity.

Methods

Sample

We use data collected in Montgomery County, Maryland, a location with a variety of built environments ranging from exurban areas to highly urbanized, transit-oriented neighborhoods. Based on a Built Environment Index score, each of Montgomery County's 318 traffic analysis zones (TAZs) was classified into one of three categories: urban, suburban and exurban. Five zones were then selected at random: two each from the urban and suburban categories and one from the exurban category. A sample of residents from each TAZ was recruited to participate in the study, providing data in several ways. First, participants answered survey questions about their perceived neighborhood environment, physical activity patterns and socio-demographic characteristics. They also kept a seven-day activity diary. In addition, the long form (27 items) of the International Physical Activity Questionnaire (IPAQ-LF) was used to measure frequency, intensity, and duration of occupational, transportation, home, leisure/sport, and sitting activity over the previous seven days. IPAQ-LF has been shown to have acceptable measurement properties (Craig et al, 2003; Hagstromer et al, 2006).

Participants supplemented the subjectively measured physical activity data by wearing an actigraph, or battery-powered activity monitor, for seven days. The model used in this study was the dual mode ActiGraph model 7164, formerly known as the Computer Science and Applications (CSA) and Manufacturing Technology Inc. (MTI) (ActiGraph, LLC, Fort Walton Beach, FL). Previous studies have demonstrated the Actigraph 7164 to be reliable and valid (Metcalf et al, 2002; Welk et al, 2004). Each activity monitor was calibrated and tested to ensure adequate operation and was set to record activity in one-minute epochs. A participant was presumed to be wearing the activity monitor from the time when the first non-zero value was recorded and was followed by one or more non-zero values being recorded. A participant was considered as not wearing the monitor if 20 or more consecutive minutes had zero counts. Missing data were not imputed. No outliers (counts exceeding 15,000 for five minutes or more) in the actigraph data were identified.

The built environment of each participant's neighborhood, defined as the area within a 20-minute walk or one-mile radius from the person's home, was classified using detailed Geographic Information System (GIS) data provided by Montgomery County. Data including the network distance to the closest instance of a specified land use, population density and sidewalk density were categorized for buffer areas of 1/8, 1/4 and 1/2 mile from each person's home.

Dependent Variables

Walking for Transport

Walking time for transportation purposes was derived from the IPAQ-LF and classified into three groups (none, less than 150 minutes/week, greater than or equal to 150 minutes/week) in order to facilitate comparison with public health guidelines and account for the variability inherent in subjective measures.

Total Walking

Two measures of total walking were also analyzed. Total walking time was derived from the IPAQ-LF and classified into the same three groups as transportation walking. Actigraph data was used to measure steps per valid day of data collection, included in models as a continuous response variable.

Exposures

Land Use Presence

Objective, participant-specific land use measures were derived from Montgomery County's GIS data. To capture the presence of land uses near participants' homes, the street distance to the closest instance of each land use was measured using ESRI's Network Analyst (Redlands, CA). Land uses considered were banks, bus stops, fast food restaurants, grocery stores, libraries, Metro stops, offices, parks, recreation centers, non-fast food restaurants, retail (including grocery stores, fast food restaurants, and restaurants), schools and sports facilities. Three general categories of land use were also included, which overlap with the specific categories above. These include night uses (restaurants, bars, theaters, sports arenas), physical activity uses (parks, playgrounds, athletic properties) and social uses (religious and cultural areas, playgrounds, athletic properties). Distances were measured in miles.

Land use Intensity

To measure intensity, a count of the number of instances of each land use within ½ and ¼ mile network buffers of each participant's home was calculated using the County GIS data and ESRI's

Network Analyst (Redlands, CA). Buffers did not extend beyond one half mile because that is generally considered walking distance (Cervero & Radisch, 1996; Frank, 2004; Hoehner et al, 2005; Pikora et al, 2002; Sallis et al, 1990; Saelens et al, 2003). Because of small sample sizes and heavily skewed distributions, the land uses considered were limited to bus stops, grocery stores, offices, parks, physical activity uses and retail. Banks, fast food restaurants, libraries, Metro stops, night uses, recreation centers, non-fast food restaurants, schools, social uses and sports facilities were excluded. This exposure was considered as a continuous variable.

Land Use Diversity

Land use diversity was included in models as the number of types of land uses within a ½ or ¼ mile buffer of the participant's home. Like the other land use variables, this measure was derived from the County GIS data and calculated with ESRI's Network Analyst (Redlands, CA). Due to overlap between the land use categories, fast food restaurants, grocery stores, night uses, physical activity uses, non-fast food restaurants and social uses were omitted from this section of the analysis. As a result, the land use categories considered were banks, bus stops, libraries, Metro stops, offices, parks, recreation centers, retail stores (including grocery stores, restaurants, fast food restaurants and other retail), schools and sports facilities. This exposure was considered as a continuous variable.

Covariates

Demographic controls were drawn from the survey responses and included age (continuous measure), sex, and education (less than high school diploma, completed high school diploma, vocational training, some college, college/university degree, or graduate/professional degree). In order to account for the effects of density and pedestrian infrastructure, two urban form variables describing each participant-specific neighborhood were also included. These were residential population density, measured as the number of residents per acre of land, and sidewalk density, measured as feet of sidewalks per acre of land.

Statistical Analyses

To examine the relationships hypothesized, multinomial logistic regression was used to estimate the associations between each land use exposure and the two categorical dependent variables, walking for transport and total walking. Linear regression was used to estimate the relationship between each land use predictor and steps. All covariates were included in each model. To account for the correlations among observations from similar TAZs, all models use robust standard errors clustered around a trichotomous neighborhood type variable (urban, suburban or exurban). Models were estimated using Stata 10.1 (College Station, TX). Separate models were estimated for each land use type in the presence and intensity analyses, and a single model was estimated for each buffer area when examining land use diversity. A 95% level of confidence was used to identify statistically significant relationships.

Results

Descriptive Statistics

Descriptive statistics for demographics, neighborhood characteristics and walking variables are shown in Table 1. After accounting for data completeness the final sample size reduced to 251. The sample consisted of more women (65.7%) than men (34.3%). This differed from the gender split in Montgomery County and the Census block groups containing the study area, which both have populations that are just over 50% female and just under 50% male. The mean age of participants was 50 years, slightly older than the county and the block groups which had mean ages of 46 and 44 respectively. Respondents tended to be more highly educated than the area's general population, with 94.1% having completed at least some college. In contrast, 76% of county residents and 80% of block group residents have reached the same level of educational attainment.

Population densities and sidewalk densities both increased as the buffer size around the participant's home decreased. In other words, these densities were greatest closest to homes. A minority of participants lived in neighborhoods classified as "urban" (15.5%), while almost half lived in exurban neighborhoods (47.4%).

The majority of participants (88.1%) did some walking for either transportation or leisure. Approximately half of participants (49.8%) were in the highest category of total walking, with 150 minutes or more of activity per week. Transportation walking was less prevalent. More than a third of participants did none (37.1%), and only 18.7% walked for transportation for 150 minutes per week or more.

Table 1. Descriptive statistics for demographics, neighborhood characteristics and walking variables (N = 251)[1]

	N	%	Mean	SD	Min, max
Sex					
Male	86	34.3%			
Female	165	65.7%			
Age (years)			50.4	14.3	19, 90
Education					
Less than high school diploma	1	0.4%			
Completed high school diploma	12	4.8%			
Vocational training (beyond high school)	2	0.8%			
Some college (less than 4 years)	26	10.4%			
College/university degree	97	38.7%			
Graduate or professional degree	113	45.0%			
Residential population density					
Within ½ mile buffer of home (persons/acre)			79.0	10.6	44.8, 100.3
Within ¼ mile buffer of home (persons/acre)			85.3	24.5	30.3, 150.8
Within 1/8 mile buffer of home (persons/acre)			89.7	35.6	27.3, 220.0
Sidewalk density					
Within ½ mile buffer of home (feet/acre)			120.9	41.3	1.1, 223.3
Within ¼ mile buffer of home (feet/acre)			129.7	53.1	2.2, 293.7
Within 1/8 mile buffer of home (feet/acre)			142.2	75.2	0, 339.8
Neighborhood type					
Urban	39	15.5%			
Suburban	93	37.1%			
Exurban	119	47.4%			
Transportation walking					
None	93	37.1%			
Less than 150 minutes/week	111	44.2%			
150 minutes/week or more	47	18.7%			
Total walking					
None	30	12.0%			
Less than 150 minutes/week	96	38.3%			
150 minutes/week or more	125	49.8%			
Steps			9867.2	3363.0	2116, 21478

[1]Includes those participants who had complete data from the survey (controls), actigraph (steps), and IPAQ portion of the study (walking minutes). Three observations that had values for steps greater than 35 standard deviations away from the mean were considered outliers and were removed.

Table 2 summarizes the descriptive statistics for the measure of land use presence, the network distance from each participant's home to the closest instance of each use. On average, participants lived closest to bus stops (at a mean distance of .23 miles from homes). Parks and physical activity uses were also relatively close to homes (.31 and .38 miles respectively). Participants lived farthest from Metro stops (2.71 miles) and libraries (2.36 miles).

Table 2. Descriptive statistics for measures of land use presence (N = 251)

	Mean distance from home to closest instance (miles)	SD	Min, max
Bank	0.99	0.45	0.03, 2.38
Bus stop	0.23	0.19	0, 1.06
Fast food restaurant	0.88	0.36	0.13, 2.17
Grocery store	0.77	0.49	0.02, 2.33
Library	2.36	1.11	0.34, 4.69
Metro stop	2.71	3.00	0.01, 9.06
Night use	0.86	0.40	0.21, 2.29
Office	0.59	0.41	0, 1.59
Park	0.31	0.24	0, 1.21
Physical activity use	0.38	0.18	0.03, 0.83
Recreation center	0.86	0.49	0.04, 2.16
Restaurant (non-fast food)	0.83	0.45	0.15, 2.31
Retail	0.62	0.39	0.02, 1.85
School	0.67	0.28	0.11, 1.52
Social use	0.47	0.32	0, 1.97
Sports facility	0.70	0.54	0.04, 2.51

Descriptive statistics for the measure of land use intensity, the count of the instances of each land use within ½ and ¼ mile buffers from each participant's home, are contained in Table 3. By far, more bus stops existed within ½ mile of participants' homes (13.4) than other uses. A substantial number of retail stores (9.0) and offices (4.0) were also found within the ½ mile buffer. Fewer instances of each land use existed within the ¼ mile buffer. The highest counts in that area were of bus stops (3.1) and retail stores (1.5). Less than one instance of every other land use was located within the ¼ mile zone.

Table 3. Descriptive statistics for measures of land use intensity within ½ and ¼ mile buffers (N = 251)

	½ mile buffer			¼ mile buffer		
	Mean count	SD	Min, max	Mean count	SD	Min, max
Bus stop	13.39	8.30	0, 33	3.05	2.98	0, 12
Grocery store	0.79	1.22	0, 5	0.18	0.41	0, 2
Office	4.00	8.83	0, 61	0.65	2.05	0, 19
Park	2.20	2.80	0, 18	0.37	0.98	0, 11
Physical activity use	2.27	2.79	0, 18	0.39	0.99	0, 11
Retail	9.02	17.99	0, 86	1.53	5.37	0, 40

Table 4 shows descriptive statistics for the measure of land use diversity, the number of types of land uses within ½ and ¼ mile buffers of each participant's home.

Table 4. Descriptive statistics for measure of land use diversity within ½ and ¼ mile buffers (N = 251)

	½ mile buffer			¼ mile buffer		
	Mean count of land use types	**SD**	**Min, max**	**Mean count of land use types**	**SD**	**Min, max**
Total count of land use types	3.36	1.83	0, 10	1.57	1.36	0, 8

Land Use Presence Results

Odds ratios for the association between the presence of land uses and transport walking are shown in Table 5 and Figures 1 and 2. After adjusting for other covariates, the distance to the closest bus stop, fast food restaurant, Metro station, office, physical activity use, recreational facility, restaurant, social use and sports facility had a significant negative association with transportation walking. Bus stops had a particularly great effect. For a one mile increase in the distance to the closest bus stop, the odds of walking for transportation for 150 minutes per week or more versus not walking for transport decreased by 0.01, all else held constant.

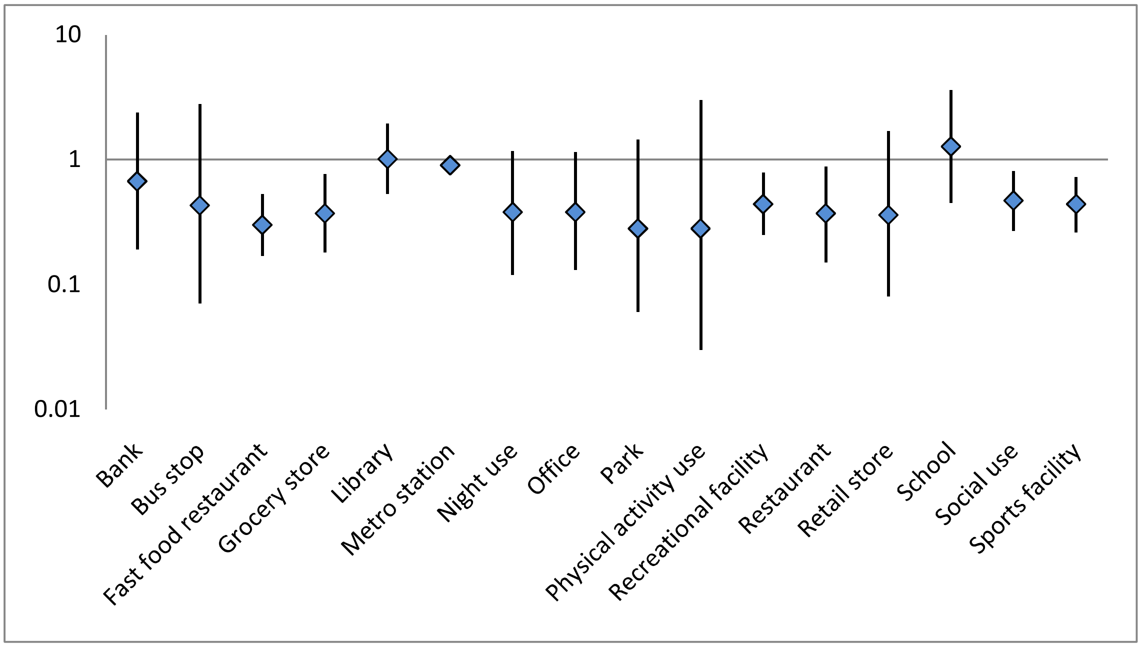
Age, education and population density within ¼ mile of a participant's home were also significant predictors of walking for transport in most models.

Table 5. Adjusted odds ratios[1] and 95% confidence intervals for the association between the distance to each land use and walking for transport (N=251)

	Walking for transport	
	L1 vs. L0 (95% CI)	**L2 vs. L0 (95% CI)**
Bank	0.67 (0.19-2.36)	0.14* (0.02-1.10)
Bus stop	0.43 (0.07-2.77)	0.01** (0-0.36)
Fast food restaurant	0.30*** (0.17-0.53)	0.49 (0.12-1.98)
Grocery store	0.37*** (0.18-0.76)	0.28* (0.07-1.10)
Library	1.01 (0.53-1.93)	0.60 (0.30-1.18)
Metro station	0.90** (0.82-0.99)	0.89 (0.75-1.05)
Night use	0.38* (0.12-1.17)	0.31 (0.05-2.02)
Office	0.38* (0.13-1.14)	0.19** (0.04-0.87)
Park	0.28 (0.06-1.44)	0.13 (0.01-2.83)
Physical activity use	0.28 (0.03-3.00)	0.11*** (0.04-0.31)
Recreational facility	0.44*** (0.25-0.79)	0.27 (0.05-1.55)
Restaurant	0.37** (0.15-0.88)	0.28 (0.05-1.56)
Retail store	0.36 (0.08-1.68)	0.25* (0.05-1.28)
School	1.27 (0.45-3.58)	0.97 (0.28-3.33)
Social use	0.47*** (0.27-0.81)	0.18*** (0.07-0.46)
Sports facility	0.44*** (0.26-0.72)	0.44 (0.12-1.64)

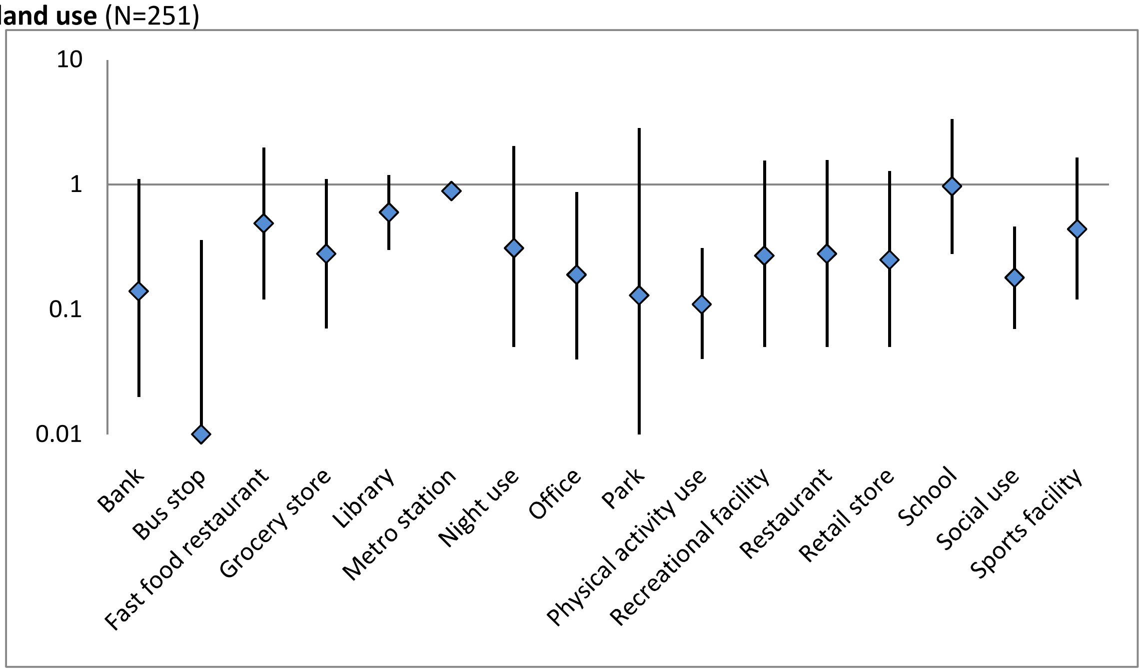
[1]Adjusted for demographics, urban form within ¼ mile of participant's home, and neighborhood type.
***, **, and * indicate p<0.01, p<0.05, and p<0.1, respectively.

Figure 1. Adjusted odds ratio[1] and 95% confidence interval of walking for transport for <150 minutes/week versus not walking for transport for each additional mile to closest instance of land use (N=251)



[1]Adjusted for demographics, urban form within ¼ mile of participant's home, and neighborhood type.

Figure 2. Adjusted odds ratio[1] and 95% confidence interval of walking for transport for ≥ 150 minutes/week versus not walking for transport for each additional mile to closest instance of land use (N=251)



[1]Adjusted for demographics, urban form within ¼ mile of participant's home, and neighborhood type.

Overall, the presence of non-residential destinations in participants' neighborhoods was associated with increased utilitarian walking. Closer proximity to bus stops, fast food restaurants, grocery stores, Metro stations, offices, physical activity uses, recreational facilities, restaurants, social uses and sports facilities was related to greater walking for transportation. An analysis of the effects of land use presence on all walking and steps is included in the Appendix.

Land Use Intensity Results

As was noted above, this section of the analysis was limited to the land uses which had adequate sample sizes. Results are shown in Table 6 and Figures 3 and 4. The number of bus stops, grocery stores, offices and retail stores within a ½ mile buffer were significant in predicting walking for transport after adjusting for the covariates. Grocery stores had the largest effect. For every additional grocery store within the buffer, the odds of walking for transport for less than 150 minutes per week versus not walking for transport are expected to increase 1.68 times, all else held constant. The significant land uses are identical for the ¼ mile buffer, but their effects on transportation walking are stronger. For instance, for every additional grocery store within this smaller buffer, the odds of walking for transport for less than 150 minutes per week versus not walking for transport are expected to increase 5.51 times, all else equal.

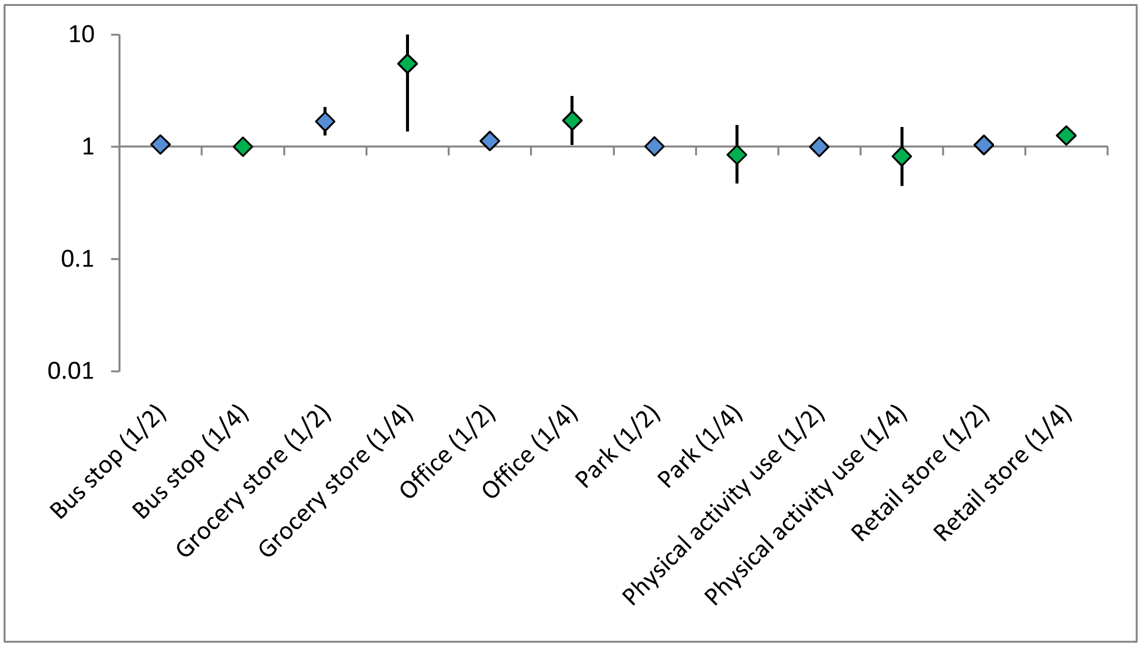
Age, education and population density within ¼ mile of participants' homes also had a significant impact on walking for transportation in almost all models.

Table 6. Adjusted odds ratios[1] and 95% confidence intervals for the association between the intensity of each land use within ½ mile and ¼ mile of homes and walking for transport (N=251)

	Walking for transport			
	½ mi buffer		**¼ mi buffer**	
	L1 vs. L0 (95% CI)	**L2 vs. L0 (95% CI)**	**L1 vs. L0 (95% CI)**	**L2 vs. L0 (95% CI)**
Bus stop	1.05*** (1.02-1.08)	1.06*** (1.02-1.10)	1.00 (0.89-1.13)	1.15***+ (1.13-1.17)
Grocery store	1.68*** (1.26-2.24)	1.67 (0.88-3.19)	5.51** (1.38-21.95)	5.01* (0.85-29.55)
Office	1.13***+ (1.10-1.16)	1.13***+ (1.10-1.17)	1.71** (1.04-2.81)	1.55* (0.99-2.44)
Park	1.01 (0.89-1.14)	1.09* (0.99-1.21)	0.85 (0.47-1.55)	0.98 (0.84-1.15)
Physical activity use	1.00 (0.88-1.13)	1.10* (0.99-1.22)	0.82 (0.45-1.50)	0.98 (0.82-1.18)
Retail store	1.04***+ (1.04-1.05)	1.05*** (1.04-1.07)	1.26*** (1.08-1.48)	1.22** (1.02-1.47)

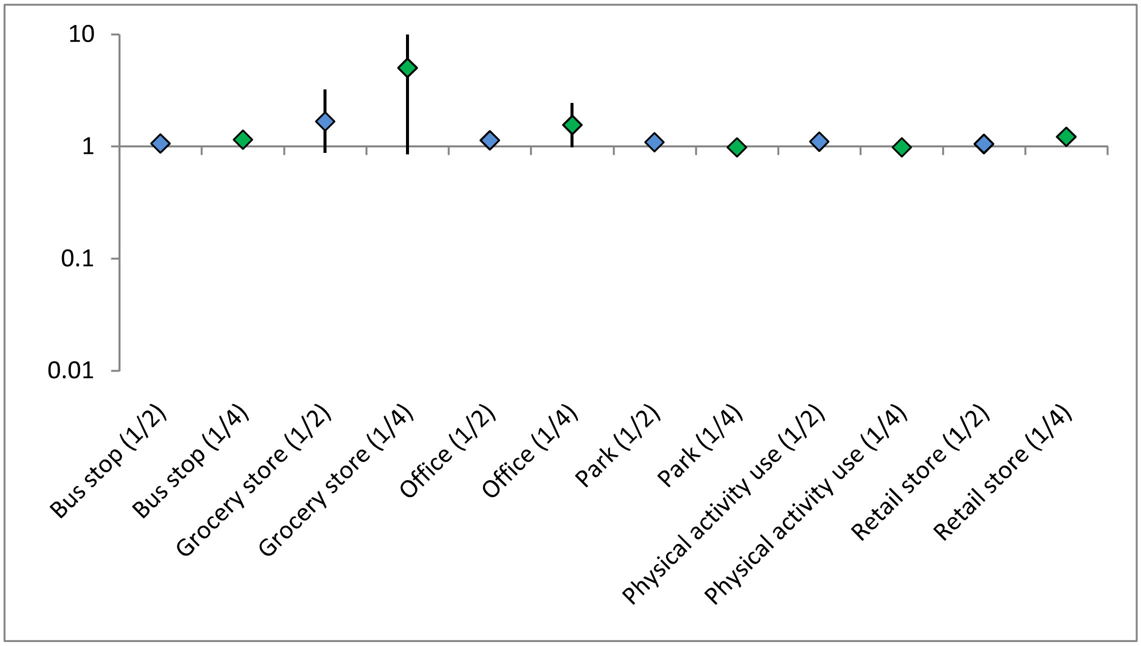
[1]Adjusted for demographics, urban form within ¼ mile of participant's home, and neighborhood type.
***, **, and * indicate p<0.01, p<0.05, and p<0.1, respectively.
+Standard errors in models with robust clustering and models without it vary considerably, indicating that robust clustering is suspect in these models and results must be interpreted with caution.

Figure 3. Adjusted odds ratio[1] and 95% confidence interval of walking for transport for <150 minutes/week versus not walking for transport for each additional land use instance within ½ and ¼ mile buffers (N=251)



[1]Adjusted for demographics, urban form within ¼ mile of participant's home, and neighborhood type.

Figure 4. Adjusted odds ratio[1] and 95% confidence interval of walking for transport for ≥ 150 minutes/week versus not walking for transport for each additional land use instance within ½ and ¼ mile buffers (N=251)



[1]Adjusted for demographics, urban form within ¼ mile of participant's home, and neighborhood type.

Land Use Diversity Results

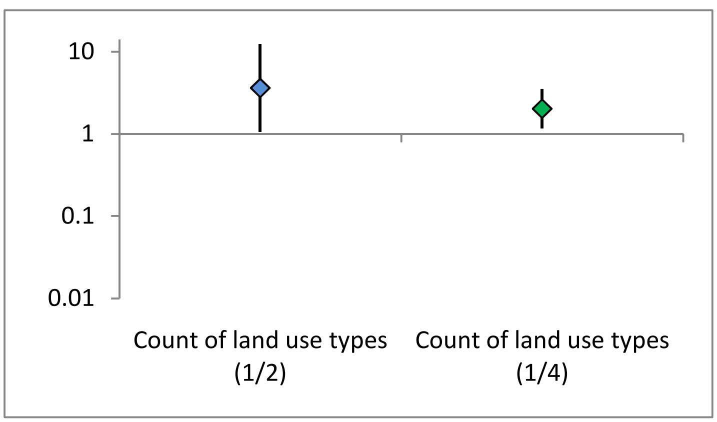
Table 7 shows that the numbers of types of land uses within ½ and ¼ mile buffers were significant in predicting walking for transport after accounting for the controls. Adjusted odds ratios are illustrated in Figures 5 and 6. For each additional destination type within ½ mile of a participant's home, the odds of walking for transport for less than 150 minutes per week versus not walking for transport increased by 3.61 times. For each additional destination type within ¼ mile, the odds of walking for transport for less than 150 minutes per week versus not walking for transport increased by about two times, and the odds of walking for transport for 150 minutes per week or more versus not walking increased by 2.35 times, all else held constant. The squares and cubes of the counts were also included in models (not shown) to test the linearity of the dose-response relationship, but they were not significant.

Table 7. Adjusted odds ratios[1] and 95% confidence intervals for the association between the diversity of land uses within ½ mile and ¼ mile of homes and walking for transport (N=251)

	Walking for transport			
	½ mi buffer		**¼ mi buffer**	
	L1 vs. L0 (95% CI)	**L2 vs. L0 (95% CI)**	**L1 vs. L0 (95% CI)**	**L2 vs. L0 (95% CI)**
Count of land use types	3.61** (1.05-12.45)	2.40 (0.22-25.89)	2.02** (1.16-3.49)	2.35*** (1.41-3.91)

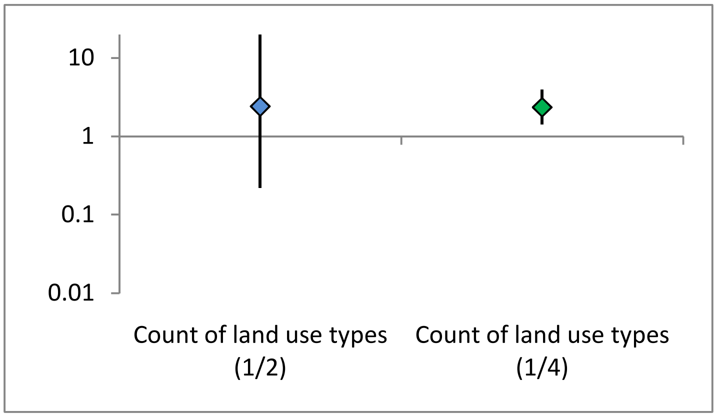
[1]Adjusted for demographics, urban form within ¼ mile of participant's home, and neighborhood type.
***, **, and * indicate p<0.01, p<0.05, and p<0.1, respectively.

Figure 5. Adjusted odds ratio[1] and 95% confidence interval of walking for transport for <150 minutes/week versus not walking for transport for each additional land use type within ½ and ¼ mile buffers (N=251)



[1]Adjusted for demographics, urban form within ¼ mile of participant's home, and neighborhood type.

Figure 6. Adjusted odds ratio[1] and 95% confidence interval of walking for transport for ≥ 150 minutes/week versus not walking for transport for each additional land use type within ½ and ¼ mile buffers (N=251)



[1]Adjusted for demographics, urban form within ¼ mile of participant's home, and neighborhood type.

Discussion

Overall, this study strengthens the evidence of an association between mixed-use development and transportation walking. The presence and intensity of certain destinations, along with land use diversity, are related to walking for transport, even when accounting for demographic and neighborhood characteristics. This represents a great opportunity for urban planners, indicating that design and policy interventions can promote alternatives to the single-occupancy vehicle and encourage physical activity.

Consistent with the first hypothesis, the presence of many functional destinations was found to be correlated with transportation walking. This suggests that the availability of destinations that people visit frequently to meet their daily needs – such as grocery stores, offices, restaurants and transit stations – can promote destination-related walking. However, as described above, past research associating these land uses with walking has produced mixed results. While Cerin et al (2007) found a correlation between grocery stores and transport walking, Forsyth et al (2008) did not. The same was true for offices. In addition, McCormack et al (2008) observed a relationship between utilitarian walking and access to both bus and rail stops, but Cerin et al (2007) did not find an association in either case. These differences may be explained by methodological discrepancies or variations in the study locations and participating populations. Whatever the cause, researchers must continue to develop this body of literature, focusing on these "everyday" destinations, so clearer patterns can surface.

In responding to the first hypothesis, some surprising results also appeared. Physical activity uses and sports facilities near a person's home were correlated with higher levels of transportation walking, a finding which is inconsistent with current research. Cerin et al (2007) did not find an association between proximity to the beach or river and walking for transport, Forsyth et al (2008) failed to find a relationship between the distance to the nearest park or gym and transport walking, and McCormack et al (2008) did not observe a correlation between access to a park, river or beach and utilitarian walking (though they note that few people in their sample lived near a beach or river). It is possible that the more inclusive nature of the physical activity and sports facility land use classifications utilized in this paper allowed them a greater likelihood of achieving statistical significance than narrower categories such as park or gym. Also, unlike in McCormack's study, participants lived relatively close to physical activity uses.

On the other hand, this result may suggest that these land uses are treated as destinations by pedestrians living nearby, who may make functional walking trips to exercise at these locations. They may also walk to these places in order to drop off or pick up their children at sporting events or play groups. Alternatively, this finding may be evidence of an indirect effect of recreational areas and open space on walking. It is possible that the presence of these amenities in a neighborhood increases the overall appeal of walking (supported by the fact that these land uses also predict total walking, as shown in the Appendix), thereby increasing all types of walking, including utilitarian walking.

Also interesting is the lack of a significant relationship between transport walking and two uses hypothesized to be associated, schools and retail stores. In the case of schools, this result is less surprising. Researchers are split on the effects of access to schools on destination walking. McCormack et al (2008) found a relationship, while Cerin et al (2007) and Forsyth et al (2008) did not. Schools are likely only significant predictors of walking for families with children, which rules out many of this study's participants, whose mean age was 50 years.

In contrast, the finding of no relationship between retail land uses and utilitarian walking is unexpected, particularly given the consensus emerging from existing research. McCormack et al (2008) observed that access to shopping malls was associated with participation in regular transport-related walking, while Cao et al (2006) and Handy & Clifton (2001) found that the distance to retail shopping was highly significant in predicting walking to shopping. Similarly, Lund (2003) saw that utilitarian walking trips were significantly higher in neighborhoods with access to local shops or local shops and parks than in neighborhoods with no access to these destinations. In addition, Cerin et al (2007) noted a positive correlation between perceived proximity of commercial destinations and weekly minutes of walking for transport. The cause of this disagreement might lie in the ambiguity of the retail land use classification discussed previously. "Retail" can incorporate destinations that are pedestrian-friendly as well as others that are not. The present study may have defined retail differently than prior work. In any case, retail's lack of significance vis-à-vis grocery stores and restaurants signals that it is too broad a land use category to produce useful findings. This result underscores the importance of distinguishing different types of retail when studying its effects on walking.

It is informative to examine the results of the transport walking analysis within the context of the analysis of total walking (see Appendix). Some land uses, including Metro stations, physical activity uses, recreational facilities, social uses and sports facilities, were related to transportation walking and all walking. The presence of these land uses may exert a strong enough influence on either transportation walking or leisure walking to affect all walking. Because these uses seem to encourage all types of walking, they may be good bets for planners aiming to promote walking as a mode choice as well as to increase physical activity.

In contrast, bus stops, fast food restaurants, grocery stores, offices and restaurants significantly predict walking for errands but not all walking. There are several possible explanations. Since fewer participants walked for transport than walked overall, it may have taken a smaller change in transportation walking behavior to achieve statistical significance for an independent variable. Alternatively, this finding could support the idea of physical activity budgets (Rodríguez et al, 2006, Krizek et al 2004). This theory suggests that as people walk more for transport, they walk less for recreation, maintaining a consistent level of total walking. This result also challenges the distinction between "transport walking" and "recreational walking" in destination-rich neighborhoods. In a mixed-use neighborhood, a resident may set out for a stroll, but decide to pick up a loaf of bread as he or she passes the supermarket along the way. The trip is now recorded as a transport walking trip rather than a leisure walking trip, when in reality it is impossible to separate the two behaviors. Similarly, a resident of a mixed-use neighborhood may walk for errands, rather than take another mode, in order to get exercise. Again, these trips would be considered transport walking when they are actually recreational walking as well.

Also illustrated in the Appendix, there is a discrepancy between the variables predicting total walking and those predicting steps. As both variables measured all walking, one would expect them to be correlated with similar land use exposures. However, steps was not predicted by any land use variable, suggesting an inconsistency between the subjective and objective measures. One reason for this could be the fact that unlike the subjective measures, steps includes walking done indoors at home, work or school. Moreover, prior research has noted the experimental nature of actigraphs and the continued uncertainty about how to interpret the data they produce (Forsyth et al, 2008). Future researchers should look more closely at the implications of objectively versus subjectively measured physical activity data.

As predicted by the second hypothesis, the intensity of many of the land uses related to utilitarian walking is itself positively related to utilitarian walking. More bus stops, grocery stores and offices – frequently visited, everyday uses – encourage more walking for transportation. The exception was physical activity uses, whose presence was correlated with transport walking but whose intensity was not. This suggests that though having parks and open space in a neighborhood may promote walking, a limited amount of this land use should be permitted. On the other hand, the presence of retail stores was not correlated with transport walking, but their intensity was. Though access to a retail store may not be enough to significantly influence utilitarian walking, access to several stores may be. However, the threshold number of stores needed to induce walking remains undefined.

The literature does not provide much clarification of the implications of land use intensity. Only one study reviewed examined the influence of land use intensity on utilitarian walking. Like the present study, Forsyth et al (2008) found transit stop intensity to be an important predictor of transport walking, but they did not find the percent of total parcel area in office uses or commercial uses, or the density of retail or food store employees, to be significant. This may be due to differences in how intensity was operationalized, as Forsyth et al (2008) used measures other than a straightforward count. In addition, Forsyth et al (2008) observed a similar interaction between the presence and intensity of transit stops as this study noted between the presence and intensity of retail, with the latter showing significance but not the former. This confirms the idea that some uses may only attract walkers when they appear with greater intensity.

As described in the literature review, other intensity studies look only at one or two land uses and total or recreation walking outcomes. Furthermore, most consider only the intensity of the specified land uses and not their presence. As a result, the interactive effect observed here is not explored. Future research on the built environment and walking should incorporate more comprehensive investigations of intensity.

Finally, the third hypothesis was confirmed with the finding of a dose-response relationship between the number of types of land uses and transport walking. This is consistent with the findings of existing research. McCormack et al (2008) and Hoehner et al (2005) both observed associations between land use diversity and destination walking. The influence of diversity on walking makes a strong case for mixed-use development in communities aiming to promote non-single occupancy vehicle travel. However, the Appendix illustrates that diversity of uses is not significantly related to total walking. This suggests that pursuing diversity may not be as effective in communities focused on encouraging physical activity.

Limitations

There are several limitations to this study. First, a major hindrance to interpreting the paper's results is the correlation between many of the land use exposures, indicated by variance inflation factors (VIFs) greater than 5. Land uses with high VIFs include banks, fast food restaurants, grocery stores, libraries, Metro stops, night uses, offices, recreation centers, non-fast food restaurants, retail stores, social uses and sports facilities. It is impossible to separate the effects of these uses due to this correlation. A crucial next step in transportation-land use research is to address this issue. Scholars must uncover methods for ranking the relative influences of the land uses or understanding their individualized effects.

Another limitation was the small sample size. This restricted the ability to consider the land use exposures as categorical or dummy variables, which would have helped to uncover nonlinear relationships between land use and walking. As a result, nonlinearities may exist, but in most cases could not be identified. Small sample sizes also kept the intensity analysis to only a few land uses. Additional limitations include the reliance on self-reported data and the use of a non-representative sample of Montgomery County adults.

Conclusions and Recommendations

This study supports mixed-use development as a strategy for encouraging sustainable transportation choices and active living, but advises careful consideration of the land uses included. While "functional" uses such as bus stops, grocery stores and offices seem to be associated with increased walking for transportation, their impact on total walking is not fully understood. Further research is needed on the interaction between transport walking and all walking, as well as on physical activity budgets and walking behavior in destination-rich neighborhoods.

This study points to four major recommendations for planners and policymakers interested in implementing mixed-use development as a means of increasing walking.

1. Clarify the goals of mixed-use development. Research suggests that different land uses influence different types of walking. A community aiming to discourage auto dependence may need to focus on different land uses than one seeking to promote

physical activity. Effectively applying the current research necessitates a clear understanding of the desired end result.

2. Planners should consider siting mixed-use developments with frequently visited, “everyday” destinations such as grocery stores in areas well served by public transit. Likewise, developing the public transport network in destination-rich neighborhoods could be an effective strategy to promote walking.

3. In the shorter term, planners should take action to encourage people living near transit stops, grocery stores, offices, recreational and social destinations to walk more. Approaches could include public awareness campaigns, safety and infrastructure upgrades to nearby streets and traffic calming.

4. Land use diversity is important. Mixing a wide variety of destination types with residential uses can increase accessibility and enhance visual interest for pedestrians. Mixed-use zoning and neighborhood commercial centers should be considered.

Acknowledgements

Preparation of this paper was supported by a grant from the Robert Wood Johnson Foundation Active Living Research program and by an educational grant from the Southeastern Transportation Center.

I would also like to extend my deepest thanks to my advisor, Daniel Rodríguez, for the invaluable feedback he provided; and to my husband, Andrew McConville, for his support throughout the research process.

References

Ball, K., Bauman, A., Leslie, E., & Owen, N. (2001). Perceived environmental aesthetics and convenience, and company are associated with walking for exercise among Australian adults. *Preventative Medicine, 33*, 434-440.

Badland, H., Schofield, G., & Garrett, N. (2008). Travel behavior and objectively measured urban design variables: Associations for adults traveling to work. *Health & Place, 14*(1), 85-95.

Boarnet, M. G., & Crane, R. (2001). The influence of land use on travel behavior: Specification and estimation strategies. *Transportation Research Part A: Policy and Practice, 35*(9), 823-845.

Boer, R., Zheng, Y., Overton, A., Ridgeway, G., & Cohen, D. (2007). Neighborhood design and walking trips in ten U.S. metropolitan areas. *American Journal of Preventative Medicine, 32*(4), 298-304.

Cao, X., Handy, S., & Mokhtarian, P. (2006). The influences of the built environment and residential self-selection on pedestrian behavior: Evidence from Austin, TX. *Transportation (Dordrecht), 33*(1), 1-20.

Cerin, E., Leslie, E., Toit, L., Owen, N., & Frank, L. (2007). Destinations that matter: Associations with walking for transport. *Health & Place, 13*(3), 713-724.

Cervero, R. (1996). Mixed land-uses and commuting: Evidence from the American housing survey. *Transportation Research Part A: Policy and Practice, 30*(5), 361-377.

Cervero, R., & Duncan, M. (2003). Walking, bicycling, and urban landscapes: Evidence from the San Francisco bay area. *American Journal of Public Health (1971), 93*(9), 1478-1483.

Cervero, R., & Kockelman, K. (1997). Travel demand and the 3Ds: Density, diversity, and design. *Transportation Research Part D: Transport and Environment, 2*(3), 199-219.

Cervero, R. & Radisch, C. (1996). Travel choices in pedestrian versus automobile oriented neighborhoods. *Transportation Policy 3*, 127–141.

Craig, C., Brownson, R., Cragg, S, & Dunn, A. (2002). Exploring the effect of the environment on physical activity: A study examining walking to work. *American Journal of Preventative Medicine, 23*, 36-43.

Craig, C., Marshall, A., Sjostrom, M., Bauman, A., Booth, M., Ainsworth., B., Pratt, M., Ekelund, U., Sallis, J., & Oja, P. (2003). International Physical Activity Questionnaire: 12-country reliability and validity. *Medicine and Science in Sports and Exercise, 35*(8), 1381-1395.

Crane, R. (1996). Cars and drivers in the new suburbs – Linking access to travel in neotraditional planning. *Journal of the American Planning Association, 62*(1), 51-65.

Crane, R., & Crepeau, R. (1998). Does neighborhood design influence travel? A behavioral analysis of travel diary and GIS data. *Transportation Research Part D: Transport and Environment, 3*(4), 225-238.

Forsyth, A., Hearst, M., Oakes, J., & Schmitz, K. (2008). Design and destinations: Factors influencing walking and total physical activity. *Urban Studies, 45*(9), 1973-1996.

Frank, L. (2004). Economic determinants of urban form: resulting trade-offs between active and sedentary forms of travel. *American Journal of Preventive Medicine, 27*, 146–153.

Frank, L., Bradley, M., Kavage, S., Chapman, J., & Lawton, T. K. (2008). Urban form, travel time, and cost relationships with tour complexity and mode choice. *Transportation (Dordrecht), 35*(1), 37-54.

Frank, L., Saelens, B., Powell, K., & Chapman, J. (2007). Stepping towards causation: Do built environments or neighborhood and travel preferences explain physical activity, driving, and obesity? *Social Science & Medicine, 65*(9), 1898-1914.

Frank, L., Schmid, T., Sallis, J., Chapman, J., & Saelens, B. (2005). Linking objectively measured physical activity with objectively measured urban form: Findings from SMARTRAQ. *American Journal of Preventive Medicine, 28*(2, Supplement 2), 117-125.

Giles-Corti, B., Broomhall, M., Knuiman, M., Collins, C., Douglas, K., Ng, K., Lange, A. & Donovan, R. (2005). Increasing walking: How important is distance to, attractiveness, and size of public open space? *American Journal of Preventive Medicine, 28*(2, Supplement 2), 169-176.

Giles-Corti, B., & Donovan, R. (2002). Socioeconomic status differences in recreational physical activity levels and real and perceived access to a supportive physical environment. *Preventive Medicine, 35*(6), 601-611.

Giles-Corti, B., & Donovan, R. (2003). Relative influences of individual, social environmental, and physical environmental correlates of walking. *American Journal of Public Health (1971), 93*(9), 1583-1589.

Guo, J., Bhat, C., & Copperman, R. (2007). Effect of the built environment on motorized and nonmotorized trip making: Substitutive, complementary, or synergistic? *Transportation Research Record, 2010*(1), 1-13.

Hagstromer, M., Oja, P., & Sjostrom, M. (2006). The International Physical Activity Questionnaire (IPAQ): A study of concurrent and construct validity. *Public Health Nutrition, 9*(6), 755-762.

Handy, S. (1996). Methodologies for exploring the link between urban form and travel behavior. *Transportation Research Part D: Transport and Environment, 1*(2), 151-165.

Handy, S., & Clifton, K. (2001). Local shopping as a strategy for reducing automobile travel. *Transportation (Dordrecht), 28*(4), 317-346.

Hoehner, C., Brennan Ramirez, L., Elliott, M., Handy, S., & Brownson, R. (2005). Perceived and objective environmental measures and physical activity among urban adults. *American Journal of Preventive Medicine, 28*, 105-116.

Joh, K., Boarnet, M., Nguyen, M., Fulton, W., Siembab, W., & Weaver, S. (2008). Accessibility, travel behavior, and New Urbanism: Case study of mixed-use centers and auto-oriented corridors in the South Bay Region of Los Angeles, California. *Transportation Research Record, 2082*, 81-89.

Kitamura, R. (1997). A micro-analysis of land use and travel in five neighborhoods in the San Francisco Bay area. *Transportation (Dordrecht), 24*(2), 125-158.

Krizek, K., Birnbaum, A., & Levinson, D. (2004). A schematic for focusing on youth in investigations of community design and physical activity. *American Journal of Health Promotion, 19*(1), 33–38.

Long, J.S. & Freese, J. (2001). *Regression models for categorical dependent variables using Stata.* College Station, TX: Stata Press.

Lovasi, G., Moudon, A., Pearson, A., Hurvitz, P., Larson, E., Siscovick, D., Berke, E., Lumley, T., & Psaty, B. (2008). Using built environment characteristics to predict walking for exercise. *International Journal of Health Geographics, 7*(10), 10.

Lund, H. (2003). Testing the claims of new urbanism - local access, pedestrian travel, and neighboring behaviors. *Journal of the American Planning Association, 69*(4), 414-429.

McCormack, G., Giles-Corti, B., & Bulsara, M. (2008). The relationship between destination proximity, destination mix and physical activity behaviors. *Preventive Medicine, 46*(1), 33-40.

Metcalf, B. S., Curnow, J. S. Evans, C., Voss, L. D., & Wilkin, T. J. (2002). Technical reliability of the CSA activity monitor: The EarlyBird study. *Medicine and Science in Sports and Exercise, 34*, 1533-1537.

Owen, N., Cerin, E., Leslie, E., Dutoit, L., Coffee, N., Frank, L., Bauman, A., Hugo, G., Saelens, B. & Sallis, J. (2007). Neighborhood walkability and the walking behavior of Australian adults. *American Journal of Preventive Medicine, 33*(5), 387-395.

Pikora, T.J., Bull, F.C., Jamrozik, K., Knuiman, M., Giles-Corti, B., & Donovan, R.J. (2002). Developing a reliable audit instrument to measure the physical environment for physical activity. *American Journal of Preventive Medicine, 23*, 187–194.

Rajamani, J., Bhat, C., Handy, S., Knaap, G., & Song, Y. (2003). Assessing impact of urban form measures on nonwork trip mode choice after controlling for demographic and level-of-service effects. *Transportation Research Record, 1831*, 158-165.

Rodríguez, D., Khattak, A., & 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), 43–54.

Saelens, B. (2003). Environmental correlates of walking and cycling: Findings from the transportation, urban design, and planning literatures. *Annals of Behavioral Medicine, 25*(2), 80-91.

Saelens, B.E., Sallis, J.F., Black, J.B., & Chen, D. (2003). Neighborhood-based differences in physical activity: an environment scale evaluation. *American Journal of Public Health 93*, 1552–1558.

Sallis, J.F., Hovell, M.F., Hofstetter, C.R., Elder, J., Hackley., M., Caspersen, C., & Powell, K. (1990). Distance between homes and exercise facilities related to frequency of exercise among San Diego residents. *Public Health Reports, 105*(2), 179–185.

Welk, G. J., Schaben, J. A., & Morrow Jr, J. R. (2004). Reliability of accelerometry-based activity monitors: A generalizability study. *Medicine and Science in Sports and Exercise, 36*, 1637-1645.

Wells, N. M., & Yang, Y. (2008). Neighborhood design and walking: A quasi-experimental longitudinal study. *American Journal of Preventive Medicine, 34*(4), 313-319.

Wen, M., Kandula, N., & Lauderdale, D. (2007). Walking for transportation or leisure: What difference does the neighborhood make? *Journal of General Internal Medicine: JGIM, 22*(12), 1674-1680.

Appendix: Analyses of Total Walking and Steps

Land Use Presence Results

Total Walking

The relationship between land use presence and total walking is shown in Table 1. After adjusting for demographics, urban form and neighborhood type, the distance to the closest Metro station, park, physical activity use, recreational facility, social use and sports facility had a significant negative impact on all walking.

The distance to the closest school, on the other hand, was positively associated with total walking, and had a relatively strong effect. Given a one mile increase in distance to the nearest school, the odds of walking for less than 150 minutes per week versus not walking increased by 2.5 times, all else held constant.

Age and education were often significant in predicting total walking, but no urban form variables had significance.

As discussed in the methodology section, neighborhood type was included as a clustered variable to prevent it from improperly removing significance from the other predictors. This approach has some risks. If models include more regressors than the number of clusters, Stata runs out of degrees of freedom to assess overall significance. These models produce singular cluster-corrected covariance matrices of coefficient estimates. This can mean that some combinations of coefficient estimates would have zero estimated variance, leading to an effect similar to collinearity among regressors (Long & Freese, 2001). To test for this problematic effect, the standard errors from models with clustering and models without clustering were compared. Where they differed greatly, results should be interpreted with caution. This was the case for Metro stations (L1 vs. L0), schools (L1 vs. L0) and sports facilities (L1 vs. L0), as indicated in Table 1.

Steps

Before adjusting for demographics, urban form and neighborhood type, the distance to the closest Metro station was a significant predictor of steps. However, after incorporating the controls, no land uses had a significant impact on steps (see Table 1). Age significantly predicted steps in every model.

Table 1. Adjusted odds ratios[1], coefficients[2] and 95% confidence intervals for the association between the distance to each land use and all walking and steps (N=251)

	All walking[1]		Steps[2]
	L1 vs. L0 (95% CI)	L2 vs. L0 (95% CI)	Coef. (95% CI)
Bank	1.02	0.49	-631.74
	(0.29-3.65)	(0.06-3.72)	(-5993.74-4730.25)
Bus stop	3.34	0.98	594.62
	(0.33-33.91)	(0.08-11.76)	(-3571.30-4760.54)
Fast food restaurant	1.24	1.16	612.29
	(0.44-3.54)	(0.39-3.45)	(-770.75-1995.32)
Grocery store	0.95	0.92	143.75
	(0.40-2.25)	(0.27-3.11)	(-2453.97-2741.47)
Library	0.90	0.70	-469.62
	(0.70-1.15)	(0.36-1.34)	(-2085.66-1146.42)
Metro station	.84***+	0.94	111.48
	(0.80-0.89)	(0.85-1.04)	(-136.43-359.40)
Night use	0.67	0.73	156.69
	(0.33-1.35)	(0.19-2.82)	(-2977.63-3291.01)
Office	2.00	1.19	272.51
	(0.69-5.79(	(0.35-4.07)	(-2418.85-2963.86)
Park	0.21***	0.22**	-920.95
	(0.08-0.57)	(0.06-0.87)	(-3021.42-1179.52)
Physical activity use	0.54	0.17**	-1741.01
	(0.06-4.70)	(0.04-0.83)	(-4017.25-523.23)
Recreational facility	0.49***	0.59	115.29
	(0.33-0.73)	(0.23-1.51)	(-1734.64-1965.23)
Restaurant	0.84	0.70	5.36
	(0.39-1.79)	(0.20-2.47)	(-2189.50-2200.22)
Retail store	2.10	1.75	447.53
	(0.24-18.00)	(0.20-15.26)	(-3311.13-4206.19)
School	2.50***+	1.39*	25.50
	(2.30-2.73)	(0.94-2.05)	(-4070.51-4121.50)
Social use	0.52***	0.70	816.37
	(0.37-0.74)	(0.31-1.56)	(-1946.36-3579.10)
Sports facility	0.31***+	0.46*	267.04
	(0.22-0.43)	(0.21-1.04)	(-650.23-1184.31)

[1]Adjusted for demographics, urban form within ¼ mile of participant's home, and neighborhood type.
***, **, and * indicate p<0.01, p<0.05, and p<0.1, respectively.
[+]Standard errors in models with robust clustering and models without it vary considerably, indicating that robust clustering is suspect in these models and results must be interpreted with caution.

Land Use Intensity Results

Total Walking

After accounting for covariates, the number of parks and physical activity uses near homes were significant predictors of total walking (see Table 2). For every additional park within a ½ mile buffer, the odds of walking for less than 150 minutes per week versus not walking would increase by a factor of .89; for every additional physical activity use in this same area, the odds would be .88 times more likely.

As with the transport walking outcome, results for ¼ mile buffers are similar. However, unlike with transport walking, the effects are weaker in the smaller buffer area. For example, with each additional physical activity use within ¼ mile, the odds of walking for less than 150 minutes per week versus not walking is expected to change by .75, all else being equal.

Steps

After adjusting for the controls, the number of parks and physical activity uses within a ½ mile buffer of a participant's home were significantly associated with steps (see Table 2). For every additional park within the buffer, a person is likely to take 71.5 additional steps per week, and for every additional physical activity use, a person will take 73.6 additional steps per week. However, none of the land use counts within the ¼ mile buffer had a significant influence over steps.

Table 2. Adjusted odds ratios[1], coefficients[2] and 95% confidence intervals for the association between the intensity of each land use within ½ mile and ¼ mile of homes and all walking and steps (N=251)

	½ mile buffer			**¼ mile buffer**		
	All walking[1]		**Steps[2]**	**All walking[1]**		**Steps[2]**
	L1 vs. L0 (95% CI)	**L2 vs. L0 (95% CI)**	**Coef. (95% CI)**	**L1 vs. L0 (95% CI)**	**L2 vs. L0 (95% CI)**	**Coef. (95% CI)**
Bus stop	0.99 (0.95-1.03)	0.99 (0.95-1.03)	-39.7 (-103.34-23.92)	0.92 (0.76-1.13)	0.97 (0.86-1.09)	-64.1 (-335.98-207.816)
Grocery store	1.33 (0.86-2.05)	1.30 (0.76-2.24)	-44.8 (-873.13-783.57)	4.14 (0.36-48.03)	2.75 (0.28-26.85)	-42.6 (-779.46-694.35)
Office	1.08* (0.99-1.18)	1.07* (0.99-1.16)	-10.5 (-89.03-68.07)	1.33 (0.63-2.79)	1.16 (0.63-2.14)	-140.9 (-411.13-129.26)
Park	0.89*** (0.81-0.97)	0.98 (0.89-1.08)	71.5**[+] (19.74-123.29)	0.77* (0.59-1.01)	0.81*** (0.70-0.95)	127.2 (-693.65-948.04)
Physical activity use	0.88*** (0.80-0.97)	0.98 (0.89-1.08)	73.6**[+] (25.58-121.59)	0.75** (0.59-0.95)	0.81*** (0.70-0.94)	120.0 (-673.14-913.13)
Retail store	1.02 (0.99-1.06)	1.03 (0.99-1.06)	8.74 (-49.65-67.13)	1.47 (0.85-2.55)	1.40 (0.83-2.37)	-62.3 (-172.54-47.92)

[1]Adjusted for demographics, urban form within ¼ mile of participant's home, and neighborhood type.
***, **, and * indicate p<0.01, p<0.05, and p<0.1, respectively.
[+]Standard errors in models with robust clustering and models without it vary considerably, indicating that robust clustering is suspect in these models and results must be interpreted with caution.

Land Use Diversity Results

Total Walking

As illustrated in Table 3, the number of types of land uses within ½ and ¼ mile buffers did not have a significant impact on all walking after adjusting for the covariates.

Steps

The number of types of land uses within ½ and ¼ mile buffers were not significant in predicting steps after accounting for the controls (see Table 3).

Table 3. Adjusted odds ratios[1], coefficients[2] and 95% confidence intervals for the association between the diversity of land uses within ½ mile and ¼ mile of homes and all walking and steps (N=251)

	½ mile buffer			**¼ mile buffer**		
	All walking[1]		**Steps[2]**	**All walking[1]**		**Steps[2]**
	L1 vs. L0 (95% CI)	**L2 vs. L0 (95% CI)**	**Coef. (95% CI)**	**L1 vs. L0 (95% CI)**	**L2 vs. L0 (95% CI)**	**Coef. (95% CI)**
Count of land use types	0.80 (0.04-15.98)	0.88 (0.09-9.13)	-2165.76 (-5922.26-1590.74)	0.33 (0.02-5.06)	0.24 (0.02-3.19)	-421.27 (-2364.77-1522.22)

[1]Adjusted for demographics, urban form within ¼ mile of participant's home, and neighborhood type.
***, **, and * indicate p<0.01, p<0.05, and p<0.1, respectively.