
Linking Objectively Measured Physical Activity with Objectively Measured Urban Form

Findings from SMARTRAQ

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Background: To date, nearly all research on physical activity and the built environment is based on self-reported physical activity and perceived assessment of the built environment.

Objective: To assess how objectively measured levels of physical activity are related with objectively measured aspects of the physical environment around each participant's home while controlling for sociodemographic covariates.

Methods: Objective measures of the built environment unique to each household's physical location were developed within a geographic information system to assess land-use mix, residential density, and street connectivity. These measures were then combined into a walkability index. Accelerometers were deployed over a 2-day period to capture objective levels of physical activity in 357 adults.

Results: Measures of land-use mix, residential density, and intersection density were positively related with number of minutes of moderate physical activity per day. A combined walkability index of these urban form factors was significant ($p=0.002$) and explained additional variation in the number of minutes of moderate activity per day over sociodemographic covariates. Thirty-seven percent of individuals in the highest walkability index quartile met the ≥ 30 minutes of physical activity recommended, compared to only 18% of individuals in the lowest walkability quartile. Individuals in the highest walkability quartile were 2.4 times more likely (confidence interval=1.18–4.88) than individuals in the lowest walkability quartile to meet the recommended ≥ 30 minutes of moderate physical activity per day.

Conclusions: This research supports the hypothesis that community design is significantly associated with moderate levels of physical activity. These results support the rationale for the development of policy that promotes increased levels of land-use mix, street connectivity, and residential density as interventions that can have lasting public health benefits.
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Introduction

There are now sufficient studies documenting associations between the built environment and physical activity to consider transportation investments and land-use decisions as critical public

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health issues.^{1–4} Transportation and urban planning studies show that land-use patterns and transportation systems design are consistently related to walking and cycling for transport.^{1,5} Studies in the health literature indicate that a wide range of environmental variables is correlated with recreational physical activity.^{6,7} The built environment may be contributing to the obesity epidemic, because obesity is more prevalent in areas where land use makes it difficult to walk to destinations^{1–4,8} and where there are relatively few recreational resources.⁹ The built environment has emerged as a high priority for public health,^{10,11} and there are many important gaps in the research that need to be filled.

Most studies to date have been limited by large-scale regionally averaged or self-reported measures of the built environment that do not provide the detailed information needed by policymakers.^{8,12,13} Virtually all

studies to date have used self-reported measures of physical activity that are known to have limited validity.¹⁴ With few exceptions,^{13,15} studies have used limited physical activity outcome variables, such as active transport or recreational activity, although total physical activity may be most predictive of health outcomes. This study focuses on moderate physical activity, and does not distinguish between transportation, recreational, and other sources of physical activity.

The present study was designed by an interdisciplinary team to fill several gaps in the literature. The present study examined multiple, objectively measured characteristics of community design. These environmental variables were examined separately, and in an index designed to reflect overall walkability of neighborhoods. Building off recent advances in environmental assessment^{4,16} each environmental variable was computed individually for each participant, using geographic information systems (GIS) to describe the “microenvironments” that people experience regularly where they live. Physical activity was measured with an accelerometer that is among the best existing measures of objective physical activity.¹⁷

Methods

Recruitment and Data Collection

Strategies for Metropolitan Atlanta’s Regional Transportation and Air Quality (SMARTRAQ) is a study of transportation, land use, air quality, and health in the 13-county metropolitan Atlanta region. A total of 523 people were recruited from the SMARTRAQ study area. Figure 1 shows the study area and the home location of these 523 participants.

Data collection occurred between 2001 and 2003. A random-digit-dialing method of computer-aided telephone interview recruitment and data collection was used, and accelerometers were mailed out and mailed back in prepaid envelopes. Participants were recruited based on age (20 to 70 years); household annual income (<\$45,000 or >\$54,999); and the level of net residential density, a ratio of the number of households to residential land area, in which they reside. To capture a range of urban form conditions, participants were recruited from both higher- and lower-density environments (below four or above six dwellings per residential acre). Efforts were also made to focus recruitment into areas with more intersections per kilometer (connectivity) and with more commercial activity (mixed use).

The response rate was the ratio between completed interviews and total eligible sample called on the telephone. The response rate was calculated for recruitment and retrieval of data. The overall response rate was determined by multiplying the two resultant rates. The overall response rate was 30.4%.

Participants were asked to wear accelerometers for 2 days. Following the recruitment call, an accelerometer device was mailed to objectively measure physical activity. Objective physical activity data were electronically downloaded from the mailed-back accelerometer. Gender, age, ethnicity, and the highest level of education attained were self-reported during

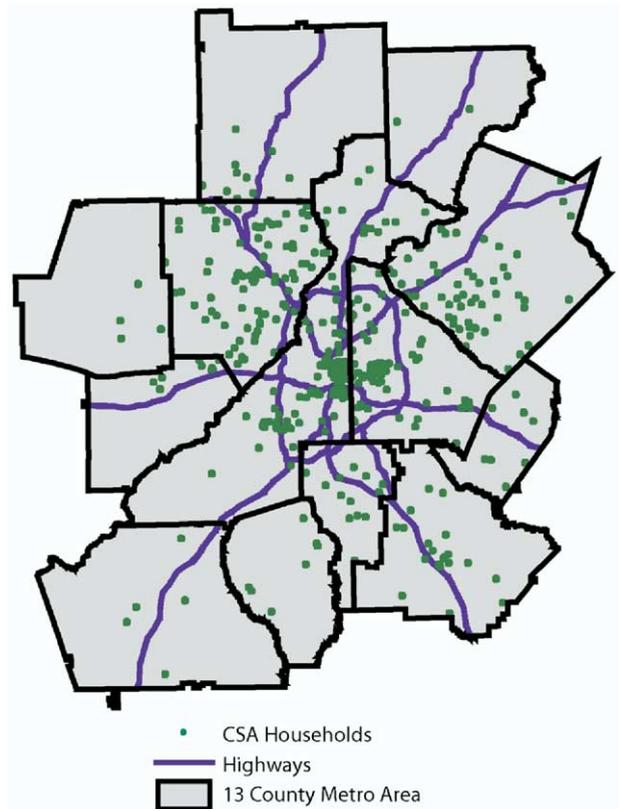


Figure 1. Study area and home location of activity monitor users ($n = 523$).

the recruitment call. Ethnicity was dichotomized into white or nonwhite, and level of education was dichotomized into having or not having attained at least a bachelor’s degree. The sample size declined from 523 to 357 persons based on the validity and completeness of the accelerometer data that were received.

Physical Activity

Participants in the present study wore a Manufacturing Technology Incorporated (MTI, formerly Computer Science and Applications, Inc. activity monitor, Fort Walton Beach FL) accelerometer for 2 days concurrent with the travel survey data collection period. Participants were randomly assigned different day pairs to ensure a range of travel and objective physical activity data for all 7 days of the week. Incentives ranging up to \$20 were paid upon receipt of the equipment with valid data. The accelerometer provides estimates of movement in the vertical plane when worn on the hip and has been shown to be reliable and valid in the estimate of adults’ physical activity,^{18,19} particularly of moderate intensity.²⁰

Measuring Urban Form

Determining the association of urban form with physical activity requires having sufficient data in contrasting urban environments. This is especially critical within a region like Atlanta with relatively few places that are not low density, single use, and characterized with poorly connected street networks. Therefore, urban form–based criteria were devel-

Table 1. Urban form measures

Measure	Definition	Scale of measurement for recruitment	Scale of measurement for target area selection	Equation	Data source(s)
Net residential density	Number of residential units per residential acre	1- × 1-km grid	Census block group	Count of households/ acres of land in residential use	2000 Census data and regional land cover data from aerial images
Street connectivity	Number of intersections/ square kilometer	1- × 1-km grid	One-kilometer network-based street buffer	Count of intersections/ kilometer	Street center-line file
Land-use mix	Evenness of distribution of square footage of residential, commercial, and office development	Not used systematically for recruitment	One-kilometer network-based street buffer	Equation below ^a	SMARTRAQ 2001 parcel-level land use database

^aLand-use mix = $(-1) \times [(\text{square footage of commercial} / \text{total square footage of commercial, residential, and office}) \ln (\text{square footage of commercial} / \text{total square footage of commercial, residential, and office}) + (\text{square footage of office} / \text{total square footage of commercial, residential, and office}) \ln (\text{square footage of office} / \text{total square footage of commercial, residential, and office}) + (\text{square footage of residential} / \text{total square footage of commercial, residential, and office}) \ln (\text{square footage of residential} / \text{total square footage of commercial, residential, and office})] / \ln (n3)$; where $n3 = 0$ through 3 depending on the number of different land uses present. SMARTRAQ, Strategies for Metropolitan Atlanta's Regional Transportation and Air Quality.

oped to focus recruitment into neighborhoods in the region that are more or less conducive for walking.¹³ Three measures of urban form were developed as target-area selection criteria and as subsequent independent predictors of physical activity in the analysis phase, and are described along with applicable data sources in Table 1. These measures of urban form were selected based on documentation within the literature of their association with travel choice.¹³ Additional testing of other urban form measures was also conducted resulting in the selection of these three measures based on their association with objectively measured physical activity.

Urban form was measured in two separate ways, within a 1-km grid system for target-area selection purposes, and within a 1-km road network-based buffer around each participant's place of residence for subsequent analysis purposes. The 1-km grid system provided a tool to determine where to geographically target recruitment based on net residential density and street connectivity as defined in Table 1. The formula for land use mix presented in Table 1 ranges from 0 to 1 and captures how evenly the square footage of commercial, residential, and office floor area is distributed within the household's 1-km network buffer. The most mixed-use buffers were assigned the highest numeric value. Areas considered more walkable had a net residential density greater than six dwelling units per residential acre and ≥ 30 intersections per square kilometer. Less walkable areas were defined as having a net residential density below four dwelling units per residential acre and < 30 intersections per square kilometer. These criteria were developed based on past research,^{5,21} preliminary results from the SMARTRAQ Travel Survey,⁸ and the distribution of households across the Atlanta region by these urban form measures. Supplemental recruitment was targeted in areas with increased proximity to shopping and other types of mixed use, which was measured through the

use of the SMARTRAQ regional parcel-level land use data as noted in Table 1. Land use variables were calculated for the area around each participant's residence defined by the distance that could be traveled in all directions using the street network for 1 km; the area identified is called a "buffer." A 1-km network buffer is shown around a hypothetical survey household in Figure 2.

Figure 2 shows the difference between straight-line (radial) and network buffer areas around a household. Network buffers establish the area that people that can actually access around their homes, and therefore constitutes a more accurate approach to measuring the physical environment unique to each participant's place of residence. The size of the network buffer for each household varies based on the connectivity of the road network; for example, more intersections allow a greater area to be covered on the ground. A plane of complete accessibility in all directions would result in the network buffer area equaling the straight-line area. Net residential density was measured at the census block group scale using 2000 census data on numbers of households divided by the land area within a given block group in residential use. Net residential density was measured at the block group level due to a lack of consistent reporting on number of dwelling units for multifamily parcels across the 13-county region.

Measures of urban form are correlated. Areas with higher residential density are often more mixed and more interconnected.^{21,22} The degree of correlation between these variables is a function of their inherent synergy in creating a walkable urban environment. However, it also creates model estimation problems associated with interactive variables or spatial multicollinearity. To avoid this problem, a walkability index was established that integrates the three variables developed for analysis shown in Table 1. A normalized

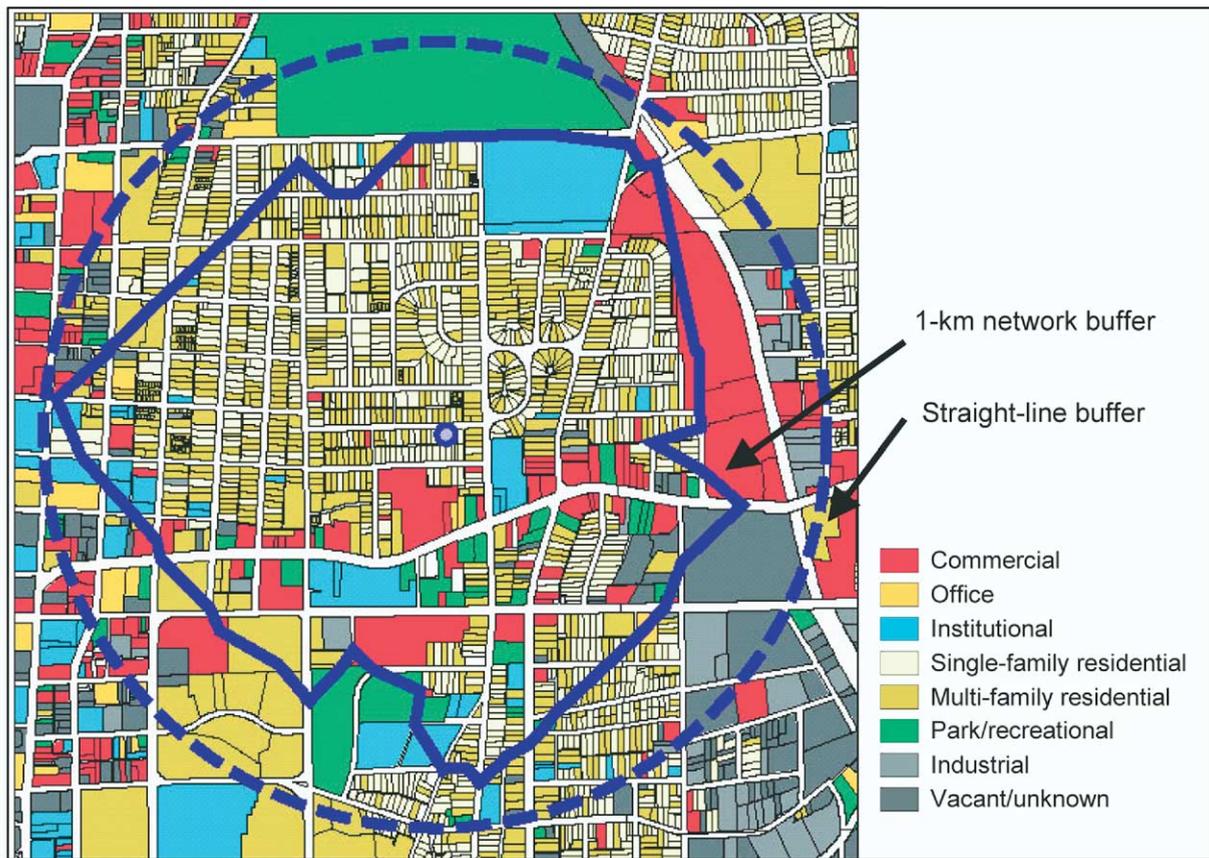


Figure 2. Measuring urban form.

distribution was taken of each variable (z-score) and then the three variables were combined into an index. A range of weights was tried for each of the three variables, resulting in the following formula, which was found to have the greatest explanatory power of the variation in the valid number of minutes of moderate activity per day:

$$\begin{aligned} \text{Walkability index} = & (6 \times \text{z-score of land-use mix}) \\ & + (\text{z-score of net residential density}) \\ & + (\text{z-score of intersection density}) \end{aligned}$$

While not included in this analysis, measures of urban form that capture the presence of sidewalks and bike paths will also advance the ability to assess the linkages between the built environment and physical activity.

Data Cleaning: Determining Valid Hours and Valid Days

In order to more accurately estimate physical activity, and to avoid considering hours in which the accelerometer was not worn as hours of being completely sedentary, criteria for valid accelerometer hours were established. Although highly sensitive to movement, it is difficult to differentiate not wearing the accelerometer from complete inactivity while wearing the accelerometer (both yield 0 activity counts). A valid accelerometer hour was considered an hour in which there were ≤ 30 consecutive minutes of 0 activity counts at any point during the hour. It is also critical to ensure that participants wore the equipment for a sufficient period each day to

adequately represent the day's physical activity. Eight or more valid hours defined a valid day.

Using software that accompanies the MTI accelerometers, activity counts per minute were converted into moderate and vigorous (hard plus very hard minutes) activity minutes for each valid hour on valid days using threshold values developed for adults in previous research.²³ The moderate and vigorous activity minutes were summed, respectively, for each valid day. The outcome variable for present analyses was moderate-intensity physical activity. Walking is the most common moderate-intensity activity, and it is expected to be more sensitive to community design than vigorous activities such as running or team sports.¹³ Very low levels of vigorous physical activity further limited its value for the present analyses. Participants who did not have ≥ 1 valid day were dropped from the analysis. When both days were valid, an average of the 2 days was used. As a result of these valid hour and valid day requirements, the sample size was reduced to 357 cases used in the analyses.

Analyses

Because the moderate physical activity variable was highly skewed, a natural log transformation was used in analyses requiring continuous variables. Partial correlations between moderate physical activity and the built environment were computed, adjusted for gender, age, and education. Multiple linear regressions were conducted using demographic variables and the walkability index as the independent variable.

Table 2. Sample characteristics ($n=357$)

	% or mean	SD	Range
Gender (% female)	55.7%	N/A	N/A
Body mass index	25.9	5.06	16.74–52.47
Age (years)	43.8	11.54	20–69
Education (% with bachelor's degree or higher)	66.4%	N/A	N/A
White (%)	74.9%	N/A	N/A
Black (%)	15.9%	N/A	N/A
Other ethnicity	9.2%		
Land use mix (for unit, see Table 1)	0.38	0.11	0–1.0
Intersection density (intersections per square kilometer)	37.27	16.62	0–104.23
Residential density (households per residential acre)	8.61	15.64	0–94.86
Walkability index (sum of weighted z-scores of three land-use variables)	2.4	13.28	–14.66–30.53

N/A, not applicable; SD, standard deviation.

The linear regression model did not allow an estimation of how changes in walkability in a community may relate to the probability of meeting the recommended ≥ 30 minutes of physical activity daily.²⁴ Thus, a logistic regression was conducted to predict meeting the ≥ 30 -minute guideline, using the walkability index divided into quartiles.

Results

Descriptive statistics are presented in Table 2 for demographics and urban form variables. Study participants were somewhat more likely to be female (55.7%), and were well educated, as 66.4% had at least a bachelor's degree. Study participants were 74.9% white and 15.9% black. The average age was 43.8 years, and 47% were overweight or obese (body mass index >25). The purposive sampling strategy resulted in a wider range of land-use mix, intersection density, and residential density than would otherwise have occurred through randomized recruitment methods. The walkability index had values ranging from –14.66 to 30.53 (based on the sum of the z-scores).

Partial correlations among environmental variables and minutes of moderate physical activity controlling for age, educational attainment, and gender are presented in Table 3. A natural log of the minutes of moderate physical activity per day was significantly correlated with land use mix ($r=0.145$, $p<0.01$), net residential density ($r=0.179$, $p<0.01$), and intersection density ($r=0.111$, $p<0.01$). As found in previous research, each of these urban form variables are signifi-

cantly correlated with one another, with the strongest association between net residential density and intersection density ($r=0.586$, $p<0.01$). Based on these strong associations between urban form measures, and previous research, a walkability index was used in the linear and logistical regression analyses that follow.

As shown in Table 4, two linear regression models (Model 1 and Model 2) were run. Model 1 included only the demographic variables, while Model 2 added the walkability index. Demographic variables were significantly related to the number of minutes of moderate physical activity, explaining 8.6% of the variance. In Model 2, when the walkability index was included, the total amount of variance explained increased a small but significant amount (total $R^2=0.107$), an increase of 2.1% in the explained variation. However, squared semipartial correlations show that the walkability index (0.158) was greater in its relationship with moderate physical activity than each of the demographic factors in the second model.

A weighted measure of walkability was used in the regression model presented in Table 4 that maximized the explained variation in the average number of minutes of moderate activity per day. Results presented in Table 5 demonstrate that an unweighted walkability index also yielded significant results (total $R^2=0.099$, $p=0.014$). However, increasing land-use mix to a factor of 6, while holding density and connectivity constant, resulted in a slight increase in the amount of explained variation in minutes of moderate activity (R^2 went from

Table 3. Partial correlations among variables, adjusting for age, gender, and education

	Adjusted for age	Adjusted for gender	Adjusted for education
1. Natural log of physical activity (minutes of moderate activity)	0.179**	0.145**	0.111**
2. Residential density (households per residential acre)		0.496**	0.586**
3. Land-use mix			0.356**
4. Intersection density (intersections per square kilometer)			

** $p < 0.001$ (bolded).

Table 4. Linear regression results, explaining natural log of minutes per day of moderate intensity physical activity ($n=340$)

Construct	β	Standard error	SR ²	Model adjusted R ²
Model 1 (demographics only)				0.086
$p < 0.001$				
Constant	1.35	0.168		
Gender ^a	-0.093	0.049	-0.009	
Age	-0.008	0.002	-0.033	
Education ^b	0.088	0.054	0.007	
Ethnicity ^c	0.169	0.062	0.019	
Model 2 (demographics + walkability index)				0.107
$p < 0.001$				
Constant	1.258	0.169		
Gender ^a	-0.086	0.049	-0.008	
Age	-0.007	0.002	-0.023	
Education ^b	0.096	0.054	0.007	
Ethnicity ^c	0.174	0.061	0.021	
Walkability index	0.006	0.002	0.024	

^a0 = male, 1 = female.

^b0 = less than a bachelor's degree, 1 = bachelor's degree or higher.

^c1 = white; 2 = nonwhite.

β , unstandardized beta coefficient; SR², squared semipartial correlation.

0.099 to 0.107, $p=0.002$). Additional increases in weight to the mix measure had no effect. Increasing the weights for the intersection and residential density variables were also tested both resulting in a reduction in the explained variation in minutes of moderate activity.

In the logistic regression analysis, as seen in Table 6, the walkability index was a significant correlate for meeting the ≥ 30 -minute physical activity recommendation, adjusting for demographic factors. Individuals were on average 30% more likely to record ≥ 30 minutes of activity with each increase in the walkability index quartile. In fact, 37% of individuals in the highest walkability index quartile met this minimum ≥ 30 minutes of physical activity, while only 18% of individuals in the lowest walkability quartile met the recommendation. A graded relationship between walkability and meeting physical activity recommendations was demonstrated. Table 6 provides the odds ratios for each walkability quartile. Results demonstrate that the odds of meeting the recommended ≥ 30 minutes of moderate activity per day was 2.4 times greater for the fourth quartile group than the referent group (least walkable) with a reported confidence interval (CI) of 1.18

to 4.88. However, the third quartile group approaches a significant difference from the referent group as well (CI=0.99–4.12).

Discussion

An objectively measured walkability index was significantly related to objectively measured moderate-intensity physical activity in adults. The association was observed, after accounting for demographic variables, with a continuous measure of moderate-intensity physical activity, and with meeting the ≥ 30 -minute/day recommendation. The results indicate that when people have many destinations near their homes and can get there in a direct pathway, they are more likely to engage in moderate physical activity for ≥ 30 minutes on a random day.

Present results extend previous findings of environmental correlates of physical activity by using objective measures for independent and dependent variables, combining multiple community design variables into a walkability index, and using individually defined environmental variables to describe "microenvironments" within 1 km of each person's

Table 5. Effects on the overall regression model of different weightings of land use mix factor within the walkability index

Land-use mix weight	NRD weight	Intersection density weight	β	Standard error	SR ²	Adjusted R ²
1	1	1	0.027	0.011	0.016	0.099
2	1	1	0.022	0.008	0.020	0.104
3	1	1	0.017	0.006	0.022	0.105
4	1	1	0.014	0.005	0.023	0.106
6	1	1	0.006	0.002	0.024	0.107
8	1	1	0.008	0.003	0.024	0.107

β , unstandardized beta coefficient; NRD, net residential density; SR², squared semipartial correlation.

Table 6. Logistic regression analysis to explain meeting the recommendation of ≥ 30 minutes of moderate-intensity physical activity on ≥ 1 study days ($n=356$)

Construct	β	Standard error	p value	Estimated odds ratio	95% CI
Gender ^a	-0.19	0.24	0.42	0.82	0.51-1.32
Age (20 to 69 years)	-0.02	0.01	0.041	0.98	0.96-0.99
Education ^b	0.16	0.28	0.57	1.17	0.68-2.01
Ethnicity ^c	0.45	0.34	0.17	1.57	0.83-2.98
Walkability index quartiles^d					
1 (lowest)			1.00 (referent)		
2	0.49	0.37	0.19	1.63	0.79-3.38
3	0.70	0.37	0.055	2.02	0.99-4.12
4	0.88	0.36	0.015	2.40	1.18-4.88

^a0 = male, 1 = female.

^b0 = less than a bachelor's degree, 1 = bachelor's degree or higher.

^c0 = non-white, 1 = white.

^dReference group is the lowest walkability quartile, with higher quartiles associated with higher walkability.

β , unstandardized beta coefficient; CI, confidence interval.

home. The ability of the walkability index to explain an overall measure of moderate-intensity physical activity is notable, because overall physical activity is expected to be the best predictor of health outcomes. However, most previous studies of community design examined only transportation-related walking and cycling.¹

Confidence in the findings is strengthened by the significant contribution of the walkability index to explaining total minutes of moderate-intensity physical activity as well as the categorical variable of meeting the ≥ 30 minutes of moderate activity on ≥ 1 of the 2 reporting days.²⁴ The finding that people living in better connected, more compact, mixed use neighborhoods are more likely to be active enough to achieve health benefits has great policy significance. As found in the logistic regression model, modest changes in the walkability of a neighborhood can translate into important, health-enhancing population-level increases of activity. Only 18% of those living in communities with the lowest level of walkability recorded ≥ 30 minutes of walking on at least 1 day, compared with 28.1% in the second, 32.3% in the third, and 37.5% in the top quartile of walkability. This result suggests that designing neighborhoods for pedestrian use could help many people meet the guidelines, although a confounding effect of neighborhood selection cannot be ruled out. In contrast to physical activity promotion programs for individuals that typically have short-term effects,²⁵ building walkable neighborhoods could be expected to have relatively permanent effects. Given that Atlanta is one of the least walkable and most sprawling regions in the United States,^{3,8} it was encouraging that even in this context, walkable neighborhood designs were related as expected to physical activity.

Based on previous findings in the transportation and urban planning literatures, land-use mix, connectivity of streets, and residential density were expected to be related to overall physical activity in bivariate analyses.¹ Our results confirmed these earlier studies. All three

variables were included in an index to determine whether the combination explained more variance in physical activity than any single variable. It is often difficult to estimate the strength of environmental associations with physical activity because land-use variables tend to be inter-related.²¹ Thus, the present demonstration of the significant association using a walkability index to explain objectively measured physical activity is a substantive advance. An index that optimally combines inter-related variables should provide a better estimate of true effect sizes, and the index may be a useful tool for explaining to planning professionals and policymakers that multiple design variables need to be considered simultaneously in creating "activity-friendly" communities.²² The walkability index presented in this paper was weighted based on preliminary analyses of the combined variables to explain the variation in moderate activity levels for this data set. However, an unweighted walkability index performed nearly as well. Because there is no reason to assume that the walkability index presented in this paper is optimal, further work is needed to evaluate other indices and their generalizability across multiple locations and population groups.

The walkability index explained a significant amount of variance in physical activity after adjusting for gender, age, education, and ethnicity, but the amount of additional variance explained was only about 2.1%. However, gender, which is one of the most consistent correlates of physical activity, explained far less than 2% of the variation in moderate physical activity. Taken as a whole, the entire model explained 10.7% of the variance; therefore, most of the variance in physical activity was unexplained. A wide variety of demographic, biological, psychological, behavioral, social, and environmental variables are correlated with physical activity,²⁵ so it is not expected that any single variable or set of variables will explain large amounts of variance. Even when

many variables are included in multivariate models, it is uncommon to explain >30% of the variance in physical activity,²⁶ and studies to date have explained much less variance in objectively measured physical activity.²⁷ Thus, the variance explained by the walkability index contributes to our overall understanding, and it is likely that other untested environmental variables, such as presence of sidewalks and bikeways, will explain additional variance.

It was also notable that each quartile increase in walkability was associated with an increase in the percent of those engaging in 30 minutes or more of moderate physical activity per day. The effect size does seem to be large enough for public health significance. In particular, the odds are 2.4 times greater that respondents in the highest walkability quartile will meet the recommended ≥ 30 minutes of moderate physical activity than respondents in the lowest walkability quartile. However, this is the first study to make the direct association between objectively measured physical activity and neighborhood walkability and additional research will help to verify these results.

There are several limitations to the present study. The Atlanta region is well known to have limited variability in land use, but oversampling in more “walkable” areas enhanced variability. In addition, this cross-sectional study design does not allow us to account for potential effects of self-selection or attitudinal pre-determinants of community choice, or the choice to walk. Although objectively measured physical activity is rarely available in studies of this kind, only a maximum of 2 days of monitoring were available, and this limitation likely led to an underestimate of true effect sizes. While the accelerometers provide an objective measure of physical activity, they do not provide a perfect picture of an individual’s level of activity. For example, accelerometers cannot measure some activities such as swimming or bicycling. The study did not measure how the presence of sidewalks and bikeways might impact levels of physical activity. Also, very low levels of vigorous-intensity physical activity precluded analyses using other health-related physical activity variables. The people in the sample who agreed to wear the monitors were more likely to be white and affluent than the population of the region. Our sample was 74.9% white as compared to 59.37% in the Atlanta region.²⁸ To reduce seasonal effects on travel patterns, data were only collected in the fall and spring, so future studies should examine seasonal effects. Although additional environmental variables are hypothesized to be related to physical activity,^{1,8} only variables available in the GIS database could be examined in the present study. “Neighborhood” was operationally defined as being within 1 km of each person’s home, but other neighborhood definitions should be explored to identify how people interact with their local environments.

Present results indicate that people are more physically active and more likely to meet recommendations of ≥ 30 minutes of moderate activity when they live in neighborhoods with nearby shops and services, with many street connections between residential and commercial districts. Community design variables were significantly related to moderate intensity physical activity for all purposes, and additional confidence in the results is justified by the objective measurements of key variables.

The results of this study add to a growing evidence base suggesting that city planners and public health professionals need to work closely together to advocate for policies that will make all neighborhoods as “activity friendly” as possible.

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References

1. Saelens BE, Sallis JF, Black JB, and Chen D. Neighborhood-based differences in physical activity: an environment scale evaluation. *Am J Public Health* 2003;93:1552–8.
2. Frumklin H, Frank LD, Jackson RJ. The public health impacts of sprawl: designing, planning, and building healthy communities. Washington, DC: Island Press, 2004.
3. Ewing R, Schmid TL, Killingsworth R, Zlot A, Raudenbush S. Relationship between urban sprawl and physical activity, obesity and morbidity. *Am J Health Promotion* 2003;18:47–57.
4. Frank LD, Andersen M, Schmid TL. Obesity relationships with community design, physical activity, and time spent in cars. *Am J Prev Med* 2004;27:87.
5. Ewing R, Cervero R. Travel and the built environment: a synthesis. *Transportation Res Rec* 2001;1780:87–122.
6. French SA, Story M, Jeffery RW. Environmental influences on eating and physical activity. *Ann Rev Public Health* 2001;22:309–35.
7. Humpel N, Owen N, Leslie E. Environmental factors associated with adults’ participation in physical activity: a review. *Am J Prev Med* 2002;22:188–99.
8. Frank LD, Engelke PO, Schmid TL. Health and community design: the impact of the built environment on physical activity. Washington, DC: Island Press, 2003.
9. Giles-Corti B, Broomhall MH, Knuiaman M, Collins C, Douglas K, Ng K, Lange A, Donovan RJ. Increasing walking: how important is distance to, attractiveness, and size of public open space? *Am J Prev Med* 2005;28(suppl 2):169–76.
10. Dannenburg AL, Jackson RJ, Frumkin H, et al. The impact of community design and land-use choices on public health: a scientific research agenda. *Am J Public Health* 2003;93:1500–8.

11. Lavizzo-Mourey R, McGinnis JM. Making the case for active living communities. *Am J Public Health* 2003;93:1386–8.
12. Bauman A, Armstrong T, Davies J, et al. Trends in physical activity participation and the impact of integrated campaign among Australian adults, 1997–99. *Aust N Z J Public Health* 2003;27:76–9.
13. Saelens BE, Sallis JF, and Frank LD. Environmental correlates of walking and cycling: findings from the transportation, urban design, and planning literatures. *Ann Behav Med* 2003;25:80–91.
14. Sallis JF, Owen N, Frank LD. Behavioral epidemiology: a systematic framework to classify phases of research on health promotion and disease prevention. *Ann Behav Med* 2000;22:294–8.
15. DeBourdeaudhuij L, Sallis JF, Saelens BE. Environmental correlates of physical activity in a sample of Belgian adults. *Am J Health Promotion* 2003;18:83–92.
16. Cervero R, Duncan M. Walking, bicycling and urban landscapes: evidence from the San Francisco Bay area. *Am J Public Health* 2003;93:1478–83.
17. Welk GJ. Use of accelerometry-based activity monitors to assess physical activity. In Welk GT, ed. *Physical activity assessments in health related research*. Champaign, IL: Human Kinetics Publishers, 2002:125–42.
18. Melanson E, Freedson PS. Validity of the Computer Science and Applications, Inc. (CSA) activity monitor. *Med Sci Sports Exerc* 1995;27:934–40.
19. Sirard JR, Melanson E, Li L, Freedson PS. Field Evaluation of the Computer Science and Applications, Inc. physical activity monitor. *Med Sci Sports Exerc* 2000;32:695–700.
20. Nichols JF, Morgan CG, Chabot LE, Sallis JF, Calfas KJ. Assessment of physical activity with the Computer Science and Applications, Inc. accelerometer: laboratory versus field validation. *Res Q Exerc Sport* 2000;71:36–43.
21. Frank LD. Land use and transportation interaction: implications on public health quality and quality of life. *J Planning Educ Res* 2000;20:6–22.
22. Cervero R, Kockelman KM. Travel demand and the 3Ds: density, diversity, and design. *Transportation Res D* 1997;2:199–219.
23. Freedson PS, Melanson E, Sirard JR. Calibration of the Computer Science and Applications, Inc. accelerometer. *Med Sci Sports Exerc* 1998;30:777–81.
24. Pate RR, Pratt M, Blair SN, et al. Physical activity and public health: a recommendation from the Centers for Disease Control and Prevention and the American College of Sports Medicine. *JAMA* 1995;273:402–7.
25. Sallis JF, Owen N. *Physical activity and behavioral medicine*. Thousand Oaks CA: Sage, 1999.
26. Baranowski T, Anderson C, Carmack C. Mediating variable framework in physical activity interventions. How are we doing? How might we do better? *Am J Prev Med* 1998;15:266–97.
27. Sallis JF, Taylor WC, Dowda M, Freedson PS, Pate RR. Correlates of vigorous physical activity for children in grades 1 through 12: comparing parent-reported and objectively measured physical activity. *Pediatr Exerc Sci* 2002;14:30–40.
28. U.S. Census Bureau. 2000 Decennial census summary. Summary tape file 1, Atlanta Metropolitan Statistical Area. Available at: www.census.gov. Accessed March 15, 2004.