Journal of Urban Health: Bulletin of the New York Academy of Medicine, Vol. 87, No. 5
doi:10.1007/s11524-010-9488-7

Relationships of Land Use Mix with Walking for Transport: Do Land Uses and Geographical Scale Matter?

Mitch J. Duncan, Elisabeth Winkler, Takemi Sugiyama, Ester Cerin, Lorinne duToit, Eva Leslie, and Neville Owen

ABSTRACT *Physical activity and public health recommendations now emphasize the creation of activity-friendly neighborhoods. Mixed land use in a neighborhood is important in this regard, as it reflects the availability of destinations to which residents can walk or ride bicycles, and thus is likely to contribute to residents' active lifestyles that in turn will influence their overall health. Relationships between land use mix (LUM) and physical activity have not been apparent in some studies, which may be because geographical scale and the specificity of hypothesized environment–behavior associations are not taken into account. We compared the strength of association of four Geographic Information Systems-derived LUM measures with walking for transport and perceived proximity to destinations. We assessed physical activity behaviors of 2,506 adults in 154 Census Collection Districts (CCDs) in Adelaide, Australia, for which "original" LUM measures were calculated, and then refined by either: accounting for the geographic scale of measurement; including only the most-relevant land uses; or, both. The refined (but not the "original") LUM measures had significant associations with the frequency of walking for transport ($p<0.05$) and area-corrected measures had significant associations with the duration of walking for transport. All LUM measures had significant associations with perceived proximity to destinations, but stronger associations were seen when using the refined measures compared with the original LUM. Identifying the LUM attributes most strongly associated with walking for transport is a priority and can inform environmental and policy initiatives that are needed to promote health-enhancing physical activity.*

KEYWORDS *Walking for transport, Land use mix, GIS, Entropy, Physical activity*

INTRODUCTION

Built environment factors have become a major focus of the physical activity and public health field, and there are now strong policy and programmatic recommendations on developing sustainable strategies for the prevention of chronic disease by creating more activity-friendly communities.[1–8] The built environment typically consists of urban design (arrangement of physical elements within the city), land use

Duncan is with the Centre for Physical Activity Studies, Institute for Health and Social Science Research, CQ University, Rockhampton QLD 4702, Australia; Winkler, Sugiyama, duToit, and Owen are with the Cancer Prevention Research Centre, School of Population Health, The University of Queensland, Herston, QLD, Australia; Cerin is with the Institute of Human Performance, The University of Hong Kong, Hongkong, CHINA; Leslie is with the School of Psychology, Deakin University, Melbourne, AUSTRALIA.

Correspondence: Mitch J. Duncan, Centre for Physical Activity Studies, Institute for Health and Social Science Research, CQ University, Rockhampton QLD 4702, Australia. (E-mail: m.duncan@cqu.edu.au)

patterns (the distribution of functions across space), and transportation system infrastructure (including roads, railway etc).[9] Studies conducted in this field continue to expand in number and sophistication; new developments include investigation of associations of specific health-related behaviors (for example, physical activity for transport, in contrast to activity for recreational or fitness purposes) with specific environmental attributes,[10–12] and methodological aspects relating to how most appropriately to characterize such neighborhood-design attributes.[13]

Land use mix (LUM), which aims to quantify the heterogeneity of land uses in geographically-defined areas, is a built environment attribute that has been shown to be associated with walking [14–17] and other physical activity behaviors.[18] An area where diverse land uses exist typically offers more non-residential destinations for walking journeys, and thus may facilitate more transport-related physical activity by residents and reduce the risk of chronic diseases.[19–21] However, in some studies expected associations between LUM and physical activity behaviors have not been found.[22,23] Such equivocal findings may be partly due to the way LUM is operationalized and determined, particularly lack of specificity in the land uses included and wide variations in geographical scale used.[13,24]

LUM measures typically include residential, commercial, institutional, industrial, recreational, and agricultural land uses; however, not all of these land uses provide commonly accessed destinations for typical residents. Including land uses that have little impact on residents' transport-related physical activity (or have an adverse impact by effectively diluting the presence of relevant destinations) may misclassify LUM and obscure its relationship with activity outcomes. In line with the recognized need for specificity of theoretical models to explain environment–behavior relationships, LUM measures that only incorporate land uses conceptually relevant to a specific behavior (e.g., walking for transport) should be examined in order to assess the contribution of LUM to behavior.[10–12]

Geographical scale used to measure LUM at the neighborhood level often varies across studies and within samples, depending on the methodology employed and the purpose of the study, since there is no consensus on the definition of what constitutes a neighborhood, nor of its appropriate size.[13,25] When measured by street network or straight line radii, the geographical scale of LUM is typically based on the plausible distances (0.2–1.6 km) that individuals are assumed to be prepared to travel to local destinations.[23,26,27] When administrative boundaries are used, often to match available complementary census data, geographical size can be variable. This variation remains present even though researchers will often use the smallest available administrative boundary, such as Census Collection Districts (CCDs) in Australia, and census tracts in the USA, to minimize within-unit variability.[24,28–31] In the case of CCDs, variation occurs as CCDs are not defined to create areas of equal geographical size. Rather, CCDs are primarily defined to create areas that are convenient and efficient for data collection during the Census, which equates to approximately 220 dwellings per CCD.[32] Consistent, meaningful scale is significant in area effects research,[25,31,33,34] and the theoretical and conceptual basis of LUM as a determinant of walking behavior suggests that it is the presence and diversity of *proximal* destinations that promotes increased walking. Measurement of LUM on an excessively large or non-uniform scale may obscure associations with physical activity outcomes.[13,31,33,34] To illustrate, residents in a larger CCD may have to travel a longer distance to reach a non-residential destination, compared to those in a smaller CCD with the same LUM value (assuming destination distributions are uniform). Despite this problem, researchers may choose to use administrative boundaries as the spatial unit for LUM to enable its use in conjunction with population census data measured at a single geographical scale. Measurement of data at a single geographical scale can avoid the introduction of errors associated with aggregating data collected at different geographical scales.[35] Thus, examination of the impact of heterogeneity in administrative boundary size, and how to correct for it, is needed.

To assess the potential importance of both geographical scale of measurement and specificity of land uses in the construction of LUM scores, we examined the magnitude of association between adults' walking for transport and four measures of LUM at the CCD level. We contrasted (1) an "original" LUM score,[29] incorporating commercial, residential, recreational, industrial/institutional, and 'other' land uses; (2) the original LUM score corrected for the geographical size of the CCD; (3) a revised LUM score in which recreational and "other" land uses were not included; and (4) the revised LUM score corrected for the geographical size of the CCD. In order to assess the concurrent validity of each of these objectively defined LUM measures, the magnitude of association between each objectively defined LUM measure and residents' perceptions of the corresponding local-environment attributes were also examined.

METHODS

Participants were recruited as part of the PLACE (Physical Activity in Localities and Community Environments) study during the period July 2003 to June 2004; details of the recruitment method and methodology are provided elsewhere.[29,36,37] The original aim of the PLACE study was to examine associations of neighborhood environmental attributes with residents' physical activity. An objective index of walkability at the CCD level (including a LUM component) was derived from geographic information systems (GIS) data for neighborhoods in the Adelaide Statistical Division.[29] Thirty-two neighborhoods composed of several adjacent CCDs were selected from the top or bottom 25% of walkability. The selection was done after field visits by the research team to ensure actual environments matched with GIS-based walkability. Residential addresses were randomly selected within the neighborhoods and residents were invited to participate in a survey. Those who were eligible (adults aged between 20 and 65 years, English-speaking, and able to walk without assistance) and agreed to participate were mailed a survey that asked for information on individual level socio-demographic factors, physical activity, and perceptions of local environmental attributes. Of the 2,650 eligible respondents this study includes 2,506 adults who provided complete survey information and had complete GIS data available. The PLACE study was conducted with the approval of the Behavioral and Social Sciences Ethics Committee of the University of Queensland.

Measures

Socio-demographics Participants reported their age, gender, level of educational attainment, employment status, household size (number of adults and presence of children aged under 18), and annual household income (before tax). Median weekly household income for each CCD was obtained from the Australian Bureau of Statistics 2001 Census.[38]

Walking for Transport

The International Physical Activity Questionnaire (IPAQ) Long Form was used to assess frequency and duration of walking for transport.[39] Participants reported their frequency and duration of walking for transport in the previous 7 days, excluding any walking that lasted less than 10 min. Standard scoring protocols were used to determine the number of weekly sessions and daily minutes of walking for transport, which were truncated at 180 min (3 h) per day.

Land Use Mix

1. Objectively defined LUM (original LUM score)

An entropy-based index of LUM was determined using the following formula:

$$-\sum_{\mathrm{k}}(\mathrm{p_k}\ \ln\ \mathrm{p_k})/\ln N,$$

where k is the category of land use; p is the proportion of the land area within a CCD devoted to a specific land use; N is the number of land use categories.[22,29,36] LUM scores ranged from 0 (no mixture, single land use) to 1 (all the land uses equally present). A LUM index that was originally designed for a 0.5 mile (0.8 km) radius buffer around home addresses was adapted by the PLACE study to refer to CCDs as the spatial unit.[40] The index measures the heterogeneity of five land uses (residential, commercial, industrial/institutional, recreational, and "other") and is referred to here as the *original LUM score*. The "residential" land use category includes non-private facilities such as hotels and hostels as well as private dwellings. All sizes and types of retail outlet such as shopping centers, white goods suppliers, as well as local post offices, were classified as "commercial", along with restaurants and business services. The "industrial/institutional" category contains utilities and, heavy and light industry in addition to libraries, schools, hospitals, and other government institutions. Sports facilities and open "green" spaces such as parks and botanic gardens are examples of "recreational" land uses. The "other" category includes land uses not classified elsewhere, such as agriculture and protected natural areas.

2. Area-corrected LUM score

To correct for geographical size differences between CCDs while keeping LUM on a 0–1 scale, the size of each CCD in square kilometers, as reported by the Australian Bureau of Statistics, was divided by the size in square kilometers of the smallest CCD in the sample to create a ratio indicating relative size of each CCD. The original LUM score for each CCD was then divided by the CCD specific ratio to create an *area-corrected LUM score*.

3. Revised LUM score

A *revised LUM score* was identified that uses the same formula for calculation as the original LUM score, but excludes land uses of low theoretical relevance to walking for transport, retaining only commercial, residential, and industrial/institutional land uses in the calculation. Recreational and other land uses were excluded as they are not typical destinations for utilitarian walking. Land uses that were presumably too small to support a destination that may be traveled to (<1 m^2) were also excluded.

4. Area-corrected revised LUM score

The revised LUM score was further refined to account for the geographical size of the CCD (using the same process as was used to create the area-corrected LUM score) to produce an *area-corrected revised LUM score*.

Perceived Proximity to Neighborhood Destinations Participants completed the Australian version of the Neighborhood Environment Walkability Scale, a valid and reliable instrument measuring perceptions of the neighborhood environment.[41,42] The land use mix-diversity subscale was used to assess the perceived proximity to destination types ranging from a 1–5-min walk from their home to a >30-min walk. Six destination types in the scale were excluded as they were considered to be of low theoretical importance to walking for transport (e.g., recreational facilities and auto services). Included destination types were local shops, supermarkets, hardware stores, greengrocers, laundries, post offices, libraries, primary schools, other schools, book shops, cafés, video outlets, pharmacies, bus or train stops, places of work, fitness or recreation centers, professional offices (e.g., dentist or doctor), and appliance stores. The number of the remaining 18 destination types within a 10-min walk of participants' homes (perceived proximity of destinations) was used as a criterion for concurrent validity of the objective LUM scores.

Statistical Analysis

First, to establish that the refined LUM measures differed from the original LUM score, correlations between LUM measures (Spearman's Rho) were assessed and the spatial distribution of LUM across the study areas was mapped and compared for the four LUM measures. Then, LUM measures were compared in terms of their strength of association with relevant outcomes, using Generalized Linear Models (GLM) with robust sandwich estimators of the standard errors of the regression coefficients to account for the clustered nature of the data.[43] To facilitate comparison, since the observed range of LUM scores was affected by area correction, each LUM measure was examined in deciles, such that each one-unit increase refers to a one-decile increase in the LUM distribution. Daily minutes of walking for transport were skewed, therefore a γ-variance function and identity link function were used to model this outcome, while a negative binomial variance function and logarithmic link function were used to examine weekly frequency of walking for transport. Perceptions of local destinations approximated a normal distribution and thus were examined using a Gaussian distribution function and identity link function. Each association was tested separately in unadjusted models, then in models that adjusted for individual socio-demographics and area-level (i.e., CCD-level) median household income. Analyses were performed in STATA 10.0 and significance was set at $p<0.05$.

RESULTS

Table 1 shows characteristics of the participant sample, which comprised more women than men and had a high proportion of tertiary-educated participants. Both

TABLE 1 Socio-demographic characteristics of participants in the PLACE study ($N=2{,}506$)

Characteristic	%, median (1st to 3rd quartile) or mean ± SD
Gender (%)	
Men	36.0
Women	64.0
Age (mean ± SD)	44.3 ± 12.3
Education (%)	
With tertiary education	46.3
No tertiary education reported[a]	53.7
Work status (%)	
Working	64.2
No work reported[a]	35.8
Children in household (%)	
Yes	30.6
None reported[a]	69.4
Adults in household (%)	
1 adult	32.0
2 adults	52.0
3 adults or more	13.9
Not reported	2.0
Annual household income (%)	
$31,199 or less	35.2
$31,200–$77,999	41.5
$78,000 or more	19.7
Not reported	3.6
Walking median (1st, 3rd quartile)	
Frequency (sessions/week)	3 (1, 5)
Duration (min/day)	12.9 (2.9, 30)
Number of destination types within a 10-min walk distance	8.6 ± 4.9

[a]Including those who did not report or reported none

the frequency and duration of walking for transport varied considerably among participants, as indicated by the wide inter-quartile ranges. Table 2 shows characteristics of the examined CCDs. The study CCDs seldom had only a single land use (1.9%); none included all five types of land uses (i.e., residential, commercial, industrial/institutional, recreational, and "other"). On average, study areas had a moderate level of land use mix based on the original (median = 0.43) and revised scores (median = 0.44), with greater variability in LUM being seen with the revised score. Area correction shifted these values downward and reduced the variability in LUM. The correlations between the refined measures and original LUM were not so high as to indicate no effect of the refinements (Spearman's Rho, 0.79 for revised LUM, 0.48 for area-corrected LUM, and 0.47 for area-corrected revised LUM).

Figure 1 shows the spatial distribution of original LUM across the entire study area and compares how the four measures classify LUM (in deciles) for a subset of study CCDs that were in an area containing large salt pans, military bases, and other such areas that may not be conducive to walking. The CCDs in the inner city tended to be small and to rank in the higher deciles of LUM; the outlying CCDs were more variable in size and LUM. The subset of CCDs tended to be classified

TABLE 2 Socioeconomic and land use mix characteristics of Census Collection Districts in the PLACE study ($N = 154$)

Characteristic	% or median (1st and 3rd quartile)
Median weekly household income (%)	
$200–$399	7.1
$400–$499	17.5
$500–$599	16.9
$600–$699	16.2
$700–$799	12.3
$800–$999	15.6
$1,000–$1,199	14.3
Number of land uses in CCD (%)[a]	
1	1.9
2	18.8
3	44.2
4	35.1
5	0
Spatial area (km^2)	0.23 (0.14, 0.31)
Dwelling density (dwellings/residential km^2)	707.67 (498.69, 872.13)
Intersection density (intersections/km^2)[b]	216.78 (137.80, 309.06)
Original LUM score	0.43 (0.28, 0.54)
Revised LUM score	0.44 (0.16, 0.69)
Area-corrected LUM score	0.09 (0.05, 0.14)
Area-corrected Revised LUM score	0.09 (0.03, 0.17)
Net retail area index (0–1)[c]	0.3 (0, 0.4)
Walkability score[d]	24.5 (15.75, 29)

[a]The five possible land uses were residential, recreational, commercial, industrial/institutional, and other

[b]Intersection density is the ratio of total number of intersections with ≥3 streets intersecting to the total area of the CCD (km^2)

[c]Net retail area index is the ratio of the retail gross floor space to the parcel area for a specific CCD

[d]Walkability score is created by summing the deciles of each of the following variables: original LUM score, net retail area, intersection density, and dwelling density

as lower in LUM by the revised method and especially by the area-corrected and area-corrected revised measures than by the original LUM measure. Notably, the larger CCDs of the subset tended to rank among the highest deciles of original LUM but were ranked much lower with area correction, in contrast to the CCDs in inner city Adelaide, which were classified similarly by all methods (data not shown).

Original LUM Score (deciles)

Table 3 shows the relationships of four LUM measures with walking for transport and perceived proximity of destinations. No significant relationships were observed between the original LUM score and either walking outcome in unadjusted or adjusted analyses. However, significant positive relationships were present between the area-corrected LUM score and daily minutes and weekly sessions of walking for transport, even after adjusting for confounders. Both the original and the area-corrected original LUM scores were significantly associated

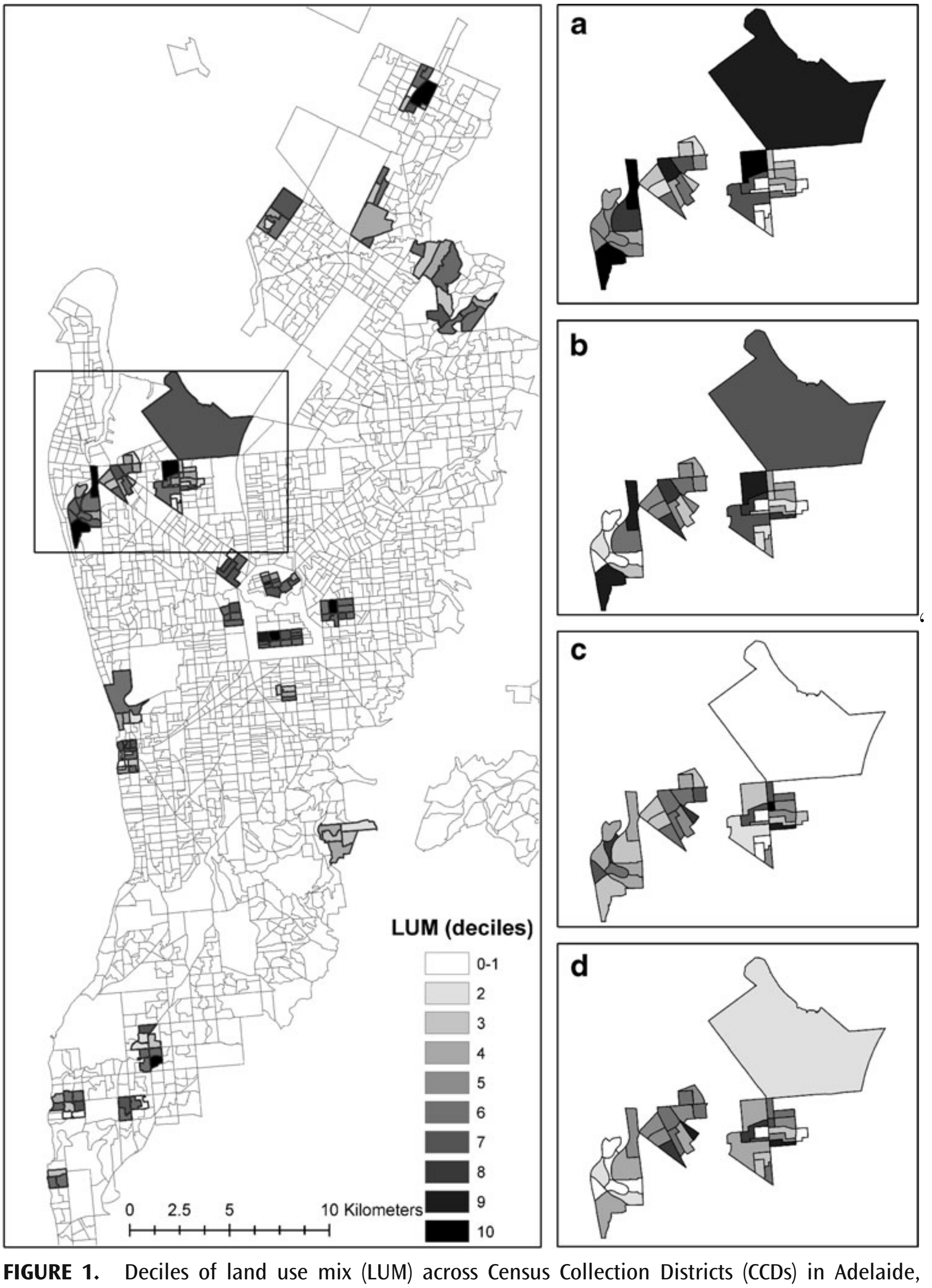

FIGURE 1. Deciles of land use mix (LUM) across Census Collection Districts (CCDs) in Adelaide, Australia; for all CCDs under original LUM classifications (*left*), and for a subset of CCDs (*right*) using; **a**) original LUM, **b**) revised LUM, **c**) area-corrected LUM, and **d**) *area-corrected revised LUM*.

with perceived presence of destinations within 10-min walking distance, however, relationships were stronger (i.e., regression coefficients were larger) for the area-corrected compared to the original LUM score in both unadjusted and adjusted models.

Revised LUM Scores (deciles)

Revised LUM and area-corrected revised LUM had stronger associations with perceived presence of neighborhood destinations and walking outcomes (i.e., larger regression coefficients) than original LUM (without area correction), although the association between revised LUM and minutes of walking for transport was not statistically significant. The associations with each outcome were similar in magnitude for area-corrected revised LUM compared with area-corrected (original) LUM.

DISCUSSION

In the context of arguments for greater specificity of behavior–environment models,[10–12] and being mindful of varying geographical scales of measurement,[24,33] this study developed four variations of an entropy-based LUM measure for administrative boundaries, and tested and examined their associations with residents' walking for transport and their perceptions of the availability of local destinations. This was performed to clarify relationships between LUM and walking for transport in order to better understand how built environments might influence physical activity. As has been previously reported,[22] the original LUM measure showed no association with the duration of walking for transport, nor with the frequency of walking for transport in this study. By contrast, the refined LUM measures all had significant associations with at least one walking outcome. Broadly, the findings suggest that the relationship between CCD-level LUM and walking for transport is better assessed by using LUM measures that account for geographical scale, include only theoretically relevant land uses, or do both. The current findings lend credence to the idea that measurement issues may partly explain the equivocal findings in the literature between LUM and physical activity, but not completely, as some null findings come from studies without variability in geographical size and appropriate land uses.[23]

Progressively enhanced associations between LUM and perceived proximity of destinations following geographical-scale corrections and exclusion of low-relevance land uses suggest that the concurrent validity of the revised LUM scores may be better than the original LUM score. Measures that are more specific and account for geographical scale may more accurately represent the underlying conceptual premises of LUM because these measures focus on land uses that provide residents with utilitarian destinations in close proximity to each other. The implementation of these LUM measures in future studies using similar area-based methods may be useful so that associations between LUM and activity outcomes are not masked by inaccurate measurement.

Accounting for geographical scale and the revision of land uses in isolation improved associations between LUM measures and walking for transport compared to the original LUM. It is therefore somewhat surprising that area-corrected revised LUM, which accounts for geographical scale and relevant land uses, did not outperform area-corrected LUM and revised LUM. One explanation may be the similarity between area-corrected LUM and area-corrected revised LUM in our study. Area-corrected revised LUM and area-corrected LUM were highly correlated (Rho $=0.84$, $p<0.001$) and as can be seen in Figure 1, many CCDs were ranked similarly in LUM by these two measures. Further study is needed to identify an optimal method of determining a LUM index for administrative boundaries.

The study location, Adelaide, is typical of Australian metropolitan areas in several aspects. However, the current findings may vary for non-metropolitan locales or in contexts where the land use distribution and the typical size of administrative

TABLE 3 Relationships between measures of land use mix (LUM, deciles, 1–10) and minutes and sessions of walking for transport and perceived proximity of destinations[a]

	Walking for transport				Perceived proximity of destinations	
	Minutes per day		Sessions per week		Index (0–18)	
	Unadjusted	Adjusted[a]	Unadjusted	Adjusted[a]	Unadjusted	Adjusted[a]
	b (95% CI)	*b* (95% CI)	*b* (95% CI)	*b* (95% CI)	*b* (95% CI)	*b* (95% CI)
Original LUM score	−0.28 (−0.84, 0.29)	<0.01 (−0.61, 0.61)	0.01 (−0.01, 0.02)	0.01 (−0.01, 0.02)	0.24 (0.04, 0.44)**	0.22 (0.02, 0.41)*
Area-corrected LUM score	0.78 (0.17, 1.39)*	1.06 (0.33, 1.78)**	0.05 (0.03, 0.06)***	0.04 (0.03, 0.05)***	0.62 (0.43, 0.80)***	0.55 (0.37, 0.72)***
Revised LUM score	0.14 (−0.42, 0.69)	0.28 (−0.29, 0.85)	0.03 (0.01, 0.04)***	0.02 (0.01, 0.04)**	0.48 (0.30, 0.66)***	0.42 (0.25, 0.60)***
Area-corrected revised LUM score	0.60 (0.07, 1.13)*	0.75 (0.22, 1.28)**	0.04 (0.03, 0.06)***	0.04 (0.03, 0.05)***	0.65 (0.48, 0.83)***	0.59 (0.43, 0.76)***

Regression coefficient (*b*) and 95% confidence interval (95% CI) from Generalized Linear Models with robust sandwich estimators to account for clustering; models use γ-variance function and identity link function (for minutes of walking for transport), negative binomial variance function and logarithmic link function (for sessions of walking for transport), and Gaussian distribution function and identity link function (for perceived destinations)

$^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$

[a]Adjusted for age, gender, education, employment, household income, number of adults (1, 2, 3+, or unknown), and presence of children (yes/no) in the household, and CCD-level median weekly household income

boundaries differ dramatically. Different settings would need to be examined before assuming our method of area correction or selection of land use types are useful across a wide range of locations. Caution is needed in assuming this particular area-corrected entropy-based measure of LUM would perform well outside the metropolitan context, as the underlying assumptions about the spatial interspersion of land uses may not be valid for geographically large areas in non-metropolitan areas.

Consideration of these methodological issues will become increasingly important as area-based research moves from studies focusing primarily on the attributes of metropolitan areas where most of the methods have been developed, to non-metropolitan areas with larger and more heterogeneous administrative boundaries, in which the need for area correction may be even more pronounced. Interestingly, the various methods of classifying LUM tended to be most disparate for the outer suburban areas rather than the inner city areas. The role of environments in influencing activity behaviors may differ by degree of urbanization,[44] and it is important to understand how broadly applicable measurement approaches developed primarily in metropolitan areas are in order to validly compare metropolitan and non-metropolitan environments.[4]

While we can conclude that the consideration of type of land use and geographical scale can improve LUM measures, our findings should not be used to evaluate the comparative usefulness of the two modifications. The current study employed a simple process of excluding land uses of low relevance to walking for transport, whereas more sophisticated approaches that include all available land uses and that assign different weightings to each land use could further increase the quality of the measures.[18,28] Future studies with sufficient sample sizes for split-half validation could provide useful further refinements to LUM measures. Research is also needed to examine whether a walkability index that includes a refined measure of LUM contributes to a better prediction of residents' physical activity.

We used the CCD as the unit of analysis for area-level measures, the smallest available at the time of the data collection and analysis, which preceded the release of a finer geographical scale (the mesh block) by the Australian Bureau of Statistics.[45] Unfortunately, we cannot examine whether area corrections and restriction of land use types would be equally beneficial when using these smaller geographical areas that may have future use in the environment–physical activity research field. While, we did demonstrate two methods that improve measures of LUM at the CCD level, our methods do not correct for all limitations inherent in the use of administrative boundaries, particularly the possible lack of concordance with individual perceptions of neighborhood boundaries.[41,42] The use of these individually defined neighborhood boundaries may offer an improved alternative, but the utility of this approach in large samples remains to be seen and the loss of spatially compatible census and socioeconomic data must also be considered.

Given our findings, it appears that previous null relationships between CCD-level LUM and walking for transport [22] may have been due to the inclusion of land uses with limited relevance and failing to correct for CCD area size. It also appears that the concurrent validity of entropy-based LUM measures can be improved using these same approaches. Land use mix is not just a research instrument for examining the impact of environments on residents' physical activity, but also a valid planning tool that practitioners and policy makers can use to make neighborhoods more conducive to active lifestyles. Accurate assessment of LUM and development of more precise benchmarks through further research may be needed to assist informed decisions about the planning and design of activity-friendly neighborhoods, which should be helpful in improving the long-term health of residents.

ACKNOWLEDGEMENTS

The PLACE study was supported by National Health and Medical Research Council (NHMRC) of Australia Project Grant #213114, by NHMRC Program Grant #301200 (Owen) and by a Research Infrastructure Grant from Queensland Health. Sugiyama is supported by a Capacity Building Grant in Population Health (#252799) from the NHMRC. Leslie is supported by an NHMRC Public Health Fellowship (#301261).

REFERENCES

1. Frank LD, Engelke PO, Schmid TL. *Health and community design*. Washington: Island; 2003.
2. Wendel-Vos W, Droomers M, Kremers S, Brug J, van Lenthe F. Potential environmental determinants of physical activity in adults: a systematic review. *Obes Rev*. 2007; 8: 425-440.
3. Saelens BE, Handy SL. Built environment correlates of walking: a review. *Med Sci Sports Exerc*. 2008; 40: S550-S566.
4. Sallis JF, Cervero RB, Ascher W, Henderson KA, Kraft MK, Kerr J. An ecological approach to creating active living communities. *Annu Rev Public Health*. 2006; 27: 297-322.
5. Heart and Stroke Foundation of Canada. *The built environment, physical activity, heart disease and stroke*. Ottawa: Heart and Stroke Foundation of Canada; 2007.
6. Cavill N. *Building health: creating and enhancing places for healthy active lives: what needs to be done?* London: National Heart Forum; 2007.
7. National Heart Foundation of Australia. *Heart Foundation Position statement: The built environment and walking*. Canberra: National Heart Foundation of Australia; 2009.
8. National Institute for Health and Clinical Excellence. *NICE public health guidance 8: Promoting and creating built or natural environments that encourage and support physical activity*. London: National Institute for Health and Clinical Excellence; 2008.
9. Handy SL, Boarnet MG, Ewing R, Killingsworth RE. How the built environment affects physical activity: views from urban planning. *Am J Prev Med*. 2002; 23: 64-73.
10. Giles-Corti B, Timperio A, Bull F, Pikora TJ. Understanding physical activity environmental correlates: increased specificity for ecological models. *Exerc Sport Sci Rev*. 2005; 33: 175-181.
11. Owen N, Humpel N, Leslie E, Bauman A, Sallis JF. Understanding environmental influences on walking: review and research agenda. *Am J Prev Med*. 2004; 27: 67-76.
12. Sallis JF, Owen N, Fisher EB. Ecological models of health behavior. In: Glanz K, Rimer BK, Viswanth K, eds. *Health behavior and health education: theory, research, and practice*. 4th ed. San Francisco: Jossey-Bass; 2008.
13. Brownson RC, Hoehner CM, Day K, Forsyth A, Sallis JF. Measuring the built environment for physical activity: state of the science. *Am J Prev Med*. 2009; 36: S99-S123. e112.
14. Cervero R, Duncan M. Walking, bicycling, and urban landscapes: evidence from the San Francisco Bay Area. *Am J Public Health*. 2003; 93: 1478-1483.
15. Frank LD, Kerr J, Sallis JF, Miles R, Chapman J. A hierarchy of sociodemographic and environmental correlates of walking and obesity. *Prev Med*. 2008; 47: 172-178.
16. Li F, Harmer PA, Cardinal BJ, et al. Built environment, adiposity, and physical activity in adults aged 50–75. *Am J Prev Med*. 2008; 35: 38-46.
17. Rodriguez DA, Evenson KR, Diez Roux AV, Brines SJ. Land use, residential density, and walking the multi-ethnic study of atherosclerosis. *Am J Prev Med*. 2009; 37: 397-404.
18. Frank LD, Schmid TL, Sallis JF, Chapman J, Saelens BE. Linking objectively measured physical activity with objectively measured urban form: findings from SMARTRAQ. *Am J Prev Med*. 2005; 28: 117-125.
19. Hayashi T, Tsumura K, Suematsu C, Okada K, Fujii S, Endo G. Walking to work and the risk for hypertension in men: the Osaka Health Survey. *Ann Intern Med*. 1999; 131: 21-26.
20. Hu G, Qiao Q, Silventoinen K, et al. Occupational, commuting, and leisure-time physical activity in relation to risk for Type 2 diabetes in middle-aged Finnish men and women. *Diabetologia*. 2003; 46: 322-329.

21. Hamer M, Chida Y. Active commuting and cardiovascular risk: a meta-analytic review. *Prev Med*. 2008; 46: 9-13.
22. Cerin E, Leslie E, du Toit L, Owen N, Frank LD. Destinations that matter: associations with walking for transport. *Health Place*. 2007; 13: 713-724.
23. Forsyth A, Hearst M, Oakes JM, Schmitz KH. Design and destinations: factors influencing walking and total physical activity. *Urban Stud*. 2008; 45: 1973.
24. Riva M, Apparicio P, Gauvin L, Brodeur JM. Establishing the soundness of administrative spatial units for operationalising the active living potential of residential environments: an exemplar for designing optimal zones. *Int J Health Geogr*. 2008; 7: 43.
25. Gauvin L, Robitaille E, Riva M, McLaren L, Dassa C, Potvin L. Conceptualizing and operationalizing neighbourhoods: the conundrum of identifying territorial units. *Can J Public Health*. 2007; 98: S18-26.
26. Wilson DK, Kirtland KA, Ainsworth BE, Addy CL. Socioeconomic status and perceptions of access and safety for physical activity. *Ann Behav Med*. 2004; 28: 20-28.
27. McCormack GR, Giles-Corti B, Bulsara M. The relationship between destination proximity, destination mix and physical activity behaviors. *Prev Med*. 2008; 46: 33-40.
28. Frank LD, Sallis JF, Saelens BE, et al. The development of a walkability index: application to the neighborhood quality of life study. *Br J Sports Med*. 2009; 29: 224.
29. Owen N, Cerin E, Leslie E, et al. Neighborhood walkability and the walking behavior of Australian adults. *Am J Prev Med*. 2007; 33: 387-395.
30. Badland HM, Schofield GM, Witten K, et al. Understanding the Relationship between Activity and Neighbourhoods (URBAN) Study: research design and methodology. *BMC Public Health*. 2009; 9: 224.
31. Zhang M, Kukadia N. Metrics of urban form and the modifiable areal unit problem. *Transportation Research Record: Journal of the Transportation Research Board*. 2005; 1902: 71-79.
32. Australian Bureau of Statistics (ABS). *Australian Standard Geographical Classification (ASGC) 2000. 1216.0*. Canberra: Australian Bureau of Statistics; 2005.
33. Guo JY, Bhat CR. Operationalizing the concept of neighborhood: application to residential location choice analysis. *J Tran Geo*. 2007; 15: 31-45.
34. Moudon AV, Lee C, Cheadle AD, et al. Operational definitions of Walkable neighborhood: theoretical and empirical insights. *J Phys Act Health*. 2006; 3: 99.
35. Openshaw S. Ecological fallacies and the analysis of areal census data. *Environ Plann A*. 1984; 16: 17-31.
36. Leslie E, Coffee N, Frank L, Owen N, Bauman A, Hugo G. Walkability of local communities: using geographic information systems to objectively assess relevant environmental attributes. *Health Place*. 2007; 13: 111-122.
37. Cancer Prevention Research Centre, School of Population Health. *Physical Activity in Localities and Community Environments (The PLACE Project): An Account of Spatially Based Survey Methods and Recruitment Outcomes*. Herston: The University of Queensland; 2005.
38. Australian Bureau of Statistics. *Census of Population and Housing CDATA 2001* [CD-ROM]. Final Release. Canberra: Australian Bureau of Statistics; 2001. http://www.abs.gov.au/.
39. Craig CL, Marshall AL, Sjostrom M, et al. International physical activity questionnaire: 12-country reliability and validity. *Med Sci Sports Exerc*. 2003; 35: 1381-1395.
40. Cervero R, Kockelman K. Travel demand and the 3Ds: density, diversity, and design. *Transportation Res Part D*. 1997; 2: 199-219.
41. Leslie E, Saelens B, Frank L, et al. Residents' perceptions of walkability attributes in objectively different neighbourhoods: a pilot study. *Health Place*. 2005; 11: 227-236.
42. Cerin E, Leslie E, Owen N, Bauman A. An Australian version of the neighborhood environment walkability scale: validity evidence. *Meas Phys Educ Exerc Sci*. 2008; 12: 31-51.

43. Williams RL. A note on robust variance estimation for cluster-correlated data. *Biometrics*. 2000; 56: 645-646.
44. Duncan MJ, Mummery WK, Steele RM, Caperchione C, Schofield G. Geographic location, physical activity and perceptions of the environment in Queensland adults. *Health Place*. 2009; 15: 204-209.
45. Australian Bureau of Statistics. *Information paper: draft mesh blocks Australia, 2005*. Canberra: Australian Bureau of Statistics; 2005.