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Walkability of local communities: Using geographic information systems to objectively assess relevant environmental attributes

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Abstract

Geographic Information Systems (GIS) can be used to objectively measure features of the built environment that may influence adults' physical activity, which is an important determinant of chronic disease. We describe how a previously developed index of walkability was operationalised in an Australian context, using available spatial data. The index was used to generate a stratified sampling frame for the selection of households from 32 communities for the PLACE (Physical Activity in Localities and Community Environments) study. GIS data have the potential to be used to construct measures of environmental attributes and to develop indices of walkability for cities, regions or local communities.
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Background

Physical inactivity is a major risk factor for overweight and obesity, diabetes, heart disease and some cancers (United States Department of Health and Human Services, 1996). In Australia, some 30% of adults are sedentary in their leisure time (Owen and Bauman, 1997) and over 50% are insufficiently active to accrue health benefits (Booth et al., 1997).

Environmental and policy interventions form one of the major strategic approaches to promoting participation in physical activity in industrialised countries (Sallis et al., 1998). While there is some new evidence that supportive attributes of community physical environments can be associated with being more active (Ball et al., 2001; King et al., 2000; Frank and Engelke, 2001), much of that evidence is derived from studies in which self-reported perceptions of environmental attributes are assessed concurrently with self-reported physical activity (Humpel et al., 2002). New research tools from social and spatial epidemiology have the

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potential to add conceptual and methodological rigour to analyses of environment–behaviour relationships (Macintyre et al., 2002).

Researchers in both public health and the urban planning and transportation fields have highlighted the importance of using objective measures to help better understand the relationships between physical environment attributes and physical activity behaviours (Saelens et al., 2003; Sallis et al., 2004; Owen et al., 2004). For example, some studies have used systematic ratings of relevant environmental attributes in specific areas by trained observers (Craig, 2002; Pikora et al., 2002). Others have used Geographic Information Systems (GIS) data to obtain spatial measures of resource accessibility (Giles-Corti and Donovan, 2002a). A review of public health research on the environmental determinants of physical activity in adults found the most consistent evidence for accessibility of facilities, opportunities for activity, and aesthetics (Humpel et al., 2002). However, the majority of studies (15 from 19) were focused on perceived rather than objective measures and only two of the studies reviewed used GIS approaches to construct objective measures of the relevant environmental attributes (Giles-Corti and Donovan, 2002a; Troped et al., 2001).

The study by Giles-Corti & Donovan used a composite measure of spatial access to built and natural recreational facilities (using GIS methods), as well as observer ratings of the functional environment (existence of footpaths and shops) and of the appeal of the environment (street type, tree coverage). They found that spatial access to recreational facilities was positively associated with the likelihood of being physically active. In a cross-sectional study of 400 adults in Massachusetts, Troped and colleagues found that GIS-based measures of distance to bikeways and steep hill barriers were both negatively associated with bikeway use (Troped et al., 2001).

In recent Australian studies, geographical location based on objectively determined place of residence (coastal as opposed to inland) was found to be associated with increased likelihood of being physically active (Bauman et al., 1999; Humpel et al., 2004). The influence of particular attributes of urban form on physical activity was highlighted in a longitudinal study carried out by Krizek in the Central Puget Sound region (Krizek, 2003). This study showed that when exposed to urban environments with different attributes, individuals changed their travel behaviour: relocating to areas with higher neighbourhood accessibility (with more options for transit, walking and cycling) was related to less automobile use.

To better understand how built environment factors can influence participation in physical activity, there is a need to identify and to document objectively, specific attributes of community environments that may be influential. Ecological models of health behaviour suggest that environmental factors should influence the likelihood of being physically active (Sallis et al., 1998; Sallis and Owen, 2002). Such propositions need to be put to rigorous empirical test, using data on objectively determined attributes. For this purpose, recent and emerging developments in the spatial information sciences have much to offer. Objectively documenting differences in environmental attributes between localities (for example, density, land use mix, street connectivity, access to services, etc.) should be helpful in identifying factors that may act to increase or to decrease the probability of people being physically active. Existing data sources and GIS methods may be utilised to develop measures of specific attributes of the built environment for selected spatial units of interest.

Walking is the physical activity behaviour that is currently the main focus of environmental and policy initiatives in public health (Sallis et al., 1998). GIS provides methods that have the potential to facilitate the development of indices of walkability at the local level in cities or regional areas, not only for the purposes of research, but also to evaluate new environmental and policy initiatives (Sallis et al., 1998; Bauman et al., 2002). This paper first outlines the broader uses of GIS methods, focusing particularly on their use in Australian studies concerned with public health. It then describes how a previously developed index of 'walkability' of community neighbourhoods was operationalised in an Australian context (Frank et al., manuscript under review). The GIS-derived walkability index is then used to classify the extent to which the objective physical characteristics of a local neighbourhood may be conducive or not to walking behaviour. Consideration is given to future developments and applications of walkability-related measures in helping to understand environmental influences on health-related behaviours.

Walkability of local communities

While research into factors associated with physical activity has tended to concentrate on demographic and psychosocial variables (Trost et al., 2002), it is argued that environments can influence physical activity behaviours directly (Sallis and Owen, 2002). The influence of attributes of the built environment on habitual behaviour patterns such as walking are not yet well understood by behavioural scientists (Sallis and Owen, 1999), but community design disciplines (particularly transportation and urban planning research) have identified some strong patterns of association (Frank et al., 2003). Some studies have reported the associations between perceived environmental variables and walking (Owen et al., 2004; Frank and Pivo, 1995); however, as yet, there are only a limited number of studies that have used environmental variables derived objectively from GIS data (Giles-Corti and Donovan, 2002a, 2003; Troped et al., 2001, 2003; Kirtland et al., 2003; Frank et al., 2005).

Characteristics of the built environment have important links to the health of communities (Diez Roux, 2003; Evans, 2003; Savitch, 2003). As research on the links between the built environment and physical activity emerges, there is a clear need to not only refine measures used to assess the built environment (Handy et al., 2002) but also to identify the particular dimensions of the built environment which enhance walking behaviour, and to operationalise these dimensions using readily available and reputable data sets. The 'walkability' of a community may be conceptualised as the extent to which characteristics of the built environment and land use may or may not be conducive to residents in the area walking for either leisure, exercise or recreation, to access services, or to travel to work. The index of walkability applied in the PLACE study is designed to predict utilitarian forms of walking to work, shop and other daily destinations rather than walking for recreation and leisure.

Saelens et al. reviewed findings from the transportation, urban design and planning literatures in order to identify the physical elements of local environments that may influence walkability (Saelens et al., 2003). They describe the aspects of local physical environments that are considered to influence walking for transport (Saelens et al., 2003). They argue that the choices to use motorised or non-motorised transport are based on two dimensions of the way land is used, proximity (distance) and connectivity (directions of travel).

Proximity is primarily determined by two key land use variables: density, or compactness of land use; and, land use mix (the degree of heterogeneity with which functionally different uses are co-located in space). The more compact and intermixed an urban environment is, the shorter the distances between destinations. Walking has to compete with other modes of travel and may be a particularly disadvantaged choice with respect to travel distance. The relative utility of walking relative to other modes of travel drops off quickly as distances between destinations increase (Frank, 2004). Distances of less than a $\frac{1}{2}$ mile between residences, shops, employment, and to regional transit service are desirable, if walking is to be a competitive mode of travel (O'Sullivan and Morrall, 1996).

Connectivity measures the directness of the pathway between households, shops and places of employment and is based on the design of the street network. Direct travel is facilitated where there is a lack of barriers (freeways, walls, physical obstacles) and where there are a number of options for travel routes. Where there are many interconnecting streets laid out in a regular grid pattern, walking for transport is facilitated (Saelens et al., 2003; Frank et al., 2003).

The findings from the studies reviewed by Saelens et al. focus on associations with journeys to work, shopping, accessing services and basic transportation. The availability of destinations together with an interconnected street network makes walking a more competitive and attractive mode of travel to other options. While not directly measured to date, the cost, availability, location, and design of parking facilities at destinations is also a critical predictor of travel choice, and impacts the relative travel time required by the car. Many of the same elements of the built environment that impact walking for utilitarian purposes could also explain the choice to walk for leisure, exercise or recreation. The ability to walk for these non-utilitarian purposes also requires pedestrian infrastructure and a street network that connects places of residence with parks and open space. It is important to point out that due to a lack of relevant data, the walkability index does not capture the presence of sidewalks and other critical infrastructure. However, compact and interconnected environments are also more likely to have sidewalks; and through this systematic co-variance, their presence may to some extent be captured by proxy.

What are geographic information systems?

GIS is a computer-based tool for the capture, storage, manipulation, analysis, modelling, retrieval and graphic presentation of spatially referenced information. GIS uses sophisticated databases and software to analyse data by location, revealing hidden patterns, relationships and trends that may not be apparent in spreadsheets or through the use of the standard statistical packages from epidemiology or the social sciences.

Spatial data is referenced to known locations on the Earth's surface. To ensure that location is recorded accurately, spatial data always employ a specific coordinate system, unit of measurement and map projection. A GIS can be conceptualised as a series of layers of information (e.g. population, road networks, land use, shopping centre locations) with each observation in each layer tied to specific points and areas on the earth's surface via a specific coordinate system (e.g. latitude and longitude; see Fig. 1).

GIS involves analysis, which cuts vertically through the relevant information layers, and analyses the relationships between phenomena co-located in space. Provided that the data are spatially referenced (that is, they have a specific coordinate system) or that they relate to a specific spatial unit (for example, a Census Collection District or Block Group) they can be included in the analysis. The methodology and technology of GIS allows these spatial patterns to be visualised in many ways. However, its capacity goes beyond mapping, to include detailed spatial analysis and modelling.

The use of GIS is still somewhat new to public health research and practice. However, it is applicable to a wide range of analyses, such as environmental health studies of atmospheric pollution and chronic disease prevention studies of cancer clusters (Melnick, 2002). In the Australian public health context, GIS has primarily been used to analyse the spread of infectious diseases, to model environmental influences on disease, to identify communities with unusually high or low incidences of disease or illness and to identify communities with low access to health services (Hugo, 1998; Hugo et al., 1999). A promising development in the measurement of environmental features related to physical activity in Australia has been the seminal work conducted by Giles-Corti and colleagues in the Perth metropolitan area (Giles-Corti and Donovan, 2002a, b, 2003). These studies have used objective measures of physical environment attributes to derive measures of spatial accessibility to recreational facilities in a sample of 1800 adults, utilising GIS data to develop individual access indices by geo-coding survey respondents addresses and road network analysis.

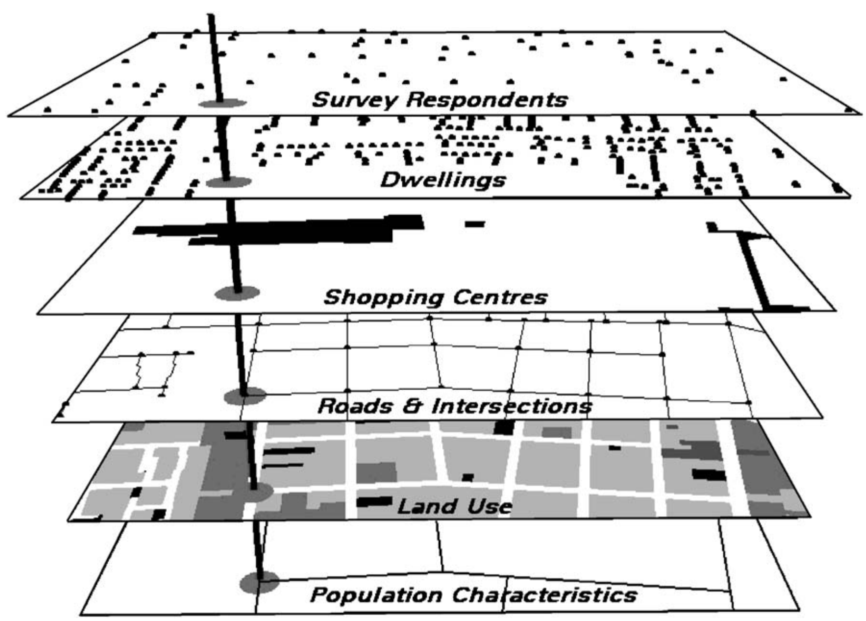

Fig. 1. A Simplified Model of a Geographic Information System. GIS cuts vertically through data layers for analysis at known spatial locations.

Using Australian GIS data to derive a walkability index

The potential walkability dimensions of proximity and connectivity described above can be readily operationalised using GIS methods. A number of approaches have previously been used to measure walkability and the connectivity of different neighbourhood designs (Aultman-Hall et al., 1997; Cervero and Kockelman, 1997; Handy, 1996; Hess, 1997; Greenwald and Boarnet, 2001; Randall and Baetz, 2001). The spatial index of walkability described in this paper is built upon the method originally developed by Frank and colleagues in the USA (Frank et al., manuscript under review), and utilises the most common measures of urban form identified in the transportation, urban design and planning literature (Saelens et al., 2003). This index was developed in the USA for use in the Neighborhood Quality of Life Study (NQLS), and its applications in NQLS are described elsewhere (Frank et al., manuscript under review). The USA and Australian research teams collaborated on the adaptation of the walkability index for use in Australia. The present paper describes the application of the walkability index in Australia for use in the Physical Activity in Localities and Community Environments (PLACE) study, located in the Adelaide Metropolitan Area (Adelaide Statistical Division), South Australia. In order to provide for comparisons between research findings from Australian and the USA, our index uses the individual USA measures, modified to suit basic administrative data, such as the cadastre or road centrelines, that are readily available for Australian cities, and as such includes details of the adaptation of this methodology not available elsewhere.

Selecting the smallest available spatial units

Since there is a considerable amount of environmental variation within cities, ideally the smallest available spatial units should be selected to minimise within-unit variability and to maximise the variation between units. It is common in such analyses to employ the smallest unit for which population census data are made available, since such data are not provided at the unit record level and there is a degree of spatial aggregation to preserve individual privacy. In Australia, this unit is the Australian Bureau of Statistics (ABS) Census Collection District (CCD). At the 2001 Census, there was an average of around 225 dwellings in each CCD, but in rural areas the numbers of dwellings per CCD declines as population densities decrease. The areal size also increases as the population density increases. In 2001, there were 37,209 CCDs across Australia, covering the entire landmass without overlap or omission. Even though the CCD is a basic unit, CCDs differ considerably in both size and population, especially between urban and regional areas.

In the Adelaide Statistical Division (ASD), there were 2150 CCDs as at the 30 June 2001. To remove the influence of size and population variation in CCDs, the Adelaide Statistical Division CCD layer was filtered to include only urban CCDs to remove the influence that larger sparsely populated CCDs would have upon the classification and analysis of walkability. This was based upon the ABS definition of urban CCDs which have a population density of >200 persons per square kilometre and are adjacent or proximal to other urban CCDs.

Spatial data sets

Tax valuation and cadastral (parcel) data, street centreline data, land use, zoning data, shopping centre location data and census data for the ASD were spatially integrated within a GIS to create an environmental characteristic index for each CCD.

Measurement of dwelling density

A point-based dwelling layer is created by selecting residential land use from the valuation data and summing the land area and counting the dwelling number for each CCD in the ASD. Net residential dwelling density is then created by dividing the dwelling count per CCD by the sum of residential land area per CCD.

In order to create a standard measure, the net residential dwelling density per CCD is classified into deciles and the groups recoded from 1 to 10, with the 1st decile value CCDs recoded 1, the 2nd decile CCDs recoded to 2 and so on to the 10th decile, which is recoded to 10. The dwelling density measure is now ready to be included in the walkability index.

Measurement of connectivity

Intersections are identified from the street centreline data and connectivity is based upon the number of unique street connections at each intersection (or the potential for different route choices available at each intersection). Only intersections with 3 or more unique intersecting streets are included in the intersection density calculation. Density is measured based on the number of intersections per square kilometre within each CCD.

As was the case with the dwelling data, intersection density is calculated by CCD (intersection count divided by CCD area) and the resultant densities classified into deciles. An identical recode is used as described in the dwelling method to provide a standard score from 1 to 10, with 1 the least dense CCDs and 10 the most dense CCDs.

Measurement of land use attributes

The land use measure is the most complex to create and calculate and uses two data sets, land-use and zoning. Land use is the activity that is taking place on the land parcel in the view of the valuer, and is the basis for levying land taxes. Zoning is the means used by local government to control the use of land and is typically grouped into broad classes such as residential, industrial, retail, recreation etc. In the land use classification it is valid to have vacant land, or land which is not being used and therefore will not attract a high land tax or council rate. Although the land is not being used, local government will have zoned the land for a specific land use that will control the activity on the land once development occurs. As vacant is a valid land use and these can be large areas that encompass many land use zones, vacant does not provide a classification that can be readily used for measuring land use mix. To overcome the problem of large vacant areas and the potential to skew the land use mix calculation, the underlying local government zoning is used to reclassify vacant parcels to the local government zoning. In this way, the intended land use (zoning) is used in place of the vacant land use for the purpose of calculating the land use mix measure. Once the vacant land is replaced with a land use zone, the land uses are reclassified into the following five classes, residential, commercial, industrial, recreation and other.

The sum of land area by CCD is used to create an entropy score for each CCD, calculated via the following formula, where k is the category of land use; p is the proportion of the land area devoted to a specific land use; N is the number of land use categories:

$$-\frac{\sum_k (p_k \ln p_k)}{\ln N}.$$

The entropy equation results in a score of 0–1, with 0 representing homogeneity (all land uses are of a single type), and 1 representing heterogeneity (the developed area is evenly distributed among all land use categories). The entropy land use score for each CCD is joined to the CCD theme and classified into deciles with the 1st decile recoded to 1 representing CCDs with the least land use mix and the 10th decile recoded to 10 representing CCDs with the most mixed land uses.

Measurement of net retail area

The final measure in the walkability index is net retail area and this measure provides the greatest challenges in finding a suitable data source. While the net retail area measure is a simple ratio, the challenge will be locating a city level data set that will enable the measure calculation. Planning South Australia created a Retail Data Base in 1993, with updates every 3–4 years. The latest available was the 1998 version. The Retail Data Base is a collection of all retail activity in centres with three or more shops or a single shop 250 m^2 or larger. Field survey teams visit all centres and measure the gross retail area, the parcel area, retail activity and a range of other data. It is the gross retail area and the parcel area that are used in this measure as a simple ratio: $NRA = -GRA/P$, where $GRA =$ gross retail area; and, $P =$ total retail parcel area.

The premise for this measure is to calculate the amount of retail floor area in relation to the total amount of land area that serves retail use. As a result, this measure captures the degree to which retail is located near the roadway edge, as is the case in a pedestrian oriented community, or set behind a sea of parking. A ratio of 1 (retail space = total parcel space) or greater than 1 indicates retail areas where less space is devoted to cars and where distances between building entrances, transit, and other activities is shortened. Most importantly, pedestrians in locations with a high retail floor area ratio are less likely to be confronted with dangerous auto dominated environments such as large parking lots that sever sidewalks from building entrances. The net retail area ratio is calculated for each CCD and to standardise for use in the walkability measure the net retail area ratio is classified into deciles and recoded 1 (1st decile) to 10 (10th decile).

Table 1 summarises and illustrates the types of measures used to create the walkability index.

Creating the walkability index

The walkability index is calculated using the above data sets. The 1–10 score for each measure (dwelling density, intersection density, land use and net retail area) is summed for each CCD resulting in a possible score of 4–40. The resulting walkability index is further classified into quartiles with the 1st quartile used to identify low walkability CCDs and the 4th quartile identifying high walkability CCDs. The final walkability indexes are mapped using GIS to visually identify areas in the Adelaide Statistical Division that are conducive or not to walking activities.

Selection of communities for the PLACE study

Once communities representing the highest 25% and lowest 25% of the walkability index had been identified, socio-demographic analysis was undertaken on the basis of census level data. SES was included as a stratification variable because it is inversely related to physical activity in many studies (Sallis and Owen, 2002), built environment may explain SES inequalities in physical activity, and SES differences have not been systematically examined in previous studies (Humpel et al., 2002; Saelens et al., 2003).

The primary data source was the ABS 2001 Census of Population and Housing. Socio-economic measures included household income and labour force status. Median household weekly income was used as the primary SES indicator. Property valuations were used to adjust this categorisation

Table 1
Elements of environmental characteristics and relationships to walking behaviour

Environmental attribute	Implied Relationship with walkability	GIS databases to identify the attribute
Dwelling density	High-density neighbourhoods include mixed-use development—improves accessibility to variety of complementary activities and thus, increased utility Associated with increases in retail and service variety, resulting in shorter, walkable distances between complementary shops and restaurants Driving and parking more difficult and time consuming	Dwellings data
Connectivity	Higher intersection densities are correlated with increased network connectivity, thus providing people with a greater variety of potential routes Higher connectivity provides easier access to major roads where public transport is available Shorter times to get to destinations	Road centre line and intersections data
Land use accessibility and diversity of uses (land use attributes)	People who live near multiple and diverse retail opportunities tend to make more frequent, more specialized and shorter shopping trips, many by walking People who live farther away from retail opportunities are more likely to chain together multiple shopping destinations, and to use a car The more varied the land use mix, the more varied and interesting the built-form, then the more conducive it is to walk to various destinations	Land use data and zoning data, shopping centres
Net area retail	More options for destinations where goods and services may be purchased More local employment opportunities that can be reached by walking	Shopping centres

since some districts can be income poor but asset rich, most notably those with high proportions of retirees. Some CCDs were excluded on the basis of the property valuations to obtain better socio-economic selection. The selection process took account of average age in each CCD. Ethnicity was not an element of socio-demographic selection, as with the changes in Australia's immigration program in the last decade or so, ethnicity is not as strongly associated with SES as it was in the early post war years (Hugo, 2004).

Thirty-two communities comprising contiguous clusters of CCDs that were identified as high or low walkable, and then selected as high or low SES based on census level data, were then selected from 2078 urban CCDs in the ASD. A total of 156 CCDs were represented in these communities. The selected communities were stratified into four study quadrants: high walkable/high SES; low walkable/high SES; high walkable/low SES; and low walkable/low SES. This aimed to facilitate comparison of physical activity level of residents possessing similar SES characteristics, but who live in high or low walkable areas. Subsequent analyses of PLACE data will examine how built environment variables may operate differently for people in high and low SES contexts.

Field validation—how does the walkability index perform?

Field validation was conducted in Adelaide, to check the performance of the walkability index and determine how well the method worked as a means of sorting areas on the basis of environmental attributes which support walking behaviour. The research team spent several days in the field, systematically visiting local areas corresponding with each of the walkability quartiles and selected income ranges. A list of all selected CCD was used to review neighbourhood characteristics and ensure they matched the attributes by which they were selected. This list was then cross-checked with tables containing socio-economic characteristics. To ensure maximum variation between high and low walkable communities, the final selection was made by choosing areas closer to shopping facilities to maximise proximity for the high walkable areas, and areas further from facilities for low walkable areas. The majority of selected areas' physical characteristics accorded with the classification of walkability objectively derived in GIS. Where they did not, they were excluded form the final selection. Through an extensive field observation process, the study team determined that the methodology does return a face-valid means of identifying areas based upon the input characteristics of dwelling data, land use and zoning, intersection data and net retail area. In addition, a study comparing residents' perceptions of walkability attributes in objectively different neighbourhoods at the extremes of walkability, found that residents of high and low walkable neighbourhoods could reliably perceive the differences between them (Leslie et al., 2005).

A few notable anomalies were observed. For example, a new large development in the North East of Adelaide, Golden Grove is characterised by a street pattern which is curvilinear, has many cul-de-sacs, relatively low land use mix and a net retail area which reflects the car dominance of the shopping centres. However, the development has a major pedestrian network which links the housing, schools, recreation areas and shopping that is not reflected in its low walkability index. Another older inner area, Dulwich, has an older grid road pattern, wide tree lined streets, good walking access to shops and recreation, but does not score in the highest quartile of walkability. In these cases, the walkability index is biased by low intersection density and poor land use mix in Golden Grove and low dwelling density and low land use mix in Dulwich.

Future developments and applications of walkability-related measures

The four characteristics utilised in the method described above are a starting point to a more detailed and informed measure of walkability. It is clear there are many other factors linked with walking behaviour, some identified in the research reviewed for this study and others that warrant further consideration. With GIS, the capacity to capture, store, manipulate and analyse different spatial characteristics is largely untapped in the physical activity and environmental influences of physical activity research. The four factors comprising the walkability index that was applied here in an Australian city build largely on research from the transport, urban design and planning fields and are related to active transport. The requirement to create an index similar to the one applied by Frank and colleagues in the USA (in order to allow for cross-country comparisons between studies) prevented the use of other factors. Thus, the index derived serves as a starting point for further work and the development of more comprehensive walking indices to capture other built environment factors related to walking. However, it should be noted that while there may be a range of factors that are worthy of consideration, data is specific to particular areas and it may not be possible to include a large range of the same factors across different areas. It is important to consider the costs associated with some of the data items listed above, as many of these data would require detailed data collection. In addition, validation and survey results are also required to test whether these characteristics are linked with walking behaviours and the extent that a more detailed walking index differs from the less detailed index described in this paper.

A limitation of the method used is that there are likely a number of other related environmental attributes plausibly related to walking that were not included. These include (but are not limited to) the presence of parks and recreation facilities (Pikora et al., 2002; Wendel-Vos et al., 2004), the presence, condition and continuity of footpaths (Handy et al., 2002; Cervero and Kockelman, 1997), accessibility or distances to facilities (Pikora et al., 2002; Giles-Corti and Donovan, 2002b, 2003), transit accessibility (Kitamura et al., 1997), factors related to natural features such as topography and physical barriers (Rodriguez and Joo, 2004), and other aspects of urban design such as building design and orientation, street lighting, planted strips. A more detailed and informed measure of a walkability index could include some or all of these characteristics. Future analyses could examine a wider range of GIS variables for their relation to physical activity, with the eventual aim of creating a more comprehensive walkability index. It may be advisable to develop environmental indices that are specific to each domain of physical activity, such as transportation and recreation.

In addition to the physical features of the built environment, there is some evidence that perceived aspects of the environment, such as aesthetics, also influence walking behaviour (Owen et al., 2004; Humpel et al., 2004; Booth et al., 2000). The extent to which parks, wide verges, linear parks along water courses, coastal parks, and reserves occur within proximity to dwellings will be influential in whether people perceive these locations as being attractive and therefore be willing to engage in recreational walking.

Distances to major services, such as a local shop, post office, public transport, local park and regional park and facilities are also likely to influence choices to make walking trips in local neighbourhoods, as is the presence (or non-presence) of dedicated walking and cycling paths. The extent to which a local environment is considered safe may also have an influence on the extent to which people will be willing to walk (Booth et al., 2000; Centres for Disease Control and Prevention, 1999). This refers to both the density of motorised traffic that has to be encountered in the course of walking and to the exposure to the risk of crime. Having greater access to areas such as public parks and reserves of a substantial size, coastal beaches, national parks and major recreational destinations which are not traversed by roads and which allow uninterrupted walking, are also likely to influence walking choices.

A further development in the application of the walkability index in public health, transport and planning research is to use these characteristics at the individual residence level. Many of the elements involved in the derivation of the index of walkability are applicable at an individual residence level and it would be desirable to calculate the index for each individual residence. This would require identifying the relevant boundaries around each residential location, within which the measures of relevant attributes can be derived and an individual walkability score calculated. This would allow a surface of walkability to be derived and this could then be aggregated to any desired spatial level to protect confidentiality and for further analysis. A measure that includes the additional elements and is built upon the actual residential location may provide a more robust measure built upon a greater range of inputs, is spatially more flexible and can be aggregated to a multitude of geographic scales at the observation, community, sub-area, and regional scale.

Conclusions

There are a wide array of potential applications of GIS methods for guiding environmental and policy initiatives to promote walking and biking, and to increase overall physical activity levels. Increased computing capabilities, in concert with the availability of GIS-based land use and transportation data provide considerable opportunity to develop objective measures of the built environment that form independent predictors of human activity patterns. As demonstrated in the PLACE study in Australia and NQLS study in the USA, a GIS-based methodology can be developed that takes into account several factors that may impact on walkability, in the form of a simple index measure. The walkability index applied here, and its component measures, provides a useful tool for the selection of communities for household recruitment that can maximize the variability in the built environment and result in an improved ability to detect differences in physical activity levels that likely occur in objectively different environments.

The walkability index, and its individual measures, also provides considerable opportunity for other applied policy research. For example, simply mapping the levels of density, mixed use, and connectivity across a city can assist decision makers in where to focus transportation investments and where to guide future growth. The systematic co-variation between the component measures of walkability can inform where opportunities exist to increase physical activity through improved walkability. This occurs where considerable disparities exist between the measures of walkability. For example, places that are compact and mixed in use but offer little ability to traverse between destinations in a direct manner can be detected and targeted for improvements in street connectivity through various approaches to transportation investment including connecting cul-de-sacs, and the completion of sidewalk systems. Places that have high levels of mixed use and good connectivity may be targeted for more residential development and increased density. This sort of a programming tool based on "transportation efficient" or pedestrian and transit supportive land use planning is ripe for investigation (Ewing and Cervero, 2001). With increasingly scarce funds for transportation improvements, the identification of targeted areas for investments that have the potential to offset auto use and relieve traffic congestion and air pollution would be seen as cost effective. Such trans-disciplinary approaches to research on the built environment and its impacts on health and quality of life are sorely needed to address contemporary public health and environmental issues (Frank et al., 2004, 2005).

Future research from the PLACE study will link individual-level behavioural data with the objective environmental data derived for communities. This will support the assessment of possible relationships between walking and other forms of physical activity and objective attributes of the built environment. A key aspect of this study is that the method for deriving a walkability index, though developed in the USA (Frank et al., manuscript under review), appears to be highly applicable to Australia. The index may be generalizable to other countries, but the requirement for detailed land use and census data can limit the ability for others to directly apply it to the degree that was possible in the current study. However, increasing emphasis on the application of GIS-based methods to guide and support urban planning and infrastructure investment decisions in both the private and public sectors has increased presence of required data and capacity for this type of research. Investigators in other locations with suitable data sources are encouraged to apply these methods so that the data on neighborhood walkability can be compared across a variety of countries and associated cultural and institutional contexts. Results will inform decision makers of the efficacy of sustainable development in the promotion of active forms of transportation and in the mitigation of adverse public health impacts of urban form.

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