DISSERTATION

Walkability and Public Health

Development of GIS-based indicators of walkability for surveillance and planning purposes in the city of Graz

submitted by

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Graz, August, 2014 ________________________________

Declaration

I hereby declare that this thesis is my own original work and that I have fully acknowledged by name all of those individuals and organisations that have contributed to the research for this thesis. Due acknowledgement has been made in the text to all other material used. Throughout this thesis and in all related publications I followed the guidelines of “Good Scientific Practice”.

Graz, August, 2014 ________________________________

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Abbreviations

AUS	Australia
BMI	Body Mass Index
BRFSS	Behavioral Risk Factor Surveillance System
BEPAS	Belgian Environmental Physical Activity Study
CB	Circular buffer
CI	Confidence interval
d/m	Days per month
FAR	(Retail or commercial) floor area ratio
GIS	Geographic information systems
IQR	Interquartile Range
IPEN	International Physical Activity and Environment Network
min/w	Minutes per week
met	Metabolic equivalent of task
nbh	Neighbourhood
NQLS	Neighbourhood Quality of Live Study
NWB	Street network buffer
PLACE	Physical Activity in Localities and Community Environments
OR	Odds ratio
SES	Socio-economic status
SMARTRAQ	Strategies for Metropolitan Atlanta's Regional Transportation and Air Quality
Twalk	Walking for transport
Tbike	Biking for transport
US	United States
UK	United Kingdom

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Zusammenfassung

Die bebaute Wohnumgebung gilt als eine relevante Determinante der Gesundheit der ansässigen Bevölkerung. Ein Zusammenhang zwischen der Bewegungsfreundlichkeit bzw. der Walkability (gemessen mit geographischen Informationssystemen (GIS) und definiert als Dichte, Landnutzungsmischung und Konnektivität) und körperlicher Aktivität, im Speziellen Zufußgehen, wurde in zahlreichen Studien, vor allem in den USA und in Australien, belegt. Weniger ist über den Zusammenhang zwischen der Walkability und anderen gesundheitsbezogenen Ergebnissen - im Speziellen in Europa und in Österreich - bekannt. Darüberhinaus könnten auf GIS basierende Walkability-Indikatoren auch in Public Health Surveillance Systemen und in der Planung eingesetzt werden, weil sie auf Routinedaten basieren, relativ einfach zu analysieren und zu verstehen sind. Das Ziel der vorliegenden Studie war es, GIS basierende Walkability-Indikatoren, die für die Gesundheit der Bevölkerung und daher für Surveillance und Planung relevant sind, für die Stadt Graz zu entwickeln. Die Forschungsfrage war: welche GIS basierende Walkability-Indikatoren der Wohnumgebung zeigen konsistent einen Zusammenhang mit gesundheitsbezogenen Ergebnissen bei Erwachsenen und sind deshalb relevant für Public Health Surveillance und Planung?

Basierend auf den Ergebnissen einer systematischen Literaturanalyse wurden Walkability-Indikatoren ausgewählt und in einer Querschnittsstudie mit gesundheitsbezogenen Ergebnissen in Zusammenhang gesetzt. Hierfür wurden repräsentative und sekundäre Befragungsdaten aus dem Projekt ‚Radfreundliche Stadt' (n=843) und Geodaten der Stadt Graz herangezogen. Walkability wurde definiert als *Bevölkerungs- und Haushaltsdichte, Entropie-Index, Prozentanteil der Fläche mit gemischter Landnutzung, Strassenkreuzungsdichte mit mindestens drei beziehungsweise mit mindestens vier Schenkeln* sowie auf diesen Parametern beruhende Indizes (*IPEN walkability index* und ein neu entwickelter *Graz walkability index*). Die untersuchten gesundheitsbezogenen Ergebnisse waren Zufußgehen zu Transportzwecken, Zufußgehen allgemein, Radfahren zu Transportzwecken,

aktive Mobilität, BMI, selbst-berichteter Gesundheitszustand und Zufriedenheit mit der Nachbarschaft. Als Confounder wurden Geschlecht, Alter, sozio-ökonomischer Status und der Wohnort innerhalb von Graz berücksichtigt. Die Wohnumgebung wurde defininert als kreisrunder 1000m Buffer und 1000m und 1500m Buffer entlang des Strassennetzes. Bivariate, kontrolliert bivariate und multivariate Regressionsanalysen wurden durchgeführt.

Die systematische Literaturanalyse zeigte einen konsistenten Zusammenhang zwischen Walkability-Indikatoren und Zufußgehen zu Transportzwecken. Weniger klar waren die Zusammenhänge zwischen Walkability und anderen gesundheitsbezogenen Ergebnissen. Auch der empirische Teil der vorliegenden Arbeit zeigte innerhalb der erwachsenen Bevölkerung in Graz einen Zusammenhang zwischen der Walkability des Wohnumfelds und gesundheitsbezogenen Ergebnissen. Ein positiver Zusammenhang zwischen den Walkability Indikatoren und Radfahren zu Transportzwecken, aktiver Mobilität und der Nachbarschaftszufriedenheit mit der Infrastruktur konnte konsistent festgestellt werden. Die durchschnittliche Nachbarschaftszufriedenheit, die Nachbarschaftszufriedenheit mit der sozialen und umweltbezogengen Qualität sowie mit dem sozialen Zusammenhalt war negativ mit der Walkability assoziert. Keine oder kaum Zusammenhänge konnte zwischen der Walkability und Zufußgehen zu Transportzwecken, Zufußgehen allgemein, BMI und selbst-berichteter Gesundheitszustand gefunden werden. Die Walkability-Indikatoren *Haushaltsdichte, Prozentanteil der Fläche mit gemischter Landnutzung, Strassenkreuzungsdichte mit mindestens vier Schenkeln* und der neu entwickelte *Graz walkability index* zeigten die statistisch stärksten und häufigsten Assoziationen mit gesundheitsbezogenen Ergebnissen. In der Subgruppenanalyse waren die oben genannten Zusammenhänge vor allem bei männlichen (weniger bei weiblichen), bei jüngeren (weniger bei älteren), bei sozio-ökonomisch besser gestellten (weniger bei sozio-ökonomisch schlechter gestellten) und bei im Osten (weniger bei im Westen) der Stadt wohnenden Personen zu beobachten.

Nachdem die Walkability-Indikatoren konsistent Zusammenhänge mit einigen gesundheitsbezogenen Ergebnissen zeigten und die meisten Kriterien für Public Health Surveillance Indikatoren erfüllten, wurde die Schlussfolgerung gezogen, dass die Walkability-Indikatoren für Surveillance und Planung in Betracht gezogen werden sollen. Als nächster Schritt zur Integration der Walkability-Indikatoren in Surveillance und Planung wäre eine Konsensfindung zwischen Entscheidungsträgern aus den Bereichen Public Health, Stadt- und Verkehrsplanung empfehlenswert. Übereinstimmung sollte darin gefunden werden, welche Indikatoren für Surveillance und Planung für die Stadt Graz sinnvoll und nützlich sind. Im Allgemeinen ist weitere Forschung zum Zusammenhang zwischen Walkability und Radfahren zu Transportzwecken und Nachbarschaftszufriedenheit erforderlich. Weiters bedarf der Unterschied im Zusammenhang zwischen Walkability und gesundheitsbezogenen Ergebnissen nach sozio-ökonomischen Status weiterer Untersuchungen.

Abstract

The built environment is considered to be one determinant of health. Walkability (defined as a combination of density, land-use mix and connectivity) measured by geographic information systems (GIS) has been shown to be associated with physical activity, especially walking. However, little is known about the association between walkability and health-related outcomes in Europe, and especially in Austria. Furthermore, GIS-based walkability has the potential to be used for surveillance and planning, since it is based on routine data and simple measures. The aim of this study was to develop GIS-based indicators of walkability that are relevant to public health for surveillance and planning purposes in Graz. The research question was: which GIS-based measures of residential neighbourhood walkability in the city of Graz are consistently associated with health-related outcomes among adults and are therefore relevant to public health surveillance and planning?

After conducting a systematic literature review on walkability indicators related to health-related outcomes, a cross-sectional study was undertaken. Based on both representative and secondary survey data from the Radfreundliche Stadt (n=843) and geodata, the association between walkability (defined as *gross-population density*, *household-unit density, entropy-index, proportion of mixed-land use, three-way intersection density* and *four-way intersection density,* respectively, *IPEN walkability index* and *Graz walkability index*) and health-related outcomes was investigated. Health-related outcomes were defined as walking for transport, general walking, cycling for transport, active modes of transport, BMI, self-rated health, and mean neighbourhood satisfaction, as well as neighbourhood satisfaction with social environmental quality, social cohesion and infrastructure. Covariates were sex, age, socio-economic status and place of residence. For these characteristics, sub-group analysis were conducted. The residential neighbourhood was defined as a circular buffer of 1000m and as street network buffers of 1000m and 1500m. Bivariate, bivariate-controlled and multivariate regression analysis were conducted.

The literature research found a consistent association between walkability and walking for transport, while the associations between walkability and other health-related outcomes was less clear. The results from the present empirical study demonstrate that walkability is associated with health-related outcomes within the adult population of Graz. There was a consistent positive association between the walkability indicators and biking for transport, active modes of transport and neighbourhood satisfaction with infrastructure. Mean neighbourhood satisfaction and neighbourhood satisfaction with both social-environmental quality and social cohesion was negatively associated with walkability. No or almost no associations between walkability and walking for transport, general walking, BMI and self-rated health were found. The walkability measures *household unit density, proportion of mixed land use, four-way intersection density* and the newly developed *Graz walkability index* showed the strongest associations between walkability and health-related outcomes. The sub-group analysis found more often an association between walkability and health-related outcomes among men than among women, among younger respondents than among older respondents, among respondents with a high socio-economic status than among respondents with a low socio-economic status and among respondents residing in the East part of the city than among respondents residing in the West part of the city.

Since the walkability indicators have shown consistent associations with some health-related outcomes and fulfil most criteria for public health surveillance indicators, it was concluded that these indicators should be considered for surveillance and planning. In order to incorporate the implementation of the walkability indicators into the surveillance and planning system, a consensus exercise should be conducted with stakeholders from public health, urban and transport planning. Agreement should be achieved which indicators are useful and meaningful for surveillance and planning in Graz. Additionally, the social gradient in the association between walkability and health-related outcomes in Graz merits further exploration. Generally, further research investigating the association between walkability and biking for transport and neighbourhood satisfaction is needed.

1 Introduction

Social ecological theories reason that built environment is one important determinant of health. For example, the model of Northridge, Sclar and Biswas (2003) on determinants of health identifies built environment as a determinant of health on the community level, which determines health behaviours such as dietary practices and physical activity but also social integration and social support. Health behaviours and social integration and support (determinants on the interpersonal level) in turn determine health outcomes such as obesity, cardiovascular diseases, diabetes, mental health and well-being. These theoretical concepts are supported by evidence that shows associations between the built environment and health, even though causality still has yet to be proven. Renalds, Smith and Hale (2010) found in their review that residents of walkable neighbourhoods are more physically active and less overweight, and report higher social capital and lower rates of depression.

The association between the built environment and physical activity has been a particular area of investigation over the last ten years, although mainly in cross-sectional studies. The results support the theoretical hypothesis that physical activity is a correlate of the built environment (Wendel-Vos et al., 2007, Duncan, Spence and Mummery, 2005, Durand et al., 2011, McCormack and Shiell, 2011, Badland and Schofield, 2005, Bauman and Bull, 2007, Butler et al., 2011, Ewing and Cervero, 2010). In particular, reviews that use only walking as an outcome have found supportive results (Saelens and Handy, 2008, Saelens, Sallis and Frank, 2003, Owen et al., 2004). Furthermore, studies using specific types (e.g. walking, cycling) and specific domains (e.g. transport, recreation) of physical activity and specific features of the built environment (e.g. function, aesthetic, safety) were more likely to find asscoiations (Owen et al., 2004). Saelens and Handy (2008) concluded that density, land-use mix and proximity are consistent correlates of walking for transport but not of walking for recreation or of total amount of walking. They also found mixed evidence on the association between connectivity and walking. However, most studies on the association between built environment and physical activity (Fraser and Lock, 2011, McCormack and Shiell, 2011) have been undertaken in the US, where the layout of cities is very different from Europe. More research across Europe is therefore needed.

The available evidence also indicates that there is an association between built environment and obesity (Papas et al., 2007, Sallis and Glanz, 2009). However, since evidence from single studies is very heterogenous, and issues related to theory, study design, methods, measurement and analysis remain, no conclusive results are available (Durand et al., 2011, Feng et al., 2010).

Researchers in the field of environmental psychology and urban planning and design have investigated the association between urban environments and sociability (Lund, 2003). Frumkin, Frank and Jackson (2004) argued that urban sprawl undermines social capital. Car-oriented neighbourhoods increase commuting and segregate communities, thereby reducing oppertunities for social interaction. Reviews show emerging evidence, that supports the association between built environment and social capital (Renalds, Smith and Hale, 2010, Wood and Giles-Corti, 2008). However, the evidence is equivocal, and further research is needed to investigate which features of the built environment are correlates of social capital. Neighbourhood walkability – as Frumkin, Frank and Jackson (2004) also argue – may be one design factor associated with social capital (Wood and Giles-Corti, 2008).

Built environment may also be a determinant of physical health, such as lower cardiometabolic risk (Coffee et al., 2013) and lower rates of coronary heart disease (Griffin et al., 2013). Since self-rated health is considered to be a predictor of a range of these diseases (Anon, 2007, NN, 2007), it may also be related to the built environment. Few studies of self-rated health measured by the SF-12 have found associations between walkability and physical (Tomey et al., 2013) and mental health (Sallis et al., 2009). Rohrer, Pierce and Deninson (2004) also found an association between perceived walkability and self-rated health among primary care patients. Even though causal relationships are not always clear, the association between self-rated health and the built environment should be explored.

Even though the built environment is considered to be an important determinant of health, there is currently no agreement on the theory of the built environment (Giles-Corti et al., 2005). Different models for explaining the association between built environment and health, and especially physical activity, have been developed in a wide range of disciplines (Giles-Corti et al., 2005, Sallis and Glanz, 2009). In the transport and urban planning field advanced behaviour-specific concepts have been developed to explain walking for transport (Giles-Corti et al., 2005). In addition, the walkability of the residential neighbourhood defined as density and proximity of activities is a rather well developed and empirically tested concept.

However, issues regarding the measurement of the built environment remain (Brownson et al., 2009). Perceived measures reported by respondents, observational measures reported by researchers (community audit) and objective measures (using geographical information systems) can be used. Brownson et al. (2009) identified a lack of clarity and large degree of variability in the operationalisation of GIS-based measures. They argue that explicit operational definitions should be standardized. Frank et al. (2005, 2006) developed walkability measures that have been tested in different studies and in different contextes mainly in the US, but also in Australia and in individual European countries (Frank et al., 2009, Frank et al., 2005, Van Dyck et al., 2010). To develop a common set of environmental measures, replication in various populations and contexts is necessary (Sallis and Glanz, 2009). Similar studies in different countries should be undertaken to validate the walkability measures and to enable pooled analysis (Frank et al., 2009). Since the built environment differs largely between the US and Europe, there is a particular need for European studies (Fraser and Lock, 2011, Rottmann and Mielck, 2013, Van Dyck et al., 2010).

Further development of the measurement of the built environment and its association with health is the precondition to devising interventions for the creation of health supporting environments. Even though reviews to date have found only a small part of the variation in health explained by the built environment, from a public health perspective, the modification of even this small part can have a large impact across the population (Owen et al., 2004, Saelens, Sallis and Frank, 2003). High-walkability neighbourhoods can add 15-30 walking minutes per week per residents (Saelens, Sallis and Frank, 2003). This is a small effect on an individual level, but it could have a large public health effect. Modifying the built environment can have a permanent impact on the whole population living in this environment, especially groups that are hard to reach by individual-oriented programms. By creating a health promoting built environment the healthier choice becomes the easier choice.

To create a health promoting built environment action in urban planning and transport policy are particularly important. The task of health policy is to reach out to these sectors for collaboration and multisectorial cooperation. However, in order to fulfill this task and to have a reliable foundation for data-based decisionmaking information systems are needed. Public health surveillance should therefore be complemented by data about the built environment (Parker et al., 2010). Public health surveillance is „the continuous, systematic collection, analysis and interpretation of health-related data needed for the planning, implementation, and evaluation of public health practice" (WHO, 2013). Because of the continuous nature of public health surveillance, it is usally based on routine data. Routine data is permanently collected by public services and should be readily available to users at a low cost (HealthKnowledge, 2011). Since surveys or audits of the built environment are rather labour and cost intensive, it is difficult to integrate them into routine data collection systems. However, GIS data is readily available at low cost. Therefore, GIS-based indicators for the built environment are considered to have the potential to be integrated into public health surveillance systems (Brownson et al., 2009). To enable integration of GIS-based indicators for the built environment into public health surveillance, valid and reliabel indicators need to be developed (Northridge, Sclar and Biswas, 2003, Parker et al., 2010). This development should be supported by a theoretical literature review (Dannenberg et al., 2003).

Furthermore, the literature-based indicators (especially on walkability) should be measured in diverse neighbourhoods and their relationship to a variety of health measures (e.g. like physical activity, obesity, social engagement, neighbourhood satisfaction) (Dannenberg et al., 2003, Srinivasan, O'Fallon and Derray, 2003). Consequently, the development of GIS-based indicators of the built environment, that show an association with population health and can be recommended for public health surveillance and planning in Europe is a relevant research area.

Graz, the second largest city in Austria, provides good preconditions to investigate the association between walkability and health-related outcomes in an European context. In 2006, Graz had 247,448 inhabitants. The median population density was 2,055 inhabitants per square kilometer. Graz has a well-developed and well-functioning public transit system. Furthermore, Graz is considered to be a very biking-friendly city with a rather good cycling infrastructure. Sixteen percent of all travel is done by bike (Bundesministerium für Verkehr, 2010). This is the second highest proportion of the larger cities in Austria, and it increased steadily between 1982 and 2008 (City of Graz, 2014). In the same time span, the share of walking trips for all trips decreased significantly from 31% in 1982 to 19% in 2008. This change was accompanied by an increase in trips done by private motor vehicle (City of Graz, without date).

The Mur river splits Graz into western and eastern halves. The city features a rather mild Mediteranean climate. The outlying districts – especially in the Northeast – have significant green space and forests. However, the inhabitants of the inner districts also have parks and green space available. The largest green space in the middle of the city is the area around the Schloßberg and the city park. Graz follows the typical pattern of an European city, which features an old town in the centre, characterised by small streets, medieval houses and pedestrian areas. As the inner districts do not have much space for parking, walking, using public transit and cycling are encouraged. The outer districts, in turn, are characterised by residential areas, including areas with single-family houses, but also semi-detached houses and apartment houses.

The city of Graz has placed an emphasis on bicycle policies, with the aim of increasing the use of cycling as a means of transport. The study Radfreundliche Stadt was conducted to further these policies. This study investigated cycling for transport among adults and its determinants (Titze et al., 2006). Part of the study was a large representative survey that also included questions on health and health-related outcomes. Furthermore, Graz has rather well developed and complete GIS data.

Therefore, the situation in Graz provides a good oportunity to develop GIS-based indicators of the built environment that are relevant to public health for surveillance and planning purposes.

2 Theory

Despite an impressive increase in the number of studies investigating the associations between GIS-based measures of the built environment and health outcomes (especially physical activity), the theoretical basis is still weak (Lee and Moudon, 2006). There is a widespread lack of a clear theory of the mechanisms linking neighbourhood and health, and a related lack of hypothesis-driven anlysis of the physical environment is wide spread (Macintyre, Ellaway and Cummins, 2002). In particular, studies using GIS-based measures are considered to be mainly exploratory and not hypothesis driven (Diez Roux, 2007). GIS-based measures for the built environment show a large degree of variability, which hinders comparisons between studies and countries (Brownson et al., 2009). Consequently a theoretical conceptualisation of the built environment and a restriction to one specific theoretical approach seems necessary to define a clear and answerable research question.

2.1 Defining built environment as walkability

To find an adequate working definition of walkabilty, a literature analysis was undertaken to identify sources that aim to define and conceptualise walkability, as well as sources that that aim to summarize GIS-based empirical results. As an analysis framework, the model created by Pikora et al. (2003) was used to enable comparison between different theoretical and empirical approaches. This model was chosen because it is the most comprehensive one currently available, and it is useful for attempts to separate different conceptual elements from each other (Pikora et al., 2003). The model describes physical environmental factors that may influence walking for recreation and mentions four features of a walkable physical environment: functional, safety, aesthetic and destination. The functionality features are the walking surface, streets, traffic and permeability. Saefty features include personal and traffic safety. Aesthetical features consider the streetscape and views, and destination features are related to the availability of facilities. Table 1 provides an overview of the comparison of different approaches to conceptualising walkability.

When examining studies that either explicitly use the term walkability or investigate factors associated with walking, it becomes obvious that a clear, theory-based definition of walkability is lacking (Southworth, 2005). Numerous studies into the influences on walking do not clearly define their understanding of walkabilty, other than the operationalised measures used therein. In some cases, walkability is simply defined as the feasibility and appeal of walking (Leyden, 2003, Lovasi et al., 2009) or the availability of convenient places to walk (Rohrer, Pierce and Deninson, 2004) (see Table 1). Other definitions go a step further by emphasising the availability of destinations as one feature of walkability. Coleman et al. (2008), for instance, state that „walkability describes the ability of a resident to walk from home to nearby destinations“ (p. 310). Meanwhile, Cutts et al. (2009) stress the importance of „neighborhood form and function for walking as a means of recreation and transport“ (p. 1314).

The definition of walkability is further differentiated by Leslie et al. (2007), who do not only include feasibility of walking, destinations and different domains of walking in the definition of walkability, but also add that walkability is a characteristic of the built environment and land use. Land use as an important measure from urban planning and transport is explicitly incorporated in this definition. Walkability is defined 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“ (Leslie, 2007, p. 113).

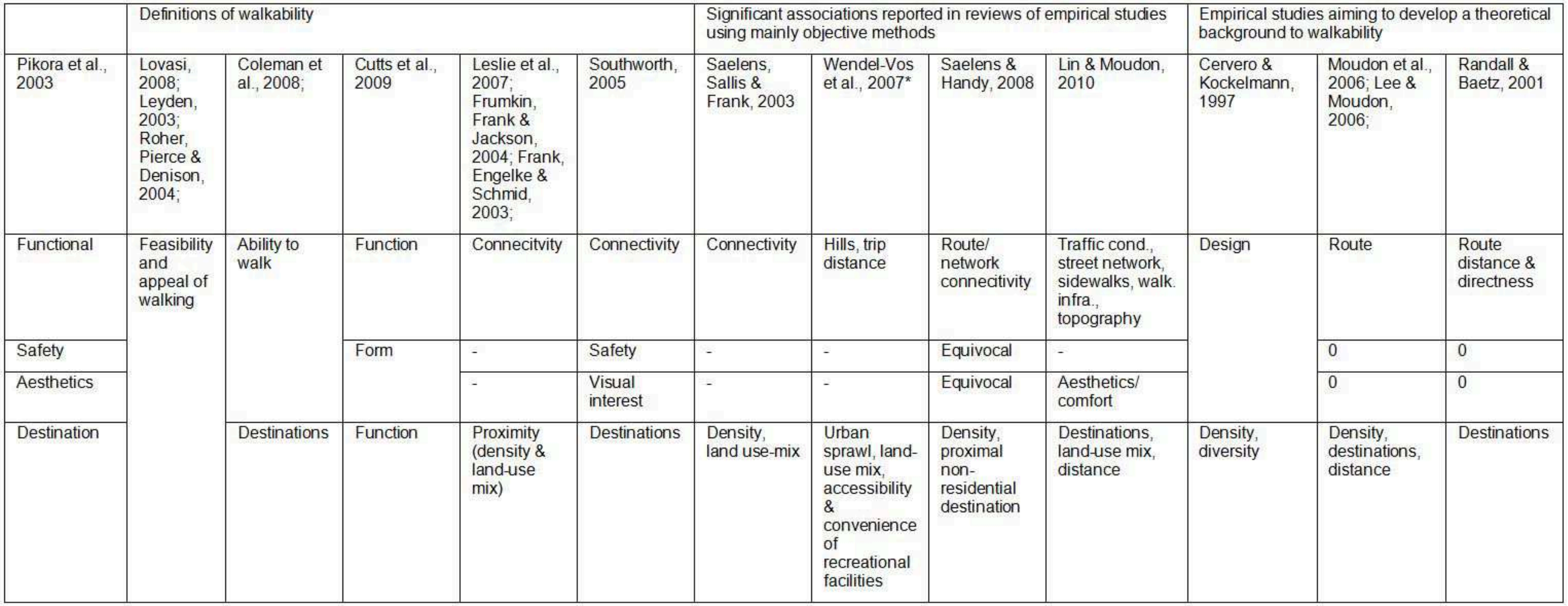
This definition is based on a research tradition in urban planning and transport that is summarised by Frumkin, Frank and Jackson (2004) and Frank, Engelke and Schmid (2003). They argue that there are two fundamental aspects of walkability: proximity to destinations and connectivity (Owen et al., 2007, Frank, Engelke and Schmid, 2003, Frumkin, Frank and Jackson, 2004). Proximity is determined by density and land-use mix (Frumkin, Frank and Jackson, 2004, Owen, 2007), while density measures the „quantity of people, households or jobs distributed over a unit of area“ (Frumkin, Frank and Jackson, 2004, p. 6). In densely populated neighbourhoods, utilitarian trips (e.g. visiting friends or family) are shorter and more convenient (Saelens, Sallis and Frank, 2003). Land-use mix can be seen as a complement to density (Frumkin, Frank and

Jackson, 2004). It measures different types of land use, such as residential and commercial uses. In mixed neighbourhoods, the distance to different utilitarian destinations will be shorter and more convenient for walking and biking than in single-use neighbourhoods (Saelens, Sallis and Frank, 2003). As the second fundamental aspect of walkability, connectivity measures the linkage between destinations. The term mainly refers to the street arrangements, with a grid pattern showing the greatest connectivity with good directness and a wide variety of routes (Owen, 2007, Frumkin, Frank and Jackson, 2004). Furhermore, connectivity is usually discussed in relation to the street network. Frumkin, Frank and Jackson (2004) argue, that street connectivity is the primary design measure because most modes of travel occur on streets, and therefore they are of central importance in terms to travel patterns. This argumentation is supported by empirical findings that show that there are consistent associations between walking for transportation and connectivity (Rodriguez and Joo, 2004, Saelens and Handy, 2008, Saelens, Sallis and Frank, 2003). The importance of pedestrian infrastructure and its quality as design features remain less clear (Lin and Moudon, 2010, Rodriguez and Joo, 2004, Saelens and Handy, 2008).

Based on these concepts of density, land-use mix and connectivity, Frank et al. (2005) calculated a walkability index that shows significant associations with physical activity. This index was then extended by the retail or commercial floor area ratio (FAR) (Frank et al., 2006). FAR is the ratio or the sum of commercial building floor area to the total commercially used land area. The ratio is meant to deliver information about whether land is covered by parking or by store fronts facing the sidewalk (Frank et al., 2007). Leslie et al. (2007) adapted this walkability index to the Australian context. They also included FAR in their walkability index, but they hypothesized that the ratio (called net area retail in the Australian version) is an indication of options for destinations to utilize goods and services and for employment options. Related to the framework of Frumkin, Frank and Jackson (2004), this hypothesized aspect is already measured by proximity and consequently there seems to be no need, from a conceptual viewpoint, to include FAR in the walkability index. However, the conceptual relationship between FAR and the walkability definition has not been clarified in any puplication using the extended walkability index (Frank et al., 2009a, Frank et al., 2007, Frank et al., 2006, Owen et al., 2007, Sallis et al., 2009). For example, FAR also fails to take underground parking into account. Interestingly, the association between FAR as a measure itself and physical activity or other health outcomes has barely been tested, although one study investigated the association between physical activity and FAR and found a positive association (Saelens et al., 2012). Thus, there seem to be some conceptual issues related to FAR. Additionally, the question of applicablity to Europe remains. The first Eurpean study (conducted in Belgium) using the walkability index omitted FAR „because of lack of relevance for a Belgium context and because no GIS data were available“ (Van Dyck et al., 2010, p. S76).

Southworth (2005) proposes a broader understanding of walkability, which includes additional components such as safety and aesthetics. He defines walkability as „the extent to which the built environment supports and encourages walking by providing for pedestrian comfort and safety, connecting people with varied destinations within a reasonable amount of time and effort, and offering visual interest in journeys throughout the network“ (Southworth, 2005, p. 248). The underlying concept of this definition from the fields of urban planning and transport is essentially identical to the model of Pikora et al. (2003).

Table 1: Comparison of different approaches conceptualising neighbourhood walkability



	Definitions of walkability					Significant associations reported in reviews of empirical studies using mainly objective methods				Empirical studies aiming to develop a theoretical background to walkability		
Pikora et al., 2003	Lovasi, 2008; Leyden, 2003; Roher, Pierce & Denison, 2004;	Coleman et al., 2008;	Cutts et al., 2009	Leslie et al., 2007; Frumkin, Frank & Jackson, 2004; Frank, Engelke & Schmid, 2003;	Southworth, 2005	Saelens, Sallis & Frank, 2003	Wendel-Vos et al., 2007*	Saelens & Handy, 2008	Lin & Moudon, 2010	Cervero & Kockelmann, 1997	Moudon et al., 2006; Lee & Moudon, 2006;	Randall & Baetz, 2001
Functional	Feasibility and appeal of walking	Ability to walk	Function	Connecitvity	Connectivity	Connectivity	Hills, trip distance	Route/ network connecitivity	Traffic cond., street network, sidewalks, walk. infra., topography	Design	Route	Route distance & directness
Safety			Form	-	Safety	-	-	Equivocal	-		0	0
Aesthetics				-	Visual interest	-	-	Equivocal	Aesthetics/ comfort		0	0
Destination		Destinations	Function	Proximity (density & land-use mix)	Destinations	Density, land use-mix	Urban sprawl, land-use mix, accessibility & convenience of recreational facilities	Density, proximal non-residential destination	Destinations, land-use mix, distance	Density, diversity	Density, destinations, distance	Destinations

* This table shows selective results i.e. walking.
- = not mentioned or not investigated, 0= no association found;

Reviews of objectively measured correlates to walking show rather consistent results (see Table 1). The evidence for an association between walking and the characteristics of the built environment strongly supports the approach used by Frumkin, Frank and Jackson (2004) and by Frank, Engelke and Schmid (2003) for conceptualising walkabilty as proximity and connectivity. According to the reviews (see Table 1), the correlates of walking are land-use mix and density, both of which are measures of proximity. Connectivity as an important feature of walkability is not supported by the review of Wendel-Vos et al. (2007) when looking at walking only. However, Wendel-Vos et al. (2007) found associations between connectivity and active commuting. Most publications included in the review of Lin and Moudon (2010) supported an association between destinations and walking (21 papers). This reviews also provided strong support for the functional aspect as a correlate of walking (8 papers). The association between aesthetics and walking has been supported by three papers, while safety has not been supported at all (Lin and Moudon, 2010). Consequently, the association between safety and aesthetic aspects and walking from GIS studies is less clear and hardly investigated.

A few researchers have conducted empirical studies using a wide range of GIS-based walkability measures to support theory development. Based on the two aspects of proximity and connectivity, Cervero and Kockelman (1997) developed the 3Ds – density, diversity and design - to capture built environment in relation to walking, biking and transit use. Density and diversity are the components of proximity, while design refers to both street network connectivity and pedestrian-oriented design. Cervero and Kockelman (1997) found that 65.5% of the variance in the built environment can be explained by using two factors consisting of 12 measures. The two factors were intensity (mainly density and land-use measures) and walking quality (mainly street and sidewalk connectivity and lighting). Consequently these results emphasise the understanding of walkability as an interplay of proximity and connectivity, but also highlight safety aspects as a relevant design element.

Other attempts to contribute to the concept of walkable neighbourhoods basically confirm the results of Cervero and Kockelman, as well as the approach used by Fumkin, Frank and Johnson (2004) and Frank, Engelke and Schmid (2003). In two publications using the same survey data, Moudon et al. (2006) showed the importance of density and route characteristics such as direct route to grocery store or school, sidewalk length and block size (Lee and Moudon, 2006, Moudon et al., 2006). These route characteristics are referred to as design by Cervero and Kockelmann (1997) or connectivity by Frumkin, Frank and Jackson (2004) and Frank, Engelke and Schmid (2003). Additionally, Moudon and colleagues (2006) identified higher quantity of destinations (especially attractor destinations such as grocery, restaurant and retail) as important factors associated with walking. Frumkin, Frank and Jackson (2004) and Frank, Engelke and Schmid (2003) would classify these as proximity, while Cervero and Kockelmann (1997) would use the term diversity (see Table 1).

Randall and Baetz (2001) used the term pedestrian connectivity as a measure „of how accessible, with regards to walking, a neighbourhood is to its residents“ (p. 3). In addition to personal health and fitness, factors that influence the decision to walk include the availability of a local destination, route distance and route directness (Randall and Baetz, 2001). Although the terminology is a bit different, the underlying concepts once again relate to proximity and connectivity.

Looking at the results of this literature (see Table 1), it seems clear that there is agreement on proximity (measured as density and land use mix) and access to destinations as key elements of walkability, especially for transportation purposes. Saelens, Sallis and Frank (2003) conclude that „virtually every study demonstrated associations between environmental variables such as density, connectivity and land use mix and walking/cycling“ (p. 86). In particular, the neighbourhood walkability index developed by Frank et al. (2005) has been widely used in GIS studies in the US (Cutts et al., 2009, Frank et al., 2004, Frank et al., 2005, Frank et al., 2006, Coleman et al., 2008) and Australia (Cerin and Leslie, 2008, Cerin et al., 2007, Leslie et al., 2007, Sugiyama et al., 2007, Owen et al., 2007), and also recently in Belgium (Van Dyck et al., 2010, Van Dyck et al., 2010a).

One possible explanation for the strong evidence in favour of proximity and connectivity and, in consequence, in favour of the walkability index in GIS-based literature is the rather good measurablity of these concepts with GIS. In studies using GIS to assess the built environment, the most frequently assessed measures to date have been land-use mix, access to recreational facilities, and street pattern, followed by population density and composite indices (Brownson et al., 2009). In contrast, the measurement of safety and aesthetics is limited by the availability of geodata, by resource-intensive GIS processes, and also by the difficulties of measuring rather subjective concepts such as safety and aesthetics using objective data, especially with GIS.

Based on the evidence presented above and on the concept of Leslie et al. (2007), Frumkin, Frank and Jackson (2004) and Frank, Engelke and Schmid (2003), the following working definition is offered for the present study: „walkability is 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.“ (Leslie et al., 2007, p. 113). There are „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 landuse mix (the degree of heterogeneity with which functionally different uses are co-located in space)“ (Leslie et al., 2007, p. 113). „The density of a place refers to the quantity of people, households or employment distributed over a unit of area. (…) Land use mix is a measure of how many types – offices, housing, retail, entertainment, services, and so on – are located in a given area“ (Frumkin, Frank and Jackson, 2004, p. 6). „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“ (Leslie et al., 2007, p. 113). „Connectivity refers to how destinations are linked (…) and is (…) discussed in the context of street network“ (Frumkin, Frank and Jackson, 2004, p. 7). Based on these arguments, the concept of proximity captures measures related to diversity, distance to destinations, availability and accessibility of destinations. Connectivity can also be seen as a concept that represents design features (e.g. sidewalk availability, pedestrian infrastructure) without using explicit measures related to design. Using this definition as a basis for this study also incorporates the walkability index, as developed by Frank et al. (2005).

This definition does not fully take into account other important theoretical aspects, such as safety and aesthetics, which have not been empirically proven to be as consistently associated with walking as proximity and connnectivity. To some extent, it can be assumend that these aspects are captured by the present working definition of walkability. For instance, increasing the connectedness may also increase safety. Also, it can be assumed that a densely populated and highly mixed community better fulfills aesthetic requirements compared to low-density, single-use communities.

Furthermore, the working definition and the related measures described above were developed in order to enable the investigation of associations between urban form and different outcomes, to detect intervention areas and to monitor urban development over time (Frank et al., 2009). These measures are also rather simple and clear. Using a wide variety of indicators and variables, Cervero and Kockelmann (1997), as well as Lee and Moudon (2006), found that primarily simple measures were significantly related to walking. Lee and Moudon (2006) argue that simplified and clear measures can serve effectively and efficiently to guide intervention strategies and surveillance efforts. Furthermore, indices, like the walkability index, are considered to capture the inter-relatedness of built environment characteristics, minimze the effect of spatial colinearity and ease communication (Brownson et al., 2009). These are features that are especially important for surveillance indicators. Since this thesis aims to develop GIS-based indicators that can be reommended for surveillance and planning purposes, it seems appropriate to make use of concepts that were developed with these intentions in mind.

An additional argument in support of the present working definition is that land use mix, residential density, street connectivity and the walkability index (calculated based on these variables) has not only correlated with walking for transport (Cerin et al., 2007, Frank et al., 2004, Frank et al., 2006, Owen et al., 2007, Frank et al., 2005, Oliver, Schuurman and Hall, 2007, Zahran et al., 2008) and physical activity (Frank et al., 2004, Sallis et al., 2009), but has also shown significant associations with overweight/obesity (Pouliou and Elliott, 2010, Sallis et al., 2009) and social capital (Leyden, 2003). Since the aim of this thesis is not only to look at walking and physical activity but also at BMI/overweigth/obesity, social cohesion and self-rated health, the working definition seems appropriate.

Before the study aim and the methods of the empirical study were developed in more detail, a systematic literature review was conducted. Based on the evidence presented, this review used the definitions of Leslie et al. (2007), Frumkin, Frank and Jackson (2004), and Frank, Engelke and Schmid (2003). The review included the walkability index, as developed by Frank and colleagues (2003), but not the commercial floor area ratio (FAR) due to conceptual issues and application issues in Europe. Nevertheless, studies using the walkability index using FAR will be included in the literature analysis to capture the full picture of the relationship between the index, walking and health outcomes. Eligibility criteria for the literature review were the use of GIS to measure exposure (as opposed to density measured with census data based on a statistical areal unit, for example) and the measurement of exposure on a neighbourhood or community level. Consequently, publications or their exposure measures were excluded if they did not fulfil the exact and explicit walkability, density, land use mix and connectivity definitions described above or were measured, for instance, on the building or site level or along the route between origin and destination.

The following two sections provide further methods of the systematic literature review.

2.2 Defining outcome and population group

Publications were included if their outcome measures were walking for transport, biking for transport or physically active transport (combining walking and cycling for transport or active transportation such as non-motorised trips), weight-related measures (body mass index, overweight, obesity, waist circumference and waist-to-height ratio), social cohesion and self-reported general health status.

Physical activity was restricted to transport-related activites. Research into physical activity domains is necessary to improve the specificity of environmental measures and models (Giles-Corti et al., 2005, Leslie et al., 2007). The walkability concept was developed in the field of transportation planning and is focused on environments determining transport-related physical activity (Saelens, Sallis and Frank, 2003). In addition, the walkability index was developed to explain utilitarian forms of physical activity rather than physical activity for recreation and leisure (Sallis et al., 2009, Leslie et al., 2007). Consequently, transport-related physical activity was used for this review and defined as those activities that are undertaken in order to accomplish a purpose other than doing physical activity (Frank, Engelke and Schmid, 2003). The prime purpose is to move from one place to another.

The field of research into obesogenic environments is quite young, and evidence is just beginning to appear (Sallis and Glanz, 2009). Therefore, weight-related measures were broadly defined in order to get a comprehensive picture of associations.

Evidence also suggests that the built environment of the residential neighbourhood is associated with self-rated health (Agyemang et al., 2007, Ross, Tremblay and Graham, 2004, Stronegger, Titze and Oja, 2010), but evidence on walkability is unknown. All one-item measures of self-rated general health were accepted for inclusion in this review.

Even less is known about the association between physical environments and social cohesion. It has been shown that social capital is associated with urban sprawl (Frumkin, Frank and Jackson, 2004). The causes thereof include time restrictions for civic involvement due to commuting or reduced opportunity for social interaction due to driving. In addition, initial studies have also shown an association between social capital and walkability (Leyden, 2003, Renalds, Smith and Hale, 2010). To assess social capital comprehensively, the broader definition of social cohesion was used to identify relevant studies for this review. Social cohesion includes not only social capital and social networks as one domain, but also common values and a civic culture, social order and social control, social solidarity and reductions in wealth disperaties, place attachment and identity (Forrest and Kearns, 2001). This definition also includes sense of community (McMillan and Chavis, 1986), which is mostly covered by the domains of place attachment and social networks.

Population was restricted to healthy, (mainly) white adults, older than 18 years, living in suburban or urban neighbourhoods. This restriction was necessary to transfer results to the population of Graz. This definition also included older adults, although this population group has specific needs that have to be taken into consideration when designing healthy neighbourhoods (Cunningham and Michael, 2004). For elderly people who are frail or restricted in their mobility and social network, the proximal neighbourhhood may be even more relelvant than it is for other population groups (Yen, Michael and Perdue, 2009). Nevertheless, not enough is known about the specific needs of the elderly and the relationship between walkability and their health (Van Cauwenberg et al., 2011). A number of reviews on the association between the built environment and physical activity in an adult population have included older adults (Badland and Schofield, 2005, Lee and Moudon, 2004, Owen et al., 2004, Saelens and Handy, 2008, Wendel-Vos et al., 2007), but there have been almost no primary studies that looked specificially at the association between GIS-measured walkability and physical activity for elderly. Because of the lack of knowledge about the association between walkability and the health of the elderly, and because of the lack of information about the upper age limit in many publications, publications on elderly people were included in the present review.

Based on these inclusion criteria, publications with young (on average younger than 18 years of age), institutionalised, minority or non-white populations were excluded.

2.3 Identifying relevant literature

Observational studies were considered eligible. In addition, to be elegible publications had to provide information on at least three out of five pre-defined quality criteria for cross-sectional studies (i.e. response rate, representativness, validity/reliability of outcome measure, sample size, description of data) and three out of six for longitudinal studies (i.e. description of study participants, similarity between groups, validity/reliability of outcome measure, amount of follow-up, sample size, similarity of groups treatment) (adapted from Petticrew and Roberts, 2008). Furthermore, publications were only included if the study had an available abstract, was accessible via scientific literature or the internet, and was published in English or German. No publication date restrictions were imposed.

Publications were identified by searching electronic databases and scanning reference lists of articles. The search in PubMed was limited to humans, English and German language and all adults aged 19 and older. Furthermore, Science Direct, the Active Living Research Literature Database and TRIS (Transportation Reseach Database of the Transportation Research Board) were searched with no limits. No time limit was applied. The search was run in August 2010.

In PubMed, two searches were conducted. The first search used Medical Subject Headings and combined the term ‘geographic information systems’ with the terms ‘motor activity, exercise, walking, bicycling, obesity, overweight, BMI, health status, social support, community networks, cooperative behaviour, interpersonal relations, social environment, social welfare’. The second search in PubMed combined the terms ‘geographic information systems, GIS, walkability’ with the terms ‘active transport, bicyc*, bik*, cycling, personal vehicle mode, physical activity, walk*, active travel, commut*, BMI, body mass index, obes*, overweight, waist circumference, waist-to-height-ratio, self rated health, self reported health, self-rated health, self-reported health, subjective health, cohesion, collective efficacy, infrastructure (except for TRIS), neighbourhood quality, social capital, social environmental quality, social network, community bonds, sense of community, sociability, social interaction, social coherence, social support’. The same search strategy was applied to Science Direct (searching the fields title, abstracts and keywords) and TRIS (searching all keywords). The search in the Active Living Research Database was limited to ‘GIS, adults/elderly/other, white ethnicity’ and ‘physical activity for transport, to and from work, utilitarian/shopping/errand travel, BMI, weight, obesity, overweigth, waist circumfence, percent fat'. Additionally, reference lists of all included publications and reference lists of recently published reviews (Brownson et al., 2009, Ewing and Cervero, 2010) related to physical activity and travel were scanned.

Eligibility assessment was performed, and a second researcher (Delfien Van Dyck, University of Ghent) then cross-checked the elegibility of full texts in an unblinded manner. Disagreement was resolved by discussion.

A data extraction sheet was developed, piloted and adapted. The following data from included publications were extracted: first author, publication year, country, study setting, study design, sample size, age and sex of participants, survey method, response rate, validity of outcome measure, analysis differentiated by sex (yes/no), statistical analysis method, information on exposure (concept, definition and calculation of exposure measure, geographical scale, buffer type, buffer source, buffer size, data source), information on outcome (concept, definition and calculation of outcome measure, data source), covariates, results for all adults, for men and for women. Here again, a second researcher (Delfien Van Dyck, University of Ghent) cross-checked the extracted data .

Data were extracted only on Whites / Caucasians, on GIS-measured walkability characteristic as defined above, on health outcomes as defined above, on urban neighbourhoods, and on results that were tested for statistical significance. No data on proxy measures (e.g. neighbourhood houses age as a proxy for land use mix) were extracted. The results were classified as statistically significant at the 0.05 significance level. Disagreements were resolved by discussion.

One author was contacted for further information because of inconsistencies between the text and the tables of the publication. No reply was received. If results from the same study were reported in more than one publication, only additional results were extracted (e.g. sub-group analysis from the same data or new analysis with different model specification from the same data).

To assess the quality of elegible publications with a cross-sectional design, the response rate, representativeness of the sample, validity and reliability of the outcome measures and control of confounders were rated against pre-defined criteria (see Table 3 for more details). The only elegible publication with a longitudinal design was rated based on the description of study participants, the similiarity of groups, the validity and reliability of the outcome measures, the percentage of follow-up and the control for confounders. The quality assessment tools were adapted from a preexisting appraisal framework for surveys, quality criteria for observational studies (Petticrew and Roberts, 2008) and a quality assessment tool for quantiative studies (EPHPP, 2009a, EPHPP, 2009b). Criteria for sample size and adequacy of statistical methods were omitted because all publications fulfilled the criteria.

Exposure measures were categorized into measures of density, land use mix and street connectivity based on measures described by Forsyth et al. (2006, 2007). Measures of density were *gross population density* (population per unit land area), *employment density* (employment per unit land area) and *housing unit density* (housing units per unit land area) (Forsyth et al., 2007). Other measures used in one publication were *population per developed land area, residential population in residential parcels* and *population plus employment per unit land area*.

Land use mix was classified into the *entropy index*, the *Herfindahl-Hirschman Index* and other land use mix measures, which were used in one publication each (e.g. *business diversity score, land use mix profile, porportion of dissimilar land uses among grid cells in an area, tertiles of number of land uses per unit land area* or an *index of commercial and residential use*). The *entropy index* is a measure of diversity (Forsyth et al., 2006). It measures the heterogenity of land use within a neighbourhood. The value 0 indicates homogeneity of land use, and the value 1 indicates the even distribution of all land use types. The *Herfindahl-Hirschman-Index* is a measure of the concentration of different land use types. An area with one land use type will result in an index value of 10,000. The lower the index value, the better the land use mix (Forsyth et al., 2006).

Measures of street connectivity included *block size, intersection density* (all kind of intersections per unit land area), *ratio of four-way or three-way intersections to all intersections* (including the *connected node ratio*, the ratio of number of intersections to number of intersections plus culs-de-sac), *number of (all kind of) intersections* and others which were used in one publication each *(*like *the alpha index,* a summary score based on link count, link node ratio, ≥3 intersection density, and census block density*, the number of junctions per kilometer of road, and the ratio of junctions to cul-de-sacs*).

Additionally, the category composite measures / *walkability index* was used. Indices were constructed from measures of density, land use mix and street connectivity only or in combination with a measure of retail density (like the commercial floor area ratio or net retail area).

To analyse associations between different exposure measures and outcomes, outcomes were classified into four categories: walking for transport, biking for transport, active transport, weight-related measures (including BMI, overweight, obesity, waist-to-height-ratio and waist circumference), self-reported health status and social cohesion.

Publication results were analysed separately for publications of good/fair quality and all included publications. The number of publications reporting statistically significant associations between the exposure and outcome measure were counted and were related to the total number of publications investigating this association. Results were shown separately for men and women in the results table. Differentiation by age was made in the text.

2.4 Selecting relevant literature

Figure 1 graphically depicts the publication selection process. The database search provided a total of 2,402 records. By searching the reference lists, the author identified 111 additional publications. After removing the duplicates, 807 publications remained for screening. In the process of screening titles and abstracts, 715 publications were excluded. The main reasons for exclusion during screening were that

- exposure was not measured by GIS
- exposure or outcome was not identical with the definitions for the present study
- the researched population were children
- publications were not accessible or abstracts were not available
- publications did not report results of primary studies or reported results of testing validitiy and reliability of walkability instruments.

Ninety-two full-texts were assessed for elegibility, 42 of these were excluded because their research question did not fulfill the inclusion criteria.

Twenty-five of the excluded full texts did not fulfill the inclusion criteria for the definition of exposure.

- For instance, publications using measures such as distance to destinations or number of destinations in a specified area (n=10) were excluded.
- Nine publications did not use GIS to measure exposure.
- Six full texts used different walkability measures.

Fourteen fulltexts used outcome measures different from the ones defined for the review.

- Six did not use walking for transport as an outcome measure.
- Five used measures on motorised transport but not on walking or cycling.
- Three did not use a health outcome at all.

Two publications were also excluded because the focus was on Hispanics and/or black populations and because the geographical scale was the community route or a city.

In addition, 15 publications were excluded because they did not meet the quality criteria for inclusion. Most excluded publications (13 out of 15) reported no information on response rate, representativness and validity of outcome measures. The 15 excluded publications were from journals in the fields of transport (10 publications), planning (3) and public health (2).

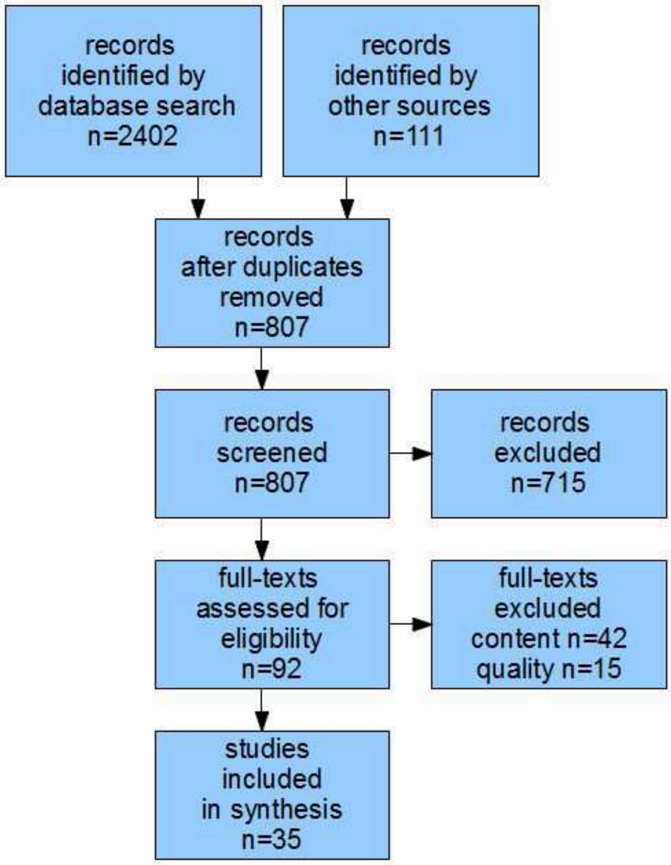


Figure 1: Flowchart of literature selection process

Table 2 shows the publication characteristics. Thirty-four publications had a cross sectional, and one had a longitudinal design (20). Most publications from the same study were based on the data collected in the Strategies for Metropolitan Atlanta's Regional Transportation and Air Quality (SMARTRAQ) project and the Twin Cities Walking Study. Three publications each analysed data from the Physical Activity in Localities and Community Environments (PLACE) study and from the Salt Lake County Drivers database. Two publications each were based on data from the Neighbourhood Quality of Live Study (NQLS), the Portland Neighbourhood Environment and Health Study, the New York Cancer Project and the Belgian Environmental Physical Activity Study (BEPAS).

As an exposure measure, the publications used density (12 publications), land use mix (13), street connectivity (20) and a walkability index (11).

Most included publications (n=20) investigated the association between walkability and weight-related measures. Two of these used measures such as waist-to-height ratio (33) or waist circumference (20). All other papers reported BMI as a continuous or categorical variable (like overweight or obesity).

Sixteen publications used walking for transport as an outcome measure. Fewer publications investigated the relation between exposure and physical activity for transport (n=5) or biking for transport (n=3). In two publications, researchers investigated the association between a measure of social cohesion and walkability. No publication was identified that investigated self-reported health status.

Seven publications differentiated in their analysis between women and men. Two covered a rather young population group of 16 years of age and older, and one covered 5 years and older. None of these three publications reported the mean age or the age distribution of the population, but all of them used large sample sizes (above 6,500). Due to the large sample sizes, it was assumed that the majority of the population was older than 18 years. Furthermore, seven publications did not provide information on age. Since no contrary information was provided, it was assumed that they dealt with an adult population. Three publications in this review reported results specificially on elderly people (50-75 years of age or 65 years and older), 13 publications used an upper age limit, and 14 publications did not provide information on the upper age limit.

Most publications (n=18) used a buffer as the geographical scale to determine neighbourhood. Ten used a street network buffer, and eight used a circular buffer. Ten publications used administrative units (e.g. census collection districts) as the geographical unit of analysis. In five publications, the authors created clusters of administrative units. Grid cells of different sizes were used in six papers. In one, publication the geographical scale was not reported.

Most publications reported results from the US (n=28). Three publications each showed associations in Australia and Europe, and one investigated Canada.

Table 2: Summary of the characteristics of included publications

Ref.no.	Author	Country	Sample	Study project	Walkability measures	D	L	C	WI	Geographical unit	Outcome	Covariates
1	Berke et al., 2007	US	n=740 age:65+ by sex	Adult Changes in Thought Cohort Study	walkability index	-	-	-	x	circular buffer of 100m, 500m, 1,000m;	BMI;	a, edu, inc, smok, hs, living alone, depression;
2	Bodea et al., 2008	US	n=10,150 age: 21+	SMARTRAQ	entropy index;	-	x	-	-	nip	obesity, overweight;	none
3	Boer et al., 2007	US	n=29,724 age: 5+	National Personal Transportation Survey	business diversity score, ratio of four-way intersections to all intersections, block length;	-	x	x	-	census block group;	having at least one walking trip per travel day;	a, s, eth, edu, empl, hhsize, statistical area, hh life cycle, month, percipitation, temperature, other environmental variables;
4	Brown et al., 2009	US	n=5,000 age: 25-64 by sex	Salt Lake County drivers	population density, entropy index, intersection density;	x	x	x	-	street network buffer of 1,000m;	BMI, overweight, obesity;	indiv: a; nbh: a, eth, inc;
5	Cerin et al., 2007	AUS	n=2,369 age: 20-65	PLACE	entropy index, composition of land use;	-	x	-	-	census collection district;	weekly minutes of walking for transport;	a, s, eth, edu, empl, ahhinc, childhh, hhsize, children's age;
6	Chatman, 2009	US	n=999 age: adult	Time Use Survey	number of four-way intersections;	-	-	x	-	circular buffer of 402m;	Non-working trips by walking or biking;	a, s, hhinc, childhh, hhsize, hhcomposition, weekday, worked two hours or more, survey area;
7	Coombes, Jones & Hillsdon, 2010	UK	n=6,803 age: 16+	Bristol Quality of Life in your Neighbourhood Survey	Herfindahl-Hirschmann index, number of junctions per km of road, ratio of junctions to cul-de-sacs;	-	x	x	-	street network buffer of 800m;	overweight or obesity;	a, s, ses, hs, area deprivation;

Cont. table 2: Summary of the characteristics of included publications

Ref.no.	Author	Country	Sample	Study project	Walkability measures	D	L	C	WI	Geographical unit	Outcome	Covariates
8	Forsyth et al., 2007	US	n=716 age: nip	Twin Cities Walking Study	gross population density, population per developed area, residential population in residential parcels, housing unit density, population plus employment per area, employment density;	x	-	-	-	blocks of 805m x 805m; 200m, 400m, 800m and 1,600m street distance and circular buffers;	met minutes per week; walking for travel per day; walking for travel (yes/no);	none
9	Forsyth et al., 2008	US	n=716 age: nip	Twin Cities Walking Study	employment density, entropy index, Herfindahl-Hirschman index, proportion of dissimilar land uses among grid, intersection and four-way intersection density, ratio of three- and four-way intersections to all intersections, connected node ratio, intersections per area;	x	x	x	-	blocks of 805m x 805m;	met minutes per week; miles per day;	a, s, ms, eth, edu, hhsize, hhowner, hs, tenure, car ownership, clustering by focus area;
10	Forsyth et al., 2009	US	n=716 age: nip by sex	Twin Cities Walking Study	gross population density, median block size;	x	-	x	-	blocks of 805m x 805m;	mean met minutes per week;	a, eth, edu, hhinc, hs, BMI;
11	Frank et al., 2004	US	n=7,134 age: nip by sex	SMARTRAQ	entropy index, intersection density;	-	x	x	-	street network buffer of 1,000m;	BMI, obesity, distance walked for travel;	a, edu, inc;
12	Frank et al., 2006	US	n=1,228 age: 20-65	NQLS	walkability index incl. FAR;	-	-	-	x	street network buffer of 1,000m;	BMI, minutes of walking and biking per week;	a, s, eth, edu, hhinc, children under 18;

Cont. table 2: Summary of the characteristics of included publications

Ref.no.	Author	Country	Sample	Study project	Walkability measures	D	L	C	WI	Geographical unit	Outcome	Covariates
13	Frank et al., 2007	US	n=3,543 age: adult	SMARTRAQ	walkability index incl. FAR;	-	-	-	x	street network buffer of 1,000m;	taking a walk trip, number of walking trips;	a, s, eth, hhinc, total vehicles in the hh, no of licensed drivers per vehicle;
14	Frank et al., 2008	US	n=13,065 age: 25+ by sex	SMARTRAQ	household unit density, number of land uses per area, intersection density;	x	x	x	-	street network buffer of 1,000m;	overweight, obesity, walk at least once over a two days period;	a, eth, edu, empl, hhinc;
15	Frank et al., 2009a	US	n=4,545 age:20-65 by sex	SMARTRAQ	walkability index incl. FAR;	-	-	-	x	street network buffer of 1,000m;	BMI;	a, edu, inc, empl, hhs, childhh
16	Huang et al., 2009	US	n=10,389 age: 18+	Health Interview Survey	population density, employment density, intersection density, street block length;	x	-	x	-	circular buffer of 500m;	Nonleisure-time walking and biking;	none
17	Kitamura et al., 1997	US	n=16,346 age: 16+	Survey	population density;	x	-	-	-	blocks of 1,609m x 1,609m;	number of non-motorized trips, fraction of non-motorized trips of all trips;	a, edu, inc, empl, hhinc, hhsize, persons 16+, no of vehicles, vehicles per person, driver's license, years in area;
18	Lee and Moudon, 2006	US	n=438 age: 18+	Walkable and Bikeable Community Project	housing unit density, mean block size;	x	-	x	-	circular buffer of 1,000m;	walking for transport (yes/no and non /moderate/frequent);	a, s, ms, eth, pa behavior, car in hh, dog in hh, attitude, nbh perception;
19	Li et al., 2008	US	n=1,221 age: 50-75	Portland Neighbourhood Environment and Health Study	entropy index, intersection density;	-	x	x	-	census block group;	overweight or obesity, minutes of walking for transport and errands per week;	a, s, eth, empl, hhinc, hs, home ownerhip, fruit and vegetable intake, fried food consumption;

Cont. table 2: Summary of the characteristics of included publications

Ref.no.	Author	Country	Sample	Study project	Walkability measures	D	L	C	WI	Geographical unit	Outcome	Covariates
20*	Li et al., 2009	US	n=1,221 age: 50-75	Portland Neighbourhood Environment and Health Study	walkability index;	-	-	-	x	block group;	waist circumference;	indiv: a, s, eth, edu, empl, hhinc, hs, smok, baseline BMI, weight & waist circumfence; nbh: eth, hhinc, density;
21	Lopez, 2007	US	n=15,538 age: nip	BRFSS	intersection density;	-	-	x	-	zip code tabulation areas;	obesity;	a, s, eth, edu, inc, smok;
22	McGinn et al., 2007	US	n=1,270 age: 18+	Survey	summary score based on link count, link node ratio, ≥3 intersection density, census block density;	-	-	x	-	circular buffer of 201m, 805m, 1,609m;	minutes of walking or biking for transport per week;	a, s;
23	Oakes et al., 2007	US	n=716 age: 25+	Twin Cities Walking Study	gross population density, median block size;	x	-	x	-	blocks of 805mx805m;	metabolic equivalent of times from walking for transport;	a, s, ms, eth, edu, hhownership, hs, lenght of tenure;
24	Owen et al., 2007	AUS	n=2,650 age: 20-65	PLACE	walkability index incl. FAR;	-	-	-	x	cluster of adjacent census collection districts;	minutes and frequency of walking for transport per week;	indiv: a, s, edu, childhh,ahhiinc; nbh: median weekly hhinc;
25	Owen et al., 2010	AUS	n=2,159 age: 20-65	PLACE	walkability index incl. FAR;	-	-	-	x	cluster of adjacent census collection districts;	bicycling for transport at least once a week;	indiv: a, s, edu, empl; nbh: ses;
26	Pouliou and Elliot, 2010	CA	n=115,548 age: 20+	Canadian Community Health Survey	household unit density, entropy index, intersection density, walkability index;	x	x	x	x	street network buffer of 1,000m;	BMI;	a, s, eth, edu, hs, smok, energy expenditure;
27	Rundle et al., 2007	US	n=13,102 age:30+	New York Cancer Project	index of residential and commercial use, intersection density;	-	x	x	-	census tract;	BMI;	indiv: a, s, eth, edu; tract: eth, poverty;

Cont. table 2: Summary of the characteristics of included publications

Ref.no.	Author	Country	Sample	Study project	Walkability measures	D	L	C	WI	Geographical unit	Outcome	Covariates
28	Rundle et al., 2009	US	n=13,102 age:nip	New York Cancer Project	gross population density, index of residential and commercial use;	x	x	-	-	street network buffer of 805m;	overweigth, obesity;	indiv: a, s, eth, edu; nbh: socio-demographics, food density;
29	Sallis et al., 2009	US	n=2,199 age:20-65	NQLS	walkability index incl. FAR;	-	-	-	x	nbh composed of 2-13 census block groups;	BMI, overweight or obesity, obesity, minutes of walking for transport per week;	a, s, ms, eth, edu, hhsize, no of vehicles/adult in hh, lenght of time at current residence, site;
30	Scott et al., 2009	US	n=1,124 age: adult	Survey	median block length, alpha index;	-	-	x	-	circular buffer of 1,609m;	BMI, frequencies of walking for transport for at least 10 minutes;	a, s, hhinc, BMI, access to car, no of markets and parks within one mile, perception of nbh safety;
31	Smith et al., 2008	US	n=453,927 age: 25-64 by sex	Salt Lake County drivers	number of intersections;	-	-	x	-	circular buffer of 402m;	BMI, overweight, obesity;	indiv: a; nbh: a, eth, inc;
32	Van Dyck et al., 2010	EU	n=1,166 age: 20-65	BEPAS	walkability index;	-	-	-	x	adjacent statistical sectors;	minutes of walking for transport per week, minutes of biking for transport per week;	a, s, edu, empl, BMI;
33	Van Dyck et al., 2010a	EU	n=1,200 age: 20-65	BEPAS	walkability index;	-	-	-	x	adjacent statistical sectors;	BMI, waist-to-height-ratio, minutes of walking for transport per week, minutes of biking for transport per week;	indiv: a, edu, empl; nbh: ses;
34	Wood, Frank & Giles-Corti, 2010	US	n=896 age:nip	SMARTRAQ	household unit density, entropy index, intersection density;	x	x	x	-	street network buffer of 1,000m;	Sense of community;	indiv: a, s, eth, edu, children under 18y, home ownership, years lived in suburb; nbh: inc, percentage of home ownership;
35	Zick et al., 2009	US	n=453,927 age:25-64	Salt Lake County drivers	number of intersections;	-	-	x	-	square of 1,000m;	BMI, obesity;	indiv: a, s; nbh: a, eth;

D=density, L=land use mix, C=connectivity, WI=walkability index; Nip= no information provided; nbh=neighbourhood; a=age; s=sex; eth=ethnicity, edu=education, empl=employment; hh=household; inc=income; hs=health status; childhh=children in household, SES=socio economic status; *=the only longitudinal study, all others were cross-sectional;

2.5 Quality of publications

Five publications were rated good, 13 fair and 17 poor (see Table 3).

Most publications (28 out of 34) using a cross-sectional study design did not meet the quality criterion on the response rate. Five publications report a response rate between 41 and 60% and partly met the quality criterion. One Canadian study reported a response rate of 81% and was the only publication meeting this quality criterion (26).

Fourteen of the publications with a cross-sectional design (n=34) provided no information on the representativness of the sample or showed major limitations and therefore scored zero on the quality criterion representativness. Twelve publications were rated as having minor limitations on the representativeness, while in eight publications the survey sample was rated as being representative of the population to whom the results were generalized.

In terms of validity and reliability of outcome measures, the quality of the included cross-sectional publications was rated better. Six publications did not meet the quality criterion, but 14 met it partly, and 14 met it fully.

In addition, controlling for confounders was widespread among the included cross sectional publications. Thirteen publications controlled for confounding on the individual and neighbourhood levels, and 18 on the individual level. In three publications, no control for confounding was reported.

The only publication with a longitudinal study design (20) met four out of five quality criteria. The publication did not provide information on the similarities between exposed and unexposed groups, so that criterion was rated as not met.

Table 3: Summary of quality assessment

	Publication	**Response rate**	**Representativness**	**Outcome measures**	**Con-founding**	**Global rating**
1	Berke et al., 2007	0	0	2	1	poor
2	Bodea et al., 2008	0	0	1	0	poor
3	Boer et al., 2007	0	0	0	2	poor
4	Brown et al., 2009	0	1	1	2	fair
5	Cerin et al., 2007	0	0	2	1	poor
6	Chatman, 2009	0	1	0	2	poor
7	Coombes, Jones & Hillsdon, 2010	0	0	1	2	poor
8	Forsyth et al., 2007	0	0	1	0	poor
9	Forsyth et al., 2008	0	0	1	2	poor
10	Forsyth et al., 2009	0	2	2	1	fair
11	Frank et al., 2004	0	0	0,5	0,5	poor
12	Frank et al., 2006	0	0	1,5	1	poor
13	Frank et al., 2007	0	2	0	1	poor
14	Frank et al., 2008	0	0	0,5	1	poor
15	Frank et al., 2009	0	2	1	1	fair
16	Huang et al., 2009	1	1	0	0	poor
17	Kitamura et al., 1997	0	1	0	1	poor
18	Lee and Moudon, 2006	0	0	2	1	poor
19	Li et al., 2008	1	1	2	1	fair
20	Li et al., 2009*	--	--	--	--	good
21	Lopez, 2007	0	0	1	0,5	poor
22	McGinn et al., 2007	0	2	2	1	fair
23	Oakes et al., 2007	1	2	2	1	good
24	Owen et al., 2007	0	1	2	2	fair
25	Owen et al., 2010	0	1	2	2	fair
26	Pouliou and Elliot, 2010	2	2	1	1	good
27	Rundle et al., 2007	0	0	2	2	fair
28	Rundle et al., 2009	0	2	2	2	good
29	Sallis et al., 2009	0	1	1	2	fair
30	Scott et al., 2009	0	2	0,5	1	fair
31	Smith et al., 2008	0	1	1	2	fair
32	Van Dyck et al., 2010	1	1	2	1	fair
33	Van Dyck et al., 2010a	1	1	1,6	2	good
34	Wood, Fank & Giles-Corti, 2010	0	0	0	1	poor
35	Zick et al., 2009	0	1	1	2	fair

* Li et al., 2009: the rating for the only publication with a longitudinal design was as follows: Are study participants adequately described (age, sex, baseline for outcomes)? Met; Are intervention/exposed and control/non exposed group similar? Not met; Are valid/reliable/standardized measures used for the outcome measure? Met; What is the follow-up? Met; Where confounders controlled? Met; Global rating: Good;

Quality criteria publications with cross-sectional design: What is the response rate? 2=>60%, 1=41-60%, 0=<40% or not known; Is the sample surveyed representative of the population to whom the result will be generalized? 2=if stated that representative or comparison with population provided; 1=if some minor limitations; 0=not met or not known; Are valid or reliable or standardized measures used for the outcome measure? 2=IPAQ, measured weight and height; 1=self-reported weight and height, 0=not met or not known (Note: If there was more than one outcome measure, each outcome measure was rated separately, and an average score was given); Were confounders controlled? 2=on individual and neighbourhood level, 1=on individual level; 0=not met or not known (Note: If there was more than one analysis undertaken, each analysis was rated separately. and an average score was given.); Global rating: good: 3 ratings 'met' OR 2 ratings 'met' and 2 ratings 'partly met', fair: 2 ratings 'met' OR 1 rating 'met' and at least 2 ratings 'parly met', poor: others (Note: Average scores between 2/1/0 (eg. 0.5 etc.) were rounded up.)

Table 4: Summary of results of included publications

	Author	**Results**
		Walking for transport
3	Boer et al., 2007	business diversity score (+, 3 vs. 4 businesses: OR 1.24, 95% CI 1.07-1.44) block length (+, <600 feet vs. 600-804 feet: OR: 1.26, 95% CI 1.04-1.52) ratio of four-way intersections to all intersections (+, <25% vs. 25-49%: OR 1.35, 95% CI 1.13-1.60; 25-49% vs. 50-74%: OR 1.40, 95% CI 1.09-1.78)
5	Cerin et al., 2007	entropy index (0) composition of land uses (+, commercial vs. recreational areas 39.6 more weekly minutes, 95% CI 0.4-78.9, p=0.048)
8	Forsyth et al., 2007	gross population density(+, all street network and circular buffer: r=0.1 to 0.2, p<0.001; 805mx805m grid: r=0.5 to 0.6, p<0.001) employment density (0, for 805mx805m grid and most street network buffers, +, for circular buffer: r=0.1, p<0.05) housing unit density(+, all street network and circular buffer: r=0.1 to 0.2, p<0.05; 805mx805m grid: r=0.5 to 0.6, p<0.001) population per developed land area (+, all street network and circular buffer: r=0.1 to 0.2, p<0.001; 805mx805m grid: r=0.5 to 0.6, p<0.001) residential population in residential parcels (+, most street network and circular buffer: r=0.1 to 0.2, p<0.001; 805mx805m grid: r=0.5 to 0.6, p<0.001) population plus employment per unit land area (+, all street network and circular buffer: r=0.1 to 0.2, p<0.05; 805mx805m grid: r=0.5 to 0.7, p<0.001)
9	Forsyth et al., 2008	employment density (0) entropy index (0) Herfindahl-Hirschman Index (0) porportion of dissimilar land uses among grid cells in an area (0) intersection density (+, r=0.4 to 0.6, p<0.05) ratio of four-way and three-way intersections to all intersections (+, for four-way intersections and the connected node ratio: r=0.4 to 0.5, p<0.05; -, for three-way intersections: r=-0.4 to 0.5, p<0.05)
10	Forsyth et al., 2009	both (only white): gross population density (+, OR: 1.97, 95% CI: 1.14-3.43, p=0.02) women: gross population density (0) men: gross population density (+, OR: 1.78, 95% CI 1.12-2.83, p=0.02) both (only white), women and men: block size (0)
11	Frank et al., 2004	women and men: entropy index (+, p<0.01) women and men: intersection density (+, p<0.001)
13	Frank et al., 2007	walkability index (+, p<0.05, except subsample neighbourhood selection:0)
14	Frank et al., 2008	household unit density (+, p<0.001) number of land uses per acre (+, p<0.001) intersection density (+, p<0.001)
18	Lee and Moudon, 2006	area level: household unit density (-, for not walking vs. walking; 0, for non vs. moderate vs. frequently) parcel level: household unit density (0, for not walking vs. walking; +, for non vs. moderate vs. frequently, OR: 2.11 for walking frequently, 95% CI 1.15-3.88, p<0.05) block size (0)
19	Li et al., 2008	entropy index (+, estimated prevalance walking for transport: 5.76, 95% CI 2.7-12.31, p<0.001; +, walking for errands: 1.5. 95% CI 1.01-2.22, p=0.047) intersection density (+, estimated prevalance walking for transport: 1.2, 95% CI 1.06-1.35, p=0.004; +, walking for errands: 1.11, 95% CI 1.01-1.21, p=0.025)
23	Oakes et al., 2007	gross population density (+, OR: 1.99, 95% CI 1.3-3.06) block size (0)
24	Owen et al., 2007	walkability index (+, for weekly frequency of walking, p<0.001; 0, for weekly minutes of walking)
29	Sallis et al., 2009	walkability index (+, 44.3 minutes per week in high-walkable areas, 12.8 minutes per week in low-walkable areas, p<0.0001)
30	Scott et al., 2009	alpha index (0) block length (0)
32	Van Dyck et al., 2010	walkability index (+, 117.3 minutes per week in high-walkable areas, 37.6 minutes per week in low-walkable areas, p<0.001)
33	Van Dyck et al., 2010a	walkability index (+, 210%, 95% CI 116-337%, more walking in respondents of high-walkable areas than of low-walkable areas)
		Cycling for transport
25	Owen et al., 2010	walkability index (+, OR: 1.82, 95% CI 1.24-2.66)
32	Van Dyck et al., 2010	walkability index (+, 82.3 minutes per week in high-walkable areas, 43.9 minutes per week in low-walkable areas, p<0.001)
33	Van Dyck et al., 2010a	walkability index (+, p<0.001)
		Overall active transportation
6	Chatman, 2009	number of intersections (+, RR: 1.03, p=0.01)
12	Frank et	walkability index (+, r=0.3, p=0.000)

	al., 2006	
16	Huang et al., 2009	gross population density (+, p≤0.001) employment density (+, p<0.01) intersection density (+, p≤0.001) block length (+, p<0.01)
17	Kitamura et al., 1997	gross population density (0, for number of non-motorized trips; +, for fraction of non-motorized trips, r=0.26)
22	McGinn et al., 2007	summary score (0)
		Weight-related measures
1	Berke et al., 2007	walkability index (all buffers) and BMI (0)
2	Bodea et al., 2008	entropy index (continuous) and overweight (0) entropy index (continuous) and obesity (0) entropy index (quartiles) and obesity (-, r=-0.055, p=0.02)
4	Brown et al., 2009	<u>BMI</u> both: gross population density (0) women: entropy index (0) men: entropy index (0, for 2 land use types entropy index; -, for 3 and 6 land use types entropy index, p<0.05) women: intersection density (0) men: intersection density (+, p<0.05) <u>overweight</u> both: gross population density (0) both: entropy index (0) both: intersection density (0) <u>obesity</u> women: gross population density (0) men: gross population density (-, in the partial correlation, p<0.05; 0, in the generalized estimating equation) women: entropy index (0) men: entropy index (0, for 2 land use types entroy index; -, for 3 and 6 land use types entropy index, p<0.05) both: number of intersections (0)
7	Coombes, Jones & Hillsdon, 2010	Herfindahl-Hirschmann Index and overweight or obesity (0) ratio of junctions to cul-de-sacs and overweight or obesity (0) number of junctions per km road and overweight or obesity (-, p<0.001);
11	Frank et al., 2004	<u>BMI</u> both: entropy index (-, p<0.001, in men: lowest vs. highest quartile decrease in BMI of 1.34 kg/m2) women: intersection density (0) men: intersection density (-, lowest vs. highest quartile decrease in BMI of 1.21 kg/m2, p<0.001) <u>obesity</u> entropy index (-, OR: 0.88, CI=0.84-0.92, with each quartile increase in entropy index, p<0.000) intersection density (0)
12	Frank et al., 2006	walkability index and BMI (-, r=0.11 kg/m2, p=0.00, explained variance: 1.14%)
13	Frank et al., 2007	walkability index and obesity (-, p<0.05)
14	Frank et al., 2008	<u>overweight</u> women: household unit density (0) men: household unit density (-) both: tertiles of land uses per acre (0) both: intersection density (0) <u>obesity</u> women: household unit density (+) men: household unit density (0) women: tertiles of land uses per acre (0) both: tertiles of land uses per acre (-, p<0.004) women: intersection density (0) men: intersection density (-, p<0.001)
15	Frank et al., 2009a	women: walkability index and BMI (0) men: walkability index and BMI (-, p=0.007))
19	Li et al., 2008	entropy index and overweight or obesity (-, estimated prevalence: 0.75, p=0.003)
20	Li et al., 2009	walkability index and waist circumference (0)
21	Lopez, 2007	intersection density and obesity (bivariate: -, RR: 0.98, 95% CI 0.97-0.99, p=0.01; mutlivariate: 0)
26	Pouliou and Elliot, 2010	household unit density and BMI (Toronto: -, r=0.05 kg/m2, p<0.01; Vancouver: -, r=0.3 kg/m2, p<0.05) entropy index and BMI (Toronto: 0; Vancouver: -, r=1.1 kg/m2, p<0.001) intersection density and BMI (Toronto: 0; Vancouver: -, r=0.1 kg/m2, p<0.001) walkability index and BMI (Toronto: 0; Vancouver: -, r=0.06 kg/m2, p<0.05)
27	Rundle et al., 2007	intersection density and BMI (0) index of commercial and residential use and BMI (-, r=0.55, p<0.01)
28	Rundle et al., 2009	<u>overweight</u> gross population density (-, highest quartile vs. lowest quartile prevalence ratio: 0.84, 95% CI 0.75-0.95)

		index of commercial and residential use (-, third and fourth quartile vs. lowest quartile prevalence ratio respectively: 0.94, 95% CI 0.89-0.99 and 0.92, 95% CI 0.87-0.97) <u>obesity</u> gross population density (-, highest quartile vs. lowest quartile prevalence ratio: 0.84, 95% CI 0.73-0.96) index of commercial and residential use (-, highest quartile vs. lowest quartile prevalence ratio: 0.91, 95% CI 0.86-0.97)
29	Sallis et al., 2009	walkability index and BMI (0) walkability index and overweight or obesity (-, OR: 1.35, 95% CI 1.1-1.69, p=0.007) walkability index and obesity (0)
30	Scott et al., 2009	median block length and BMI (0) alpha index and BMI (-, p=0.004)
31	Smith et al., 2008	number of intersections and BMI (both: 0) number of intersections and overweight (both: -, men: p=0.004, women: 0.042) number of intersections and obesity (men: -, p=0.004, women: 0)
33	Van Dyck et al., 2010a	walkability index and BMI (0) walkability index and waist-to-height-ratio (0)
35	Zick et al., 2009	number of intersections and BMI (+, r=0.1 kg/m2, 95% CI 0.09-0.12, p<0.01) number of intersections and obesity (+, OR: 1.06, 95% CI 1.06-1.07, p<0.01)
		Social cohesion
34	Wood, Frank & Giles-Corti, 2008	residential density (0) entropy index (-, p<0.003) intersection density (0)

Note: + = significant positive association, - = significant negative association, 0 = no significant association

2.6 Density and health-related outcomes

Walking for transport

Table 5 shows that six publications (8, 9, 10, 14, 18, 23) used density as an exposure and walking for transport as an outcome measure. Five of the six publications showed a significant association between these measures. The results of publications with good and fair quality did not differ from the results of all included publications.

Two publications of good and fair quality detected an association between *gross population density* and walking (10, 23). All included publications supported this association (8, 10, 23). However, all the evidence reported in these publications came from the Twin City Walking Study. Oakes et al. (2007) described the overall results on *gross population density* (23), while Forsyth et al. (2009) published sub-group analysis using a smaller number of covariates (10). Forsyth et al. (2007) performed additional explorative analysis using different geographical units and different outcome measures without adjusting for covariates (8). Oakes et al. (2007) and Forsyth et al. (2009) found that all respondents and only white respodents living in high-density areas were twice (all: 95% CI 1.3 to 3,1; white: 95% 1.1 to 3.4) as likely to walk than those respondents living in low-density areas (10, 23). Men living in high-density neighbourhoods were 1.8 times (95% CI 1.1 to 2.8) more likely to walk compared to men living in low-density neighbourhoods (10). For women, no significant associationswere found (Forsyth et al., 2009). The relation between *gross population density* and walking was supported by the explorative analysis of Forsyth et al. (2007), who found significant correlations between exposure and outcomes without controlling for covariates. In particular, using a 805m x 805m grid system to define neighbourhood led to significant correlation coefficients of about 0.5 to 0.6 ($p<0.001$), depending on the outcome measure used. Using street network and circular buffers of different size resulted in correlation coefficients of 0.1 to 0.2 ($p<0.001$) (8).

The results on *employment density* were less clear (see Table 5). *Employment density* was identified as a significant correlate of walking in one (8) of two publications (8, 9). Both publications reported results from the Twin City Walking Study. Forsyth et al. (2008) found no significant associations when controlling for a range of covariates (9), and Forsyth et al. (2007) found no significant associationswithout adjusting for confounders for a 805m x 805m grid, but minor correlations (r=0.1, mainly p<0.05) for some buffers of different type and size (8).

Three publications from three different studies reported results on *housing unit density*. Once again, the exploratory publication of Forsyth et al. (2007) found significant correlations between *housing unit density* and walking without controlling for confounders (8). The same pattern appears as for *gross population density*, with correlation coefficients of 0.5 to 0.6 (p<0.001) for neighbourhoods of 805m x 805m and of 0.1 to 0.2 (p<0.001) for buffer based neighbourhoods of different type and size (8). Frank et al. (2008) observed *housing unit density* as the strongest predictor of walking (p<0.001) (14). Lee and Moudon (2006) reported mixed results (18). Respondents living in high housing unit density areas – measured on a parcel level - were 2.1 times (95% CI 1.2-3.8, p<0.05) more likely to walk five or more times per week than respondents living in low density areas (18). No significant association was found looking at non-walkers vs. walkers at the parcel level. Lee and Moudon (2006) found no significant association on an area level when comparing no, moderate and frequent walking. Looking at walking versus non-walking on an area level, an unexpected association appeared. Respondents in high *housing unit density* areas were 80% less likely to walk at all than respondents in low *housing unit density* areas (OR= 0.2, 95% CI 0.0 to 0.8, p<0.05). Overall the evidence on *housing unit density* was not entirely conclusive.

In their exploratory publication, Forsyth et al. (2007) also used other density measures, such as *population per developed land area, residential population in residential parcels*, *population plus employment per unit land area*. These exposure measures showed a strong correlation (r=0.5 to 0.7 depending on the outcome and exposure measure, p<0.001) with walking at a grid level of 805m x 805m, and minor correlations (r=0.1 to 0.2 depending on the outcome and exposure measure) for street network and circular buffers of different sizes without controlling for covariates (8).

Overall active transport

Two publications of poor quality showed associations between *gross population density* and active transport (16, 17) (see Table 5). Kitamura et al. (1997) found a positive association between the fraction of non-motorized trips and *gross population density* (r=0.26), but no association between the total number of non-motorized trips and density (17). Huang et al. (2009) observed that residents in areas with high *gross population density* and high *employment density* did more non-leisure-time walking and cycling than residents in other areas (all clusters at least p<0.01) (16).

Table 5: Publications reporting significant associations between exposure and outcome

Outcome measures*	**Walking for transport**		**Cycling for transport**	**Active transport**		**Weight-related measures**	
Exposure measures	Publications of good (n=2) and fair quality (n=6)	All included publications (n=16)	All included publications (n=3) (good (n=1) and fair quality (n=2))	Publications of good (n=0) and fair quality (n=1)	All included publications (n=5)	Publications of good (n=4) and fair quality (n=8)	All included publications (n=20)
Density							
Gross population density	2 of 2 (10, 23) [men only (10)]	3 of 3 (8, 10, 23) [men only (10)]	--	--	2 of 2 (16, *17*)	2 of 2 (*4,* 28) [men only(*4*)]	2 of 2 (*4,* 28) [men only (*4*)]
Employment density	--	1 (*8*) of 2 (*8*, 9)	--	--	1 of 1 (16)	--	
Housing unit density	--	3 of 3 (8, 14, ***18***)	--	--	--	1 of 1 (26)	2 of 2 (*14*, 26) [men only (***14***)]
Others	--	1 of 1 (8)	--	--	--	--	--
Land use mix							
Entropy index	1 of 1 (19)	2 (11 ,19) of 4 (5, 9, 11, 19)	--	--	--	3 of 3 (*4*, 19, *26*) [for men, but not for women (*4*)]	5 of 5 (*2*, *4*, 11, 19, *26*) [2 of 2 for men (*4*, 11), 1 (11) of 2 for women (*4*)]
Herfindahl-Hirschman Index	--	0 of 1 (9)	--	--	--	--	0 of 1 (7)
Others	--	3 (3, 5, 14) of 4 (3, 5, 9, 14)	--	--	--	2 of 2 (27, 28)	3 of 3 (*14*, 27, 28) [men only (*14*)]
Connectivity							
Block size	0 of 3 (10, 23, 30) [not for men, and not for women (10)]	1 (3) of 5 (3, 10, 18, 23, 30) [not for men, and not for women (10)]	--	--	1 of 1 (16)	0 of 1 (30)	0 of 1 (30)
Intersection density	1 of 1 (19)	4 of 4 (9, 11, 14, 19) [men only (11)]	--	--	1 of 1 (16)	1 (*26*) of 2 (*26*, 27)	4 (*11, 14*, *21, 26*) of 5 (*11, 14*, *21, 26*, 27) [men only (*11, 14*)]
Ratio of four-way or three-way intersections to all intersections	--	2 of 2 (3, **9**)	--	--	--	--	--
Number of intersections	--	--	--	--	1 of 1 (6)	3 of 3 (***4***, *31*, **35**) [2 of 2 for men (***4***, *31*), 1 (*31*) of 2 for women (4*,* *31*)]	3 of 3 (***4***, *31*, **35**)[2 of 2 for men (***4***, *31*), 1 (*31*) of 2 for women (4*,* *31*)]
Others	0 of 1 (30)	1 of 2 (9, 30)	--	0 of 1 (22)	0 of 1 (22)	1 of 1 (30)	2 of 2 (*7*, 30)
Composite measures / Walkability indices							
Housing unit density, entropy index, intersection density	2 of 2 (32, 33)	2 of 2 (32, 33)	2 of 2 (32, 33)	--	--	1 (*26*) of 2 (*26*, 33)	1 (*26*) of 2 (*26*, 33)
Same as above plus FAR	2 of 2 (*24*, 29)	3 of 3 (13, *24*, 29)	1 of 1 (25)	--	1 of 1 (12)	2 of 2 (*15*, *29*) [men only (15)]	4 of 4 (12, 13, *15*, *29*) [men only (15)]
Others	--	--		--	--	0 of 1 (20)	0 of 2 (1, 20) [men only (1)]

*: because of the limited evidence on social cohesion, it was not included in this table.
Note: Italic=mixed results; bold=including assosications in unexpected direction

Weight-related outcomes

In four of 20 publications on weight-related outcomes, researchers recorded an association between density and weight-related outcomes (4, 14, 26, 28). Three of these were of good and fair quality. In two publications each, *gross population density* and *housing unit density* were used as operationalisations of density (see Table 5).

Brown et al. (2009) investigated the association between *gross population density* and BMI, overweight and obesity for men and women (4). They observed that higher density was associated with lower likelihood of obesity in men ($p<0.05$) (4). Associations for the other outcomes and for women were not statistically significant. Rundle et al. (2009) found an obesity (95% CI 0.73 to 0.96) and overweight (95% CI 0.75 to 0.95) prevalence ratio reduction of 16% among residents in the highest compared to the lowest *gross population density* areas. Comparisons between other quartiles were insignificant (28).

Pouliou and Elliot (2010) achieved a good quality score in the present review and used *housing unit density* as a measure for walkability. They found that each unit increase in *housing unit density* brought a decrease in BMI of 0.05 ($p<0.01$) in Toronto and 0.3 ($p<0.05$) in Vancouver (26)(Pouliou and Elliott, 2010). Frank et al. (2008), which had a poor quality rating, showed mixed results (14). Male residents of more dense neighbourhoods had a lower likelihood of overweight than male residents in less dense neighbourhoods ($p<0.001$). This association was not found for obesity or for women. On the contrary, white women without a degree were more likely to be obese if they lived in dense neighbourhoods (14).

Social cohesion

One study analysed the association between *housing unit density* and a composite measure of sense of community. Wood, Frank and Giles-Corti (2010) found no association between density and sense of community.

2.7 Land use mix and health-related outcomes

Walking for transport

Six publications (3, 5, 9, 11, 14, 19) based on 4 different studies (PLACE, Twin City Walking Study, SMARTRAQ, Portland Neighbourhood Environment and Health Study) dealt with land use mix and walking for transport. Five of these publications (3, 5, 11, 14, 19) found a significant association between land use mix and walking. One (19) of these five was of fair quality. The quality of all other included publications (3, 5, 9, 11, 14) was rated as poor.

The publication of fair quality based on data from the Portland Neighbourhood Environment and Health Study (19) reported an increase in walking associated with an increase in the *entropy index* based on three land use types (Li et al., 2008). One unit increase in land use mix was associated with 5.8 times (95% CI 2.7 to 12.3, $p<0.001$) more walking for transport and 1.5 times (95% CI 1.0 to 2.2, $p<0.05$) more walking for errands. Including all the available evidence, Frank et al. (2004) observed a significant positive association for men ($p<0.01$) and women ($p<0.001$) (11) in the SMARTRAQ project, while the publications of the PLACE (5) and the Twin City Walking Study (9) found no significant association between the *entropy index* and walking (5, 9). However, different *entropy indices* were used. The Twin City Walking Study used an index based on six, the PLACE study used an index based on five, SMARTRAQ used an index based on four, and the Portland Neighbourhood Environment and Health Study used an index based on three different land use types. The first two found no association, while the second two found associations.

One publication from the Twin City Walking Study reported no significant association between the *Herfindahl-Hirschman index* and walking (9).

Four publications used other measures to operationalize land use mix (3, 5, 9, 14). Three (3, 5, 14) of these four, all rated as being of poor quality, found a significant association between mixed land use and walking. Frank et al. (2008) operationalized land use mix as *tertiles of the number of land uses per acre* (14). They observed that participants living in higher density neighbourhoods were more likely to walk if the land use was mixed ($p<0.001$). Cerin et al. (2007) identified natural clusters of residential, recreational and commercial/industrial land uses in the PLACE study (5). This measure was called *land use mix profile*. Cerin et al. (2007) observed that respondents living in commercial areas walked 39.6 (95% CI 0.4 to 78.9, p<0.05) minutes per week more for transport than respondents in recreational areas. They identified no difference between respondents living in residential and other areas (5). Boer et al. (2007) used a *business diversity score* measuring the number of different business types to operationalize land use mix (3). They identified higher odds of walking when comparing the respondents living in areas with 2 business types (OR 1.14, 95% CI 0.96 to 1.35) to respondents living in areas with 3 business types. The same applied when comparing areas with 3 to 4 business types (OR 1.24, 95% CI 1.07 to 1.44). Boer et al. (2007) found no differences in walking between respondents living in areas with five or more business types and those with two or fewer different business types (3). From the Twin City Walking Study, Forsyth et al. (2008) reported the use of the *proportion of dissimilar land uses among grid cells in an area* to measure land use mix (9). No associations were found.

No study was exploring the association between land use mix and overall active transport (see Table 5).

Weight-related outcomes

In nine publications, researchers selected land use mix as a walkability exposure (2, 4, 7, 11, 14, 19, 26, 27, 28). Five of these nine publications were rated to be of good or fair quality (1, 19, 26, 27, 28) and showed results similar to all included publications. Three publications used data from the SMARTRAQ project (2, 11, 14). Bodea et al. (2008) (2) did a re-analysis of the data used in Frank et al. (2004) (11) using different model specification. Frank et al. (2008) used a different operationalisation of land use mix than in the other SMARTRAQ publications (14). In two publications, researchers analysed data from the New York Cancer Project Survey and used different outcome measures (27, 28).

Results pertaining to the association between land use mix and weight-related measures differed depending on which weight-related measures were used (see Table 6). In five publications (2, 4, 11, 14, 28), researchers used obesity, and in four they used BMI as a continuous variable (4, 11, 26, 27) as an outcome measure. All of these publications demonstrated a negative association between land use mix and obesity or BMI. The associations between land use mix and overweight and overweight or obesity were less clear. In four publications (2, 4, 14, 28), researchers used overweight as an outcome. One (28) of these four demonstrated an association. Two publications (7, 19) used overweight or obesity, and one of them (19) identified an association with land use mix.

Table 6: Comparison of associations between land use mix and different weight-related measures

Weight-related measure	**Reference number**	**Results**
Overweight	2, 4, 14, 28	Mixed results
Obesity	2, 4, 11, 14, 28	Significant negative association
Overweight and obesity	7, 19	Mixed results
BMI (continuous)	4, 11, 26, 27	Significant negative association (for men only)

All five publications using the *entropy index* demonstrated associations with weight-related outcomes (2, 4, 11, 19, 26). However, the formula of the index differed in the numbers of land use types used among the publications (see Table 7). Brown et al. (2009) experimented with indices using two, three and six land use types (4), while the researchers of all other publications used only one specified *entropy index*. They found no associations for the *entropy index* with two land use types for both sexes. For the index with six land use types, they reported no associations between the index and weight-related outcomes in women. In men, the six-land-use-type *entropy index* was significantly associated with lower BMI ($p<0.05$) and with lower likelihood of obesity ($p<0.05$), but not with overweight.

Table 7: Comparison of associations between different constructions of entropy indices and weight-related outcomes

No of land use types	Reference number	Results
2	4	Not significant
3	4, 19	Significant negative association (for men only);
4	2, 11	Significant negative association;
5	26	Significant negative association in Vancouver, but not in Toronto;
6	4	Significant negative association (for men only and not for overweight);

Brown et al. (2009) (4) and Li et al. (2008) used three land use types for the construction of the *entropy index* (19). In the publication of Brown et al. (2009), the results were the same as for the six-land-use-type *entropy index* (4). Li et al. (2008) found that one unit increase in land use mix was associated with a 25% reduction in overweight or obesity prevalence (p=0.003) (19).

Bodea et al. (2008) and Frank et al. (2004) used a 4-land-use-type *entropy index* (2, 11). Frank et al. (2004) found a significant negative association between the *entropy index* and weight-related outcomes for men, for women and for the whole group analysed (p<0.001). Overall, the likelihood of being obese decreased by 12.2% with each quartile increase in land use mix (OR: 9.88, 95% CI: 0.84 to 0.91) (11). In men, an increase from the lowest to the highest quartile of land use mix was associated with a decrease in mean BMI of 1.34 kg/m2 (p<0.001). Bodea et al. (2008) explored the sensitivity of results to different variable definitions and model specifications. The *entropy index* was associated with obesity (p=0.02) (vs. others) when using a logistic regression. However, the results were insignificant when using a multinominal logit model (non-overweight vs. overweight vs. obese).

Pouliou and Elliot (2010) used a five-land-use-type *entropy index* and found no significant associations in Toronto (26). In Vancouver, one unit increase in land use mix was associated with a decrease in BMI by 1.1 kg/m2 (p<0.001). To conclude, the only *entropy index* that did not show associations with weight-related outcomes was the one using two land use types. All other operationalisations of the *entropy index* were associated to some extent with weight-related outcomes.

The *Herfinahl-Hirschman Index* did not show a significant association with odds of being overweight or obese in the UK (Coombes, Jones and Hillsdon, 2010).

Three publications used two other land use measures (14, 27, 28). Frank et al. (2008) used *tertiles of number of land uses per acre* and found no significant association with overweight or obesity in women (14). Men with a degree living in a mixed neighbourhood were less likely to be obese ($p<0.004$), but no association was found for overweight. Rundle et al. (2007 and 2008) measured land use mix with an *index of commercial and residential land use* (27, 28). They found significant associations between their index and BMI, overweight and obesity. Rundle et al. (2007) showed that with each unit increase in land use mix, mean BMI decreased by 0.46 kg/m2 ($p<0.05$) (27). Residents living in neighbourhoods with a land use mix in the third or fourth quartile had a six (95% CI 1% to 11%) and eight percent (95% CI 3% to 13%) reduced prevalence ratio for overweight compared to the lowest quartile of land use mix. Comparing the residents of highly mixed areas with those in homogenous areas resulted in a nine percent reduction in obesity prevalence (95% CI 3% to 14%) (28).

Social cohesion

One study analysed the association between the *entropy index* and a composite measure of sense of community. Land use mix was associated with sense of community, but in the reverse direction. In neighbourhoods with low land use mix, respondents were 23.3% more likely to report a high sense of community compared to respondents in neighbourhoods with high land use mix ($p<0.003$) (Wood, Frank and Giles-Corti, 2010).

2.8 Connectivity and health-related outcomes

Walking for transport

Nine publications (3, 9, 10, 11, 14, 18, 19, 23, 30) showed evidence of an association between street connectivity and walking for transport. Three of the publications originated from the Twin City Walking Study (9, 10, 23), two from the SMARTRAQ project (11, 14), and one from the Portland Neighbourhood Environment and Health Study (19).

Four publications were rated to be of good or fair quality (10, 19, 23, 30). One (19) of these used data from the Portland Neighbourhood Environment and Health Study and established a significant association between connectivity and walking. The other three (10, 23, 30) found no significant associations. Five (3, 9, 11, 14, 19) of the nine included publications indicated associations between connectivity and walking.

The remaining four publications used *block size* as a measure of connecitivity (10, 18, 23, 30) and showed no association with walking for transport. Additionally one publication (3) reported inconsistent results. Boer et al. (2007) reported significantly higher odds of walking when comparing residents living in areas with a block size of 600-804 feet with residents living in areas with a block sizes of < 600 feet in the text of their article, but statistically insignificantly higher odds in the table (3).

The association between *intersection density* and walking for transport was supported by all included publications (9, 11, 14, 19). Two publications came from the SMARTRAQ project (11, 14). One of these publications reported results of a sub-group analysis by ethnicity and sex (11). One publication – Li et al. (2008) – was rated to be of good quality (19). By each unit increase in *intersection density,* Li et al. (2008) observed an increase in walking for transport prevalence of 20% (95% CI 6% to 35%, $p<0.01$) and in walking for errands of 11% (95% CI 1% to 21%, $p=0.03$) (19). The results of the publications rated to be of poor quality supported this association. Forsyth et al. (2008) recorded significant correlation coeffiencients between 0.4 and 0.6 (all $p<0.05$) depending on the operationalisation of walking for transport (9). Frank et al. (2004) found significant positive associationsfor white men and white women (p<0.001) (11). Furthermore, the data from the SMARTRAQ project showed that participants living in dense neighbourhoods were more likely to walk if streets were also well connected (p<0.001) (14).

Two publications (3, 9), both of poor quality, used the *ratio of four-way or three-way intersections to all intersections* as an exposure measure. Both publications found significant associations between connectivity and walking. Forsyth et al. (2008) observed positive correlations (r=0.4, p<0.05) between *ratio of four-way intersections to all intersections* and walking for transport (9). However, they also found a negative correlation (r=-0.4, p<0.05) when using the *ratio of three-way intersections to all intersections* (9). Boer et al. (2007) also identified a positive association between *the ratio of four-way intersections to all intersections* and walking (3). They compared areas with 25-49% four-way intersections to areas with less than 25% four-way intersections, and areas with 50-74% four-way intersections to areas with 25-49% four-way intersections. These comparisons resulted in a 35-40% increased probability of walking (i.e. 1.4, 95% CI 1.1 to 1.6; 1.4, 95% CI 1.1 to 1.8) (3). Further increase in the *ratio of four-way intersections to all intersections* did not result in significant associations (3).

One publication used *the alpha index* to operationalize street connectivity and found no significant association between connectivity and walking (30). Forsyth et al. (2008) used the *connected node ratio* (ratio of all intersections to cul-de-sacs) and observed an increase in walking for transport with increased connectivity (9).

Overall active transport

Huang et al. (2009) reported associations between *block length* and *intersection density* and active transport time (all clusters at least p<0.01) (16). Furthermore, the *number of four-way intersections* was observed to be associated with active transport (6). Chatman et al. (2006) described a 3.2% increase in walking and biking frequency with each additional four-way intersection in the area (p=0.01) (6). This effect decreased to 2.6% if neighbourhood self-selection was included in the model (p=0.05).

Weight-related outcomes

Half (n=10) of the publications looking at associations between walkability and weight-related measures used street connectivity as an exposure measure (4, 7, 11, 14, 21, 26, 27, 30, 31, 35). Six out of 10 publications were of good or fair quality (4, 26, 27, 30, 31, 35). Nine of the included publications (n=10) showed significant associations (4, 7, 11, 14, 21, 26, 30, 31, 35). However, two (4, 35) of these nine publications demonstrated associations in the opposite direction, and five (11, 14, 21, 26, 31) showed mixed results.

As shown for walking for transport, *block size* was not a correlate of weight-related measures (30).

Five of the 10 publications on connectivity and weight-related measures used *intersection density* as an exposure (11, 14, 21, 26, 27). Of the two publications of good or fair quality, one (27) demonstrated no significant association, and one found associations in Vancouver but not in Toronto (26). With each unit increase in *intersection density,* BMI decreased by 0.01 kg/m2 (p<0.001) in Vancouver (26). Looking at all of the included publications (n=5) confirms this impression of inconsistent evidence. Four (11, 14, 21, 26) of the five publications demonstrated significant and insignificant associations between *intersection density* and weight-related outcomes, such as the two publications based on data from the SMARTRAQ project (11, 14). Frank et al. (2008) anlaysed the whole data set and found that men with a degree were less likely to be obese if they lived in an area with high *intersection density* (p<0.001) (14). They found no such association for overweight and for women (14). In the sub-group analysis of the SMARTRAQ project looking only at the white population, Frank et al. (2004) showed that an increase of *intersection density* from the lowest to the highest quartile was associated with a decrease in BMI of 1.21 kg/m2 (p<0.001) in men (11). They recorded no association for women, for overweight and for obesity. Lopez et al. (2007) identified a relative risk reducation for obesity among residents of areas with high *intersection density* (0.98, 95% CI 0.97 to 0.99, p=0.01) in the bivariate analysis, without controlling for covariates (21). This association disappeared in the multiple regression analysis when controlling for covariates (21).

Three publications were based on data from the Utah Population Database and used *numbers of intersections* as exposure measure (4, 31, 35). Two of these three publications showed significant associations between *number of intersections* and weight-related outcomes within a 1,000m street network buffer (4) and a 1,000m grid system (35), but not in the expected direction. An increase in connectivity was associated with an increase in BMI and obesity. Zick et al. (2009) reported an increase in BMI of 0.02 kg/m2 ($p<0.01$) and a 6% increase in obesity risk (OR: 1.06, 95% CI 1.06 to 1.07) with an increase in *number of intersections* in a 1,000m grid (35). The analysis of Brown et al. (2009) resulted in significant positive associations between *number of intersections* and BMI for men in a 1,000m street network buffer (4). The third publication used a 402m circular buffer as the geographical unit and showed mixed results. Higher *numbers of intersections* were associated with lower overweight and lower obesity in men and with lower overweight in women (31). However, no association was found for BMI and for obesity in women (31).

The two publications using other exposure measures found significant associations between connectivity and weight-related outcomes. Scott et al. (2009) showed that a higher *alpha index* was associated with a lower BMI ($p=0.004$) (30). In the UK, Coombes, Jones and Hillsdon (2010) found negative associations between *number of junctions per road kilometer* and being overweight or obese ($p<0.001$). However, they also found no association when using a *ratio of junctions to cul-de-sacs* as an exposure measure.

Social cohesion

One study analysed the association between *three-way intersection density* and a composite measure of sense of community. Wood, Frank and Giles-Corti (2010) found no association between connectivity and sense of community.

2.9 Walkability indices and health-related outcomes

Walking for transport

Five publications demonstrated an association between a composite measure of walkability and walking (13, 24, 29, 32, 33). Four of these five were rated to be of good or fair quality (24, 29, 32, 33).

Two of the publications used a *walkability index* based on *housing unit density*, *the entropy index* and *intersection density* (32, 33). Both publications were based on data from the BEPAS study but reported results from different analyses and from using different covariates (32, 33). Van Dyck et al. (2010) observed that residents of high-walkable neighbourhoods reported 80 minutes per week more walking than residents in low-walkable neighbourhoods (p<0.001) (32). In the analysis of 2010a, van Dyck et al. found a 210% (95% CI 116 to 337%) increase of walking in residents of high-walkable areas compared to residents of low-walkable areas (33).

Three publications operationalized walkability as an index of *housing unit density, the entropy index, intersection density* and *the ratio of building floor area ratio to the total land area* (13, 24, 29). The *entropy index* used was different in the three publications. Frank et al. (2007) used an *entropy index* with three different land use types, Owen et al. (2007) used one with six, and Sallis et al. (2009) used one with five different land use types. All publications found an association between the *walkability index* and walking. Sallis et al. (2009), whose publication was rated to be of fair quality, observed 44.3 minutes of walking per week in respondents living in high-walkable areas and 12.9 minutes of walking per week in respondents living in low-walkable areas (p=0.00) (29). Frank et al. (2007) adjusted for neighbourhood selection and identified an increased likelihood of walking in areas in the third (OR: 1.7, 95% CI 1.1 to 2.7) and fourth quartiles of the walkability index (OR: 2.6, 95% CI 1.7 to 3.9) compared to areas in the lowest quartile (13). Owen et al. (2007) attributed 4.2% of the variance in the weekly frequency of walking to the *walkabilty index* (p<0.001) (24). However, Owen et al. (2007) found no association between the sum of weekly minutes of walking and walkability (24).

Cycling for transport

Three publications, all of good or fair quality, showed associations between different composite measures and cycling for transport (25, 32, 33). Two of the three publications were based on data from the BEPAS study in Belgium and differed in the statistical analysis and in the included covariates (32, 33). Van Dyck et al. (2010 and 2010a) found a positive association between cycling and the *walkability index* based on *housing unit density*, *the entropy index* and *intersection density* (p<0.001). Respondents in high-walkable neighbourhoods cycled 40 minutes per week more than respondents in low-walkable neighbourhoods (p<0.001) (32). Owen et al. (2010) used the same *walkability index* as Van Dyck et al. (2010), extended by the *net retail floor area ratio* (25). In Australia, they observed that residents of high-walkable areas were almost twice as likely to bike for transport compared to residents in low-walkable areas (OR: 1.82, 95% CI 1.24 to 2.66, p<0.01).

Overall active transport

One publication demonstrated an association between the *walkability index* based on *housing unit density,* the *entropy index, intersection density and retail floor area ratio* (12). Based on the NQLS study, Frank et al. (2006) reported an increase of 0.3 minutes of active transportation with each unit increase in the *walkability index* (p=0.00). The *walkability index* explained 8.3% of the variance in active transport.

Weight-related outcomes

Eight publications used a composite measure of walkabilty (1, 12, 13, 15, 20, 26, 29, 33). More than half of them were rated to be of good or fair quality (15, 20, 26, 29, 33). The results between the good or fair quality studies and all included studies did not differ significantly.

In two publications (26, 33), researchers devised a *walkability index* based on *housing unit density*, the *entropy index* and *intersection density*. Pouliou and Elliot (2010) observed a decrease in BMI of 0.06 kg/m2 (p<0.05) with each unit increase in the walkability index in Vancouver, but not in Toronto (26). Van Dyck et al. (2010a) found no direct association with BMI and waist-to-height-ratio in Belgium (33). However, van Dyck et al. (2010) showed negative associations for the outcomes related to cycling for transport ($p<0.05$ and $p<0.001$, respectively).

Four publications used a *walkability index* based on *housing unit density*, the *entropy index* and *intersection density* and a measure for retail density (12, 13, 15, 29). All four publications, including two of fair quality (15, 29), found associations between the *walkability index* and weight-related outcomes. Frank et al. (2007 and 2009) used data from the SMARTRAQ project, but they analysed different outcome measures and sub-samples (13, 15). One sub-sample was based on a survey on neighbourhood selection and one on neigbhorhood preferences (13). In both sub-samples, obesity prevalence was lower in the most walkable areas compared to the least walkable ($p<0.05$). This association remained when it was adjusted for neighbourhood selection (OR for being obese 0.67, 95% CI 0.49 to 0.89), but disappeared when adjusted for neighbourhood preference. Analysing the whole SMARTRAQ sample, Frank et al. (2009) found a significant negative association between walkability and BMI ($p=0.007$) for men, but not for women (15). Frank et al. (2006) and Sallis et al. (2009) used both data from the NQLS study (12, 29). Once again, Frank et al. (2006) used only a sub-sample since all of the data was not available at the time of publication. The two papers also used different statistical methods and different covariates and showed different results. Frank et al. (2006) found a decrease in BMI by 0.11 kg/m2 ($p=0.00$) with each unit increase in *walkability index* (12). Sallis et al. (2009), analysing the whole sample, reported no significant association between the *walkability index* and BMI and obesity (29). However, they also observed an increase of being obese or overweight by 35% (OR: 1.35, 95% CI 1.09 to 1.69, $p=0.007$) in low-walkable neighbourhoods compared to high-walkable neighbourhoods. This association remained after adjusting for neighbourhood selection ($p=0.01$).

Berke et al. (2007) and the prospective study of Li et al. (2009) used *other walkability indices*. Neither study found significant associations between their walkability index and BMI (1) and waist circumference (20).

Social cohesion

Sallis et al. (2009) measured the perceived neighbourhood social cohesion and found no association between the *walkability index* and social cohesion.

2.10 Summary

Density measures (especially *gross population density*, but also *housing unit density* to some extent) were consistently related to walking for transport. The evidence on the association between density and weight-related measures was mixed. However, there was some indication of a negative association between density and weight-related measures.

Among the land use mix measures used in research, the *entropy index* was clearly the most prevalent one. There was a clear positive association between the *entropy* index and walking for transport, even though most publications were of poor quality. There was no consistent evidence of a negative association between the *entropy index* and the weight-related measures. One reason for the mixed findings on the *entropy index* could be differences in the operationalisation of the index (i.e. different numbers and types of land use were used to create the index).

Among the connectivity measures, *intersection density* was the most used and the best performing measure. *Intersection density* was consistently positively related to walking for transport. Results on the association between weight-related measures and connectivity were mixed.

Evidence on the composite measures was of rather good quality and consistently showed a positive association between *walkability indices* and walking for transport, cycling for transport and active transport. Results from studies investigating the association between *walkability indices* and weight-related measures were mixed.

Consequently, the measures *gross population density, housing unit density, intersection density* and *walkability indices* can be considered as rather well established measures of walkability related to walking for transport. Results on weight-related measures were mixed. However, since most studies were undertaken in the US, the applicability of the results to the European context needs further research. Evidence on all walkability measures and cycling for transport, active transport and social cohesion was rather scarce. Evidence on the association between GIS-based walkability and self-reported general health status was completely lacking. Therefore, these associations should be further investigated.

3 Research question and hypotheses

The present study aimed to develop GIS-based walkability indicators relevant to public health for surveillance and planning purposes in the city of Graz.

The following research question was answered: Which GIS-based measures of residential neighbourhood walkability in the city of Graz are consistently associated with health-related outcomes among adults and are therefore relevant to public health surveillance and planning?

Based on the evidence shown in the literature analysis the study investigated the walkability measures *gross population density, housing unit density, entropy index, intersection density* and the *walkability index* in an European context.

Health-related outcomes include the same measures discussed in the literature review: walking, biking and physical activity for transport, BMI, self-reported general health status and social cohesion. Since the survey data used for this study did not provide data on social cohesion, neighbourhood satisfaction with social cohesion, social environmental quality and infrastructure was used as an outcome measure. In addition, general walking (including walking for recreation and transport) was included as an outcome.

Before discussing the associations between walkability and health, it is important to be clear on the hypothesised associations and on the underpinning conceptual model (Diez Roux, 2007, Macintyre, Ellaway and Cummins, 2002). Figure 2 shows the hypothesised associations between walkability and health-related outcomes and health. Based on the model of environmental and social determinants of health by Northridge, Sclar and Biswas (2003), the hypothesis was that walkability would be associated with physical activity, weight-related measures and neighbourhood satisfaction. These health-related outcomes, in turn, would be associated with self-rated general health. There might be also associations between physical activity and weight-related measures or neighbourhood satisfaction. However, only the associations between walkability and health-related outcomes and self-rated health were explored (shown as continuous lines in Figure 2), since the aim of the present study was to develop walkability measures as indicators for health. Other associations among the different health-related outcomes or the associations between the different health-related outcomes and self-rated health (shown as doted line in Figure 2) were not investigated in this study.

Furthermore, it was hypothesised that the association between walkability and health-related outcomes and self-rated health would be confounded by sex, age, socio-economic status and place of residence.

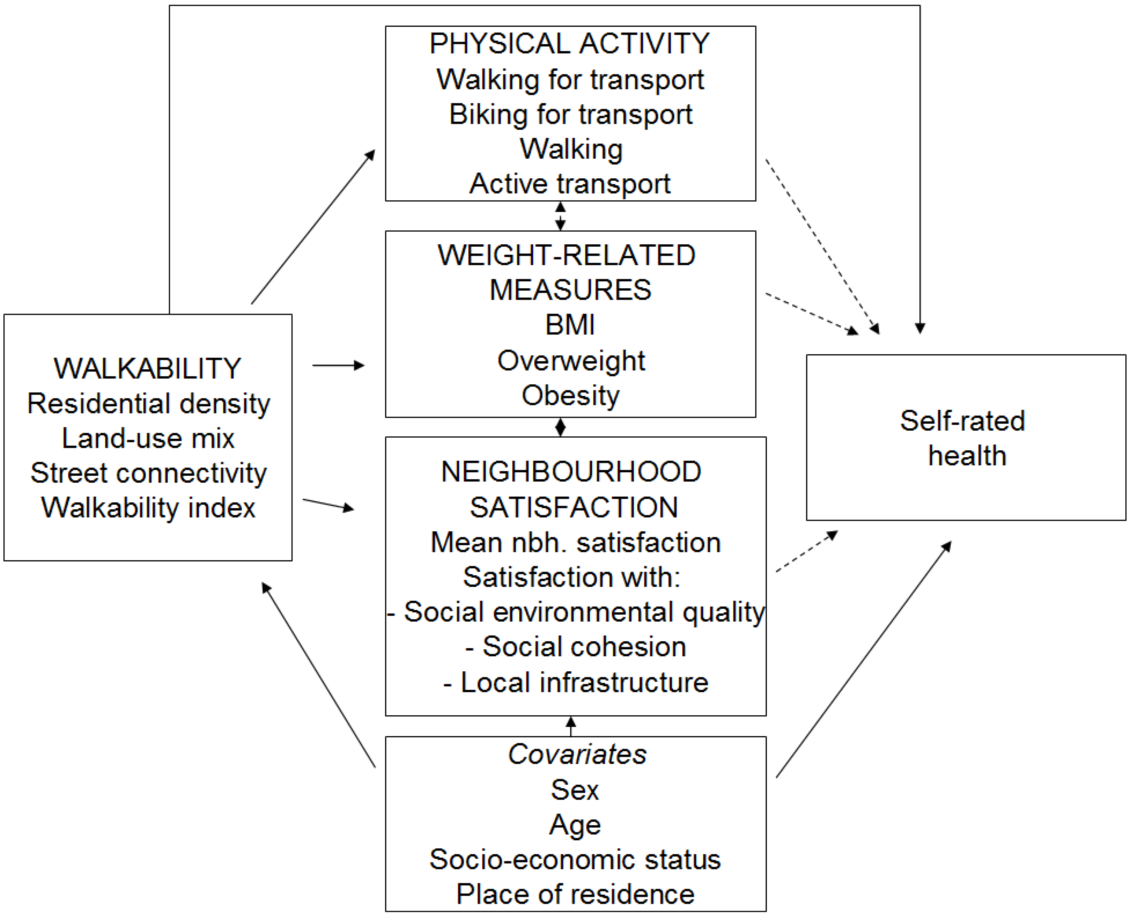


Figure 2: Model of the hypothesised associations between walkability and health-related outcomes and health

4 Methods

4.1 Study design and participants

Within the research project Radfreundliche Stadt, a representative cross-sectional survey was conducted. Computer-assisted telephone interviews (CATI) were conducted among the population of Graz ages 15-60 years in autumn 2005. The protocol was approved by the ethics committee of the local medical university (No. 17-083ex05/06).

Subjects were randomly called based on the last digit of their landline and mobile telephone numbers in the telephone directory of the city of Graz (Titze et al., 2008). Up to five calls were made to reach the respondents. There were two possible reasons for exclusion: first, respondents were permanently unable to cycle because of health problems; and second, respondents had lived less than two months in the area. Overall, 2,951 telephone numbers were called, from which 1,509 respondents were excluded because they did not fit the sample due to gender, age or education. From those reached, 444 people refused to be interviewed (Stronegger et al., 2010). One person was removed because of duplication. A representative sample of 997 individuals was achieved, with a response rate of 69.2% among the elegible population. Of the 997 participants, 843 provided a valid residential adress and were included in the present analysis. Table 9 in the results section shows the descriptive characteristics of the final sample. Descriptions of the questionnaire development, survey procedures and participants can be found in more detail in other sources (Titze et al., 2007, Titze et al., 2008, Stronegger et al., 2010).

4.2 Dependent variables

Walking for transport (for at least 10 minutes) was assessed by the question ‘On average, how many times during the past 12 months did you use the following modes of transportation within the city?’ Answers were given on a five-point Likert-type scale ranging from ‘almost daily’, ‘several times/week’, ‘about 1-2 times/week’, ‘about 1-3 times/month’, to ‘(almost) never’. The results were then converted into a days/month scale and used as a continuous variable. In addition, respondents were assigned in two groups: ‘Walking for transport users' were respondents who reported walking 'almost daily' or 'very often, several times a week' or 'once or twice a week'. All other respondents were assigned to the group 'walking for transport non-users'. The same question and procedure were applied for cylcing for transport. For the creation of the variable 'active transport users vs. non users', respondents were categorised as active transport users if they walked or cycled for transport 'almost daily' or 'very often, several times per week'. All other respondents were categorised as active transport non-users. General walking was assessed in minutes per week within the last seven days.

BMI was based on self-reported weight and height. BMI was used in the analysis as a continuous variable. In addition, it was used as a categorical variable based on the International Classification of Adult Overweight and Obesity (WHO, 2012). First, BMI was grouped in a binary variable: 'being overweight or obese' (BMI ≥ 25.00) and others (capturing 'normal-' and 'underweight'). Second, it was used as a variable in three groups: 'being overweight' (BMI 25.00 – 29.99), 'being obese' (BMI ≥ 30.00) and 'others'.

Self-rated general health was assessed on a five-point-Likert-type scale with responses ranging from 'very good' to 'very poor'. For analysis purposes, self-rated health was dichotomised. Respondents reporting 'very good' and 'good' health formed one group, with the others (capturing 'middle', 'poor' and 'very poor') forming a second group.

The questionnaire included ten items concerning the individual satisfaction with the neighbourhood. These ten items were assessed on a five-point rating scale ranging from one (very satisfied) to five (not satisfied at all). The mean of these ten items was calculated as the mean neighbourhood satisfaction.

Furthermore, three indicators were created and dichotomized around the median forming the categories 'high' and 'low' (Stronegger et al., 2010):

- general socio-environmental quality (including reputation/appearance, location of the neighbourhood, safety, recreational walking opportunities, environmental quality)
- social cohesion (including social cohesion, relationship with neighbours)

- local infrastructure (including public transport, shops and medical services, recreational and leisure time infrastructure).

4.3 Independent variables

This section will provide a description of the GIS-based measurement of walkability. To make this section easier to understand a glossary of GIS terms can be found in the appendix (see Appendix 1).

The walkability measures were caluclated using ESRI® ArcMap^{TM} 10.0 and ESRI® ArcCatalog^{TM} 10.0. The geodata on the statistical sectors (Wiener Zählsprengel) and on zoning was provided by the city of Graz covering the area of the city. Since some respondents were living on the outskirts of the city, geodata on the statistical sectors and on zoning for the area surrounding Graz was also requested from the county of Styria. Furthermore, the county of Styria provided street center line data.

The residential adresses of the respondents had to be converted to spatial data, in order to link their adress with geographic information on their residential neighbourhood. This process is called geocoding and was conducted by Michael Haberl, BSc at the Institute for Highway Engineering and Transport Planning of the Technical University of Graz. Some adresses had to be corrected to enable the geocoding process. Using the opensource software geocoder, the coordinates of each complete and valid address were determined. To validate the delivered coordinates, the data was cross-checked with the coordinates delivered by geoplaner V2.3 (Haberl, 2011).

4.3.1 Buffering

Buffer types

There is no optimal spatial definition of neighbourhood. Since relationships between health and the built environment are sensitive to the geographical scale of the neighbourhood, it is important to use different scales (Diez Roux, 2007, Macintyre, Ellaway and Cummins, 2002). There are two different types of GIS-based neighbourhood definitions used in the literature: the euclidian or circular buffer and the street network buffer. The first one is simply a circle of a specified distance around the home of the respondents (see Figure 3). To create a street network buffer, a specified distance is measured along the street network, and the created points are connected (see Figure 3). The circular buffer is supposed to better represent the characteristics of the neighbourhood, while the street network buffer may better represent the area relevant for physical activity (Oliver, Schuurman and Hall, 2007). The systematic literature review (see section 2.4) showed that more studies use street network buffers, and consequently more studies have shown that associations between walkability measures and walking are mainly observed within street network buffers (Brown et al., 2009, Coombes, Jones and Hillsdon, 2010, Forsyth et al., 2007, Frank et al., 2004, Frank et al., 2009a, Frank et al., 2008, Frank et al., 2007, Frank et al., 2006, Rundle et al., 2009). Since it is important to test different types of neighbourhood, it was decided to use both buffer types.

Figure 3: 1,000m circular buffer, 1,000m street network buffer, 1,500m street network buffer around the respondents home

Buffer distance

In addition, the scale of the neighboorhood has to be defined. Most studies use buffer distances of 800m or 1,000m. Most of these studies also found associations between walkability and health-related outcomes within these distances (Brown et al., 2009, Coombes, Jones and Hillsdon, 2010, Forsyth et al., 2007, Frank et al., 2004, Frank et al., 2009a, Frank et al., 2008, Frank et al., 2007, Frank et al., 2006, Rundle et al., 2009). A buffer distance of 1,000m is also supported by a qualitative study of Smith et al. (2010). They found that more than 94% of all destinations to which respondents reported walking were within a 1 km and 1 mile circular and network buffer (Smith et al., 2010). Furthermore, the author assumed that a walking distance of 15 to 20 minutes is reasonable, and that a healthy person walks 1 km in 15 to 20 minutes. Therefore, the present study used buffer distances of 800m and 1,000m.

In the present study, the areas of the different buffer types were very different from each other. The area of the 1000m circular buffer was 3.14 km^2, while the median area of the 1000m street network buffer was 1.47 km^2. The impression arose that the 1,000m street network buffer did not adequately capture the characteristics of the area. In addition, there are many footpaths and shortcuts in the Graz area. Futhermore, the binary analyses showed that the 1,000m street network buffer performed worse than the 1,000m circular buffer (see section 5.2.1). Most studies using 1,000m street network buffers were conducted in the US and Australia, where the transport behaviour of the population and the built environment is very different from Europe. In Europe, a larger network buffer may be more suitable. Inhabitants of European cities may also walk or cycle to destinations that are up to 1.5 km away from home. Furthermore, research in Graz has shown that 3.5 km is a reasonable distance for the population in Graz to cycle from home to a destination (Titze and Pfaffenbichler, 2014). Therefore, using a 1.5 km buffer around home would cover about half the distance the population of Graz is willing to cycle. In subsequent analysis, a 1,500m street network buffer was also incorporated, in order to gain more knowledge about neighbourhood scale, particularly in an European context.

Buffer creation

Using the buffer tool in ArcMap, circular buffers were created at a distance of 800m and 1,000m around the geocoded home address of each respondent. For the creation of the street network buffers, the dissolved and corrected street center line data was used (see section 4.3.2). A ‘split line at vertices’ operation was conducted to break the line feature down into individual street sections and to enable an efficient network analysis. To create a street network buffer, a network geodatabase must first be created in ArcCatalog. In the geodatabase, the basic model conditions were defined as follows: no modeling of turns, elevations and driving directions. Further definitions of the calculation of the street network buffers were conducted in ArcMap. As facilities, the home adress of each respondents was defined. The impedance was set to be 800m, 1,000m and 1500m, in order to create the street network buffer in three different distances.

4.3.2 Geodata modeling

The geodata provided by the city of Graz was delivered in the projected coordinate system MGI Austria GK East (projection: Transverse Mercator). Since the geocoded addresses and the geodata from the county of Styria were provided in WGS 1984 UTM Zone 33 N (projection: Transverse Mercator), all geodata was transformed to the second coordinate system.

Statistical sector data

The transformed data on the statistical sectors of the city of Graz and the area surrouding Graz was merged to one file. In three cases, the city of Graz splits one statistical sector as used by Statistics Austria into two different statistial sectors. This difference was corrected by merging these six statistical sectors in the geodata of the city of Graz to the three sectors used by Statistics Austria.

For each statistical sector, the number of residents and the number of household units were needed to calculate *gross population* and *household unit density*. Place of residence was defined as having the principal residence in Graz or in the area surrounding Graz. The number of residents for each statistical sector was provided by the city of Graz and by the county of Styria for the year 2006. The number of residents and the number of households for each statistical sector concerned were added manually, and the redundant sectors were deleted. The number of household units was delivered by Statistics

Austria and was only available for the year 2001, the year of the last census before the survey data was collected. Only private household units were included. The difference in statistical sectors also had to be corrected in the population data. The numbers of the statistical sectors in the provided population data had to be assigned to an ArcGis-compatible dbf-format. The tables produced were then joined in ArcMap with the statistical sector geodata. The result was that the row density numbers and the area of each statistical sector were in one file.

Zoning data

The transformed data on zoning of the city of Graz and the area surrouding Graz was merged into one file. This procedure delivered a rather large area and a large number of polygons with zoning information. The zoning file was clipped by the dissolved neighbourhood file to reduce the dataset to the necessary information and to enable a more efficient analysis. The zoning data was validated by running a topology with the following rules:

- polygons must not overlap
- polygons must not self-overlap
- the area must have no gaps

Errors were repaired individually in the editing mode. The attribute table of the zoning file was exported as a dbf file and imported into Microsoft Office Excel 2003. The zoning information was provided in abbreviated form. To decode the abbreviations, the current version of the regulation on zoning (Steiermärkische Landesregierung, 2007) was used primarily. Since not all abbreviations were found in the current version, an older version was also used (Steiermärkische Landesregierung, 2003). In Excel, the zoningen information was categorised into five categories:

1. pure residential (residential area, but services for daily living allowed)
2. mainly residential (residential, but buildings with commercial, social, religious and cultural services allowed)
3. mixed use (areas with great land use variety and higher population density, used mainly for social, religious, educational,

cultural, commercial and public buildings, but residential buildings are allowed)

4. commercial and industrial
5. green area (open space, recreational area, agricultural, silvicultural or horticultural purposes).

Areas covered by water or used for traffic purposes were excluded. About 10,000 polygons were decoded and categorised individually. After categorisation, the excel file was saved as a dbf file and joined with the zoning geodata.

Street center line data

The street center line geodata was provided separately for the area of the city of Graz and for the area surrounding Graz. The geodata files were merged to one file. According to the protocol of Forsyth et al. (2006), freeways should be excluded. Since the geodata included freeways, all line features capturing freeways were attributed individually to enable an exclusion. Based on the attribution, the freeways were excluded from the geodata and from the analysis. The street center line data was then validated by running a topology with the following rules:

- must not overlap
- must not self-overlap

Topology errors of the rule 'must not self-overlap' were corrected individually. The rule 'must not overlap' delivered about 1,700 errors. By going through the errors one at a time, it became clear that a large number of streets/line features were recorded twice but were identical to each other. A number of different GIS operations were tried to overcome this problem. The working solution was to run a dissolve operation, which dissolved all streets to one line feature. Furthermore, by looking through the topology errors, it was discovered that some streets were recorded twice but not identical to each other. These errors were corrected by comparing the street center line data with data provided by Google Earth and then corrected one at a time.

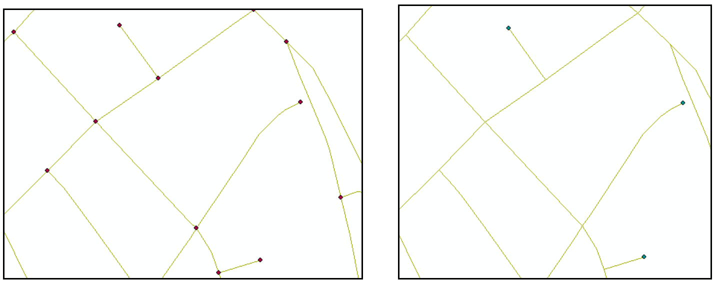


Figure 4: Creating points at both ends of each vertices and then at each dangle point

Create nodes

The dissolved street center line data was used to create three-way intersections. First, points were created at both ends of each vertices and then at each dangle point (see Figure 4). By using the overlay operation symetrical difference, the dangle points were removed from the shape file with the points at both ends of each vertices. The result was a point shape including all intersections with at least three legs. Large intersections with feeder lines or large roundabouts were captured with more than one point, even though it was only one intersection (see Figure 5). To overcome this problem, the area was first clipped by the dissolved neighbourhood file to reduce the dataset to the necessary information and to enable a more efficient analysis. Then, a circular buffer of 10m was created around each point, including a ‘dissolve all’ operation. All buffers were now captured in one polygon. To create single buffers, the operation ‘multipart to singlepart’ was run (see Figure 5). This resulted in single buffers of 314.16m^2 for intersections, where intersections were at least 10m away from each other. To identify the large intersections and roundabouts, all buffers larger than the area of 314.16m^2 were examined and edited individually. For each roundabout or large intersection with feeder lines, the automatically created points were removed, and one new point for each intersection was created manually.

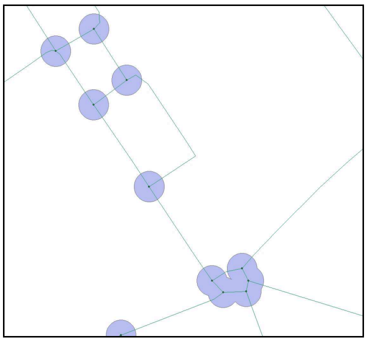


Figure 5: 10m buffer around each intersection including one roundabout

To calculate four-way intersections, the dissolved street center line data was used. A ‘split line at vertices’ operation was conducted to break down the line feature into single street sections. Using the ArcScript Cacluate Fnode, Tnode intersections were calculated based on the street center line data. To each intersection, the ArcScript automatically assigned the valence. The same problem occurred as with the creation of the three-way intersections. The large intersections with feeder lines or roundabouts were captured with more than one point, even though they were only single intersections. Therefore, the same procedure was applied as for the three-way intersections.

4.3.3 Geodata analyses

The input data for the density analyses were the neighbourhoods of the respondents and the modelled statistical sector geodata. In this case, only one operation was necessary to transfer the density information from the statistical sector geodata to the neighbourhoods. The geodata was split into two parts because the data file was too large to analyse at once in ArcMap. An ‘intersect’ operation was then run to assign the statistical sector and its row population number and number of household units to the neighbourhood of each respondent. The resulting attribute table was exported in order to conduct the further analysis in SPSS Statistics 17.0. The data was merged during the SPSS analysis.

The modelled zoning data and the shape files with the different neighbourhood types were the input geodata for the land use mix analysis. Because of the large data sets, it was necessary to split the data set in two parts. To transfer the information on land use mix from the zoning geodata to the neighbourhoods, an ‘intersect’ operation was run. Next, the neighbourhood of each respondent was assigned the different land use type and area. To unite the areas with the same land use type within the neighbourhood of each respondent, a ‘dissolve’ operation was conducted based on the ID of the respondent and on the land use type. Afterwards, the split data set was merged to one shape file, the attribute table of the geodata was exported, and further analyses were conducted in SPSS.

To calculate the connectivity measures, the geodata with the three-way and the four-way intersections and the neighbourhoods were used. Since both intersection files were point shapes, a different operation was necessary than the one used for the density and land use mix analyses. To assign the number of three-way and four-way intersections to each neighbourhood, a ‘spatial join one to many’ operation was conducted. This operation summarised all points within each neighbourhood. To calculate the number of three-way and four-way intersections per area in square kilmoeters, a new field was added to the attribute table of the shape file, the area was converted to square kilometers, and the number of intersections was divided by the area of the neighbourhood. Now, the attribute tables were ready to be exported and to serve as the basis for further analyses in SPSS.

4.4 Calculation of independent variables in SPSS

Gross population and household density

Because residential neigbhourhood was defined as buffers, the borders of the neighbourhood were not identical with the borders of the statistical sectors. Statistical sectors were cut at the end of the buffered neighbourhood. Therefore, the population number and the number of household units had to be apportioned according to the percentage of land area falling inside and outside of the neighbourhood (Forsyth et al., 2006). First, the area of each neighbourhood was summarized and converted to square kilometers. Then, the percentage of land area falling inside the neighbourhood was calculated by dividing the area of each statistical sector falling inside the neighbourhood by the total area of the statistical sector. The result was multiplied by the population number or the number of household units of the relevant statistical sector. Next, the apportioned population or household units of the statistical sectors falling within a neighbourhood were summarized. The result was divided by the total area (excluding area covered by water and area for traffic purposes) of the neighbourhood (see formulas Table 8).

Land use mix

To calculate the *entropy index,* the following formula based on Forsyth et al. (2006) and Frank et al. (2004) was used: $\{-\sum [(pi)\ (\ln pi)]\ \} / \ln n$, where pi is the area of each land use type divided by the total area of all land use types defined for the study (excluding area covered by water and area for traffic purposes), and n is the number of land use types used in the study (see also Table 8). Some studies used the total area of the neighbourhood as a denominator for the calculation of pi (Bodea et al., 2008, Frank et al., 2004, Frank et al., 2007). They argue that neighbourhoods where the total area of all land use types defined for the study is highly mixed but covers only a small part of the buffer will have the same *entropy index* as neighbourhoods that are highly mixed throughout the whole area. For the present study, this differentiation is less important because only areas used for traffic and water were excluded. The *entropy index* was calculated once based on the five land use types defined (see section 4.3.2). In the binary analyses, the *entropy index* with five land use categories did not perform very well. Therefore, a second *entropy index* was calculated using four land use types by combing the land use types ‘mainly residential’ and ‘mixed use’ to a new type ‘mixed use’. The *entropy index* ranges from 0 to 1. The value 0 captures areas with only one land use type and no land use mix. The value 1 represents a perfect distribution in the area of all included land use types. A land use mix as close as possible to 1, which reflects a highly mixed environment, is desired.

The information provided in the zoning data did not allow for proper differentiation between different land uses because two land use types in the actual zoning data can be considered to be mixed use. By definition, the land use types ‘mainly residential’ (defined as residential, but buildings with commercial, social, religious and cultural services allowed) and ‘mixed use’ (defined as areas with great land use variety and higher population density, used mainly for social, religious, educational, cultural, commercial and public buildings, but residential buildings are allowed) capture high land use mix. For example, if the area of one neighbourhood is categorised as *mixed use* only, the *entropy index* will be zero. There is only one land use type present, and therefore there is no land use mix. This does not properly capture the real situation. To overcome this issue, a new land use mix parameter was developed. The area of the land use categories ‘mainly residential’ and ‘mixed use’ were summarized within the neighbourhood. Then the sum was divided by the total area of all land use types defined for the study. In this way the *proportion of mixed land use* within the neighbourhood was calculated. Neighbourhoods with low values were considered to have a low land use mix, and neighbourhoods with high values were considered to have a high land use mix.

Connectivity

Based on the protocol of Forsyth et al. (2006) and on the study of Forsyth et al. (2008), *three-way* and *four-way intersection densities* were calculated as described above in ArcGis (see section 4.3.3). The number of intersections was divided by the area of the neighbourhood in square kilometers. The measure *three-way intersection density* is widely used in the literature, while *four-way intersection density* is less common. However, for a European setting such as Graz, the measure *four-way intersection density* may be more suitable. Three-way intersections are rather common in Graz, even in less walkable areas. *Four-way intersection density* may enable a better differentiation between walkable and less walkable areas, since they are less common in less walkable neighbourhoods.

Table 8: Formulas for calculating independent variables

Independent variable	**Formula**
Gross population density	Apportionment of population number: area of statistical sector within the neighbourhood / total area° of the statistical sector * number of residents Density: sum of number of apportioned residents within the neighbourhood / total area of the neighbourhood
Household unit density	Apportionment of number of household units: area of statistical sector within the neighbourhood / total area of the statistical sector * number of household units Density: sum of number of apportioned household units within the neighbourhood / total area of the neighbourhood
Entropy index using four or five land use types	{-∑ [(pi) (ln pi)] } / ln n pi = the area of each land use type / the total area of all land use types defined for the study n = the number of land use types used in the study (n=4 or n=5)
Proportion of mixed land use	sum of area of land use categories ‘mainly residential’ and ‘mixed use’ within the neighbourhood / the total area of the neighbourhood
Three-way intersection density	Number of three-way intersections / the total area of the neighbourhood
Four-way intersection density	Number of four-way intersections / the total area of the neighbourhood
IPEN walkability index	(2*z-score three-way intersection density) + (z-score household unit density) + (z-score entropy index using five land use types)
Index of Frank et al. (2007)	(z-score three-way intersection density) + (z-score household unit density) + (z-score entropy index using five land use types)
Graz walkability index	(z-score four-way intersections) + (z-score proportion of mixed land use) + (z-score household-unit-density)

°total area is in all cases excluding area covered by water and area for traffic purposes

Walkability indices

Based on formulas used in the literature and on the formula used by the International Physical Activity and the Environment Network (IPEN), a walkability index was calculated using the z-scores of each component variable. The following formula was computed: (2*z-score *three-way intersection density*) + (z-score *household unit density*) + (z-score *entropy index* using five land use types). In the NQLS (Frank et al., 2006, Sallis et al., 2009) and PLACE (Owen et al., 2007) studies, the ‘retail floor area ratio’ was also included in the index. This variable was omitted in the present study due to lack of relevance for a European setting (Van Dyck et al., 2010) such as Graz and because no geodata was available.

The weighting within the *IPEN walkability index* seemed not entirely suitable for Graz, since connectivity generally was not a very strong correlate of health-related outcomes in the binary analyses. Therefore, as a starting point we also used the formula of Frank et al. (2007). This formula is the same as for the *IPEN walkability index*. The only difference is that each component variable has the same weight.

As mentioned above, the *entropy index* did not seem to be entirely appropriate for the zoning data available. Furthermore, the binary analyses showed that connectivity measured as *four-way intersection density* related more often and stronger to health-related outcomes than *three-way intersection density*. Consequently, the author computed another *walkability index* which seemed to be more adequate for Graz, or perhaps for a European setting in general. Instead of the *entropy index,* the author used the *proportion of mixed land use* in the neighbourhood. Instead of the *three-way intersection density,* we used the *four-way intersection density*. Nevertheless, to normalize the values of the variables, z-scores were calculated. Components were not weighted. Subsequently, the following formula was computed: z-score *four-way intersection density* + z-score *proportion of mixed land use* + z-score *household unit density*.

The formula for the *IPEN* and the *Graz walkability index* were based on normalized values, using z-scores. In the PLACE study, deciles were used to deliver a score from 1 to 10, and the index was computed by summing up these decile scores (Owen et al., 2007). Following this example, the present study additionally used percentiles and deciles to standardize the independent variables and to compute the indices using percentiles and deciles.

4.5 Covariates

Evidence suggests that associations between walkability and health-related outcomes differ by sex (Grasser et al, 2013), age (Van Cauwenberg et al, 2011) and education (Forsyth et al, 2009, Owen et al, 2007, Frank et al, 2008). For the study area of the city of Graz, it was additionally assumed that associations between walkability and health-related outcomes would differ by population density, as a proxy for different urban structures. Therefore, the bivariate analyses were stratified by sex, age, education and *gross population density*. The variables age and *gross population density* were split around the median. Education was dichotomized into compulsory school, apprentice training, and intermediate vocational degree versus high school diploma and polytechnic school/university.

The bivariate analyses showed that the stratification by education and *gross population density* yielded no statistically significant results in many cases. Because, some studies have found associations between walkability and health-realted outcomes differ by socio-economic status (Sallis et al, 2009, Turrel et al, 2013, Witten et al, 2012) we replaced education by socio-economic-status. Furthermore, reports on the population of Graz have shown differences in the perceived quality of life between the populations residing on the west and east sides of the river (City of Graz, 2009). The west side of the river is traditionally considered to be the place of residence for blue collar workers, while the east side of the river, where the old universities and most of the cultural heritage sites are located, is considered to be the home of the intellectuals. Therefore we replaced “gross population density” by “place of residence (west and east side of the river).

Consequently, for the bivariate controlled analyses, sex, age, socio-economic status and place of residence were used as covariates and for stratification.

As a covariate, age was used as a categorical variable in nine groups (see Table 9). For the individual socio-economic status, a cumulative score was computed. The score included educational status, occupational status and income. As a covariate, the score was used as a continuous variable.

For stratification purposes, both age and the socio-economic status score were split around the median.

4.6 Data analyses

Analyses were performed using the SPSS Statistics 17.0 software for Windows.

The independent walkability variables were analysed in quartiles and used as categorical variables.

The analyses began with the following dependent health-related outcomes (see also section 4.2) as continuous, binary and categorical variables.

Continuous variables:

- Walking for transport (days per month)
- Cycling for transport (days per month)
- General walking (minutes per week)
- BMI (kg/m^2)
- Mean neighbourhood satisfaction (mean of the neighbourhood satisfaction scores 1-5)

Binary variables:

- Walking for transport (users versus non-users)
- Cycling for transport (users versus non-users)
- Active transport (users versus non-users)
- BMI (overweight and obese versus others)
- Self-rated general health (very good and good versus others)
- Neighbourhood satisfaction with general socio-environmental quality (dichotomized around the median)
- Neighbourhood satisfaction with social cohesion (dichotomized around the median)
- Neighbourhood satisfaction with local infrastructure (dichotomized around the median)

The only ordinal variable was BMI in three groups (obese versus overweight versus others).

The distribution of the continuous variables was analysed. The distribution of walking for transport was left skewed. The distribution of cycling for transport had two peaks at the lowest and the highest value, with the highest peak at the highest value. The distribution of general walking, BMI and neighbourhood satisfaction were right skewed. For these variables the logarithm was calculated and used for the analyses. In all cases, parametric tests were used, because parametric tests are robust if the sample size is large (Fagerland, 2012, Skovlund and Fenstad, 2001).

For all analyses the results section reports the p-values. Results with p-values smaller than 0.05 were considered to be statistically significant. Nevertheless, to provide additional information and to report p-values, that are borderline not statistical significant, the results also report the p-values smaller than 0.250, while p-values larger than 0.250 were not reported.

Before the investigation of the bivariate associations between walkability and health-related outcomes, the performances of differently scaled dependent and independent variables were explored. First, the best weight-related measures and the best measures for walking and biking for transport were determined. The bivariate associations between walkability and BMI as a continuous, binary and categorical variable, as well as walking and cycling for transport as continuous and binary variable were calculated, and the better performing measures were used for further analyses. Second, different measures for land use mix and connectivity and different walkability indices were explored in the same way. For continuous outcome variables, ANOVAs were conducted, while chi^2-tests were performed for binary variables.

The bivariate analysis was then conducted to examine the association between each indivudual walkability variable and the health-related outcomes, as well as how these assocations differed by age, sex, education and *gross population density*. Here again, ANOVAs and chi^2-tests were used, and the results were stratified by the aforementioned covariates.

Controlled bivariate analyses were conducted to examine the association between each individual walkability variable, controlling for the covariates sex, age, socio-economic status and place of residence. Moreover, these bivariate controlled analyses were stratified by sex, age, socio-economic status and place of residence. ANOVAs were used for continuous outcome variables and binary logistic regression was used for binary outcome variables.

In the ANCOVAs, the continuous health-related outcome was the dependent variable, while the independent walkability variable, sex, age and place of residence were fixed factors. The individual socio-economic status as a continuous variable was treated as a covariate in the model. In a customized model, each variable was tested for its main effects.

In the binary logistic regression, the binary health-related outcome was the dependent variable, while the independent walkability variable, sex, age, socio-economic status and place of residence were defined as covariates. Furthermore, sex, age, place of residence and the walkability variable were defined as categorical variables. The choosen method was ‘Enter’.

Finally, multiple models were used to examine the association between multiple walkability variables and each individual health-related outcome. These models were controlled for sex, age, socio-economic status and place of residence. The walkability variables included in the models were chosen based on the following criteria:

- Strong and frequent association with health-related outcomes in the bivariate and bivariate controlled analyses
- Only one variable from each dataset

When these selection criteria were applied, *household unit density, proportion of mixed land use* and *four-way intersection density* remained as relevant walkability measures.

Here again, ANCOVAs and binary logist regressions were performed.

The ANCOVAs included the continuous health-related outcome as the dependent variable and the three selected independent walkability variables, sex, age and place of residence as fixed factors. As in the other ANCOVAs, the individual socio-economic status was defined as a covariate in the model. Once again, each variable was tested for its main effects using a customized model. In addition to the p-values of each variable the results section also provides the *R* squared of the full model. The *R* squared shows the proportion of variance of each health-related outcome explained by the walkability measures and the covariates.

As with other binary logistic regressions the binary health-related outcome was the dependent variable, and the choosen walkability variables, sex, age, socio-economic status and place of residence were entered as the covariates. Here again, the walkability variables, sex, age and place of residence were defined as categorical variables. In addition to the p-values, the results provides the Nagelkerke R squared to show the proportion of the variance of each health-related outcome explained by all included factors.

To ensure results of the statistical models are not violated by interactions between different included variables (i.e. sex, age, health-related outcomes) all analysis were stratified by sex, age, socio-economic status and place of residence.

5 Results

This chapter describes the initial sample characteristics and then provides the results of the analyses which were undertaken to explore different possibilities for operationalizing the outcome and exposure measures used in the present study. Finally, the results of the analyses are described. The results are structured by the different walkability indicators and provide one table for the uncontrolled and one table for the controlled analysis. The text describes the results structured by health-related outcomes. Starting with the outcomes that did not show an association, the physical activity variables are discussed first, followed by the neighbourhood satisfaction variables.

5.1 Description of the sample

The sample contained sligthly more women than men (see Table 9). The respondents were almost equally distributed across the nine age groups. There were more respondents not achieving general qualification than respondents achieving general qualification for university entrance. Since the sample was split around the median, there were the same number of respondents with high and low socio-economic status. More respondents lived on the east side of the river.

Men cycled less often for transport, were less often users of active transport modes, and had a higher BMI than women. Men also rated their health less often as good and were less often satisfied with the social cohesion in the neighbourhood. Respondents age 35-45 biked more often than other age groups. BMI increased and self-rated health decreased with age. Respondents achieving general qualification for university entrance and respondents with a high socio-economic status walked less often for transport and in general, but biked more often for transport than respondents with a lower educational status. Furthermore, they reported a smaller BMI, better self-rated health and higher satisfaction with the social environmental quality of the neighbourhood than lower educated respondents. On the other hand, they were less often satisfied with the social cohesion and local infrastructure of their neighbourhood than respondents with low education and a low socio-economic status. Respondents residing in the eastern part of Graz biked more frequently, were more often users of active transport, reported a better health status and reported being more satisfied with the social environmental quality, social cohesion and local infrastructure than respondents residing in the West of Graz (see also section 5.3.1).

Table 9: Descriptive characteristics of the sample based on health-related outcomes

		No	**Twalk d/m**	**Tbike d/m**	**Walk min/w**	**BMI**	**Nbh sat**	**Act trans**	**Self-rated health^**	**Social env. quality**	**Social cohesion**	**Infrastructure**
			Median (IQR)	Median (IQR)	Median (IQR)	Median (IQR)	Median (IQR)	%	%	%	%	%
Sex	Male	401	24 (18)	6 (21)	150 (189.7)	24.2 (4.4)	2.1 (0.8)	82.5	80.0	49.6	43.1	51.1
	Female	442	24 (12)	9 (24)	150 (174.7)	22 (4.4)	2.1 (0.8)	90.5	83.5	50.0	55.9	52.3
Age	15-19	85	24 (12)	6 (15)	120 (184.8)	20.4 (2.9)	2.0 (0.8)	92.9	96.5	55.3	56.5	50.6
	20-24	80	12 (12)	6 (24)	120 (189.7)	21.6 (3)	2.1 (0.9)	86.3	83.8	48.8	41.3	43.8
	25-29	107	12 (18)	6 (21)	120 (189.7)	22.4 (3.7)	2.2 (0.8)	82.2	85.0	46.7	38.3	54.2
	30-34	83	24 (12)	6 (21)	180 (210)	22.8 (4.3)	2.2 (1.0)	85.5	84.3	47.0	49.4	59.0
	35-39	108	12 (18)	12 (21)	145 (189.7)	22.8 (4.8)	2.0 (0.9)	85.2	83.3	50.0	50.0	58.3
	40-44	101	24 (12)	12 (24)	179 (174.7)	22.9 (4.9)	2.1 (0.7)	85.1	79.2	51.5	49.5	55.4
	45-49	97	24 (12)	6 (24)	120 (202.8)	24.2 (4.5)	2.1 (1.0)	88.7	72.2	47.4	51.5	39.2
	50-54	80	24 (12)	6 (23)	210 (202.8)	24.4 (4.1)	2.1 (0.9)	83.8	80.0	55.0	55.0	57.5
	55-60	102	24 (12)	6 (21)	180 (240)	25 (4.1)	2.0 (0.8)	91.2	74.5	48.0	57.8	47.1
Education°	Low	480	24 (12)	6 (21)	152 (189.7)	23.5 (5.0)	2.1 (0.9)	87.5	80.0	48.3	52.3	53.1
	High	363	12 (18)	12 (21)	150 (189.7)	22.3 (4.0)	2.1 (0.8)	85.7	84.3	51.8	46.6	49.9
SES	Low	422	24 (12)	6 (24)	180 (174.7)	23.2 (4.9)	2.1 (0.9)	88.4	79.4	45.3	49.3	53.8
	High	421	24 (18)	12 (21)	150 (190)	22.8 (4.2)	2.0 (0.8)	85.0	84.3	50.4	49.6	54.5
Residence*	West	334	24 (18)	6 (24)	150 (189.7)	23.7 (4.9)	2.3 (0.9)	84.7	77.2	34.7	43.4	47.3
	East	509	24 (12)	12 (21)	150 (174.7)	22.5 (4.2)	2.0 (0.7)	88.0	84.9	59.7	54.0	54.6

twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; ^ = very good and good self-rated health; ° low = not achieving general qualification for university entrance, high = achieving general qualification for university entrance; *Residence on the west or east side of the river;

Table 10: Descriptive characteristics of the sample based on the density variables

			Gross population density per km2			**Household unit density per km2**		
			CB 1000m	NWB 1000m	NWB 1500m	CB 1000m	NWB 1000m	NWB 1500m
		No	Median (IQR)	Median (IQR)	Median (IQR)	Median (IQR)	Median (IQR)	Median (IQR)
Sex	Male	401	4215 (4531)	4592 (5242)	4129 (4213)	1837 (2259)	2071 (2583)	1860 (2076)
	Female	442	3800 (4219)	4356 (4528)	3913 (4287)	1701 (2161)	1980 (2374)	1736 (2156)
Age	15-19	85	3546 (3535)	3736 (3740)	3561 (3580)	1580 (1820)	1654 (2001)	1627 (1867)
	20-24	80	4363 (5705)	4122 (6572)	4230 (5095)	2012 (2727)	1969 (3115)	1896 (2626)
	25-29	107	4659 (3512)	5339 (3811)	4570 (3401)	2147 (1765)	2450 (1832)	2171 (1753)
	30-34	83	4721 (3792)	5376 (4233)	4450 (3247)	2193 (1908)	2452 (2340)	2121 (1713)
	35-39	108	3049 (3639)	3465 (4163)	3459 (3923)	1342 (1830)	1513 (2178)	1489 (2080)
	40-44	101	4333 (4414)	4443 (4656)	4344 (4027)	1914 (2185)	2060 (2481)	1922 (1962)
	45-49	97	3412 (4397)	3742 (5246)	3380 (4655)	1472 (2135)	1552 (2685)	1474 (2165)
	50-54	80	4193 (5085)	4749 (5904)	4352 (4508)	1926 (2356)	2233 (2922)	1976 (2326)
	55-60	102	3656 (4174)	4324 (4416)	4004 (4155)	1624 (2141)	1942 (2267)	1721 (2074)
Education°	Low	480	4031 (4122)	4502 (4723)	4126 (4130)	1857 (2055)	2081 (2349)	1898 (2042)
	High	363	4413 (4787)	4797 (5195)	4478 (4645)	2063 (2454)	2246 (2530)	2091 (2318)
SES	Low	422	4401 (4292)	4919 (4903)	4472 (3918)	2036 (2101)	2282 (2396)	2067 (1888)
	High	421	3990 (4419)	4338 (4691)	4083 (4357)	1855 (2172)	2022 (2456)	1894 (2218)
Residence*	West	334	4050 (3929)	4646 (4184)	4144 (3378)	1818 (1957)	2084 (2118)	1861 (1654)
	East	509	4291 (4776)	4618 (5114)	4366 (4869)	2030 (2511)	2197 (2629)	2059 (2566)

° low = not achieving general qualification for university entrance, high = achieving general qualification for university entrance; *Residence on the west or east side of the river; CB = circular buffer, NWB = street network buffer;

Table 11: Descriptive characteristics of the sample based on land use mix variables

			Entropy index			**Proportion of mixed land use**		
			CB 1000m	NWB 1000m	NWB 1500m	CB 1000m	NWB 1000m	NWB 1500m
		No	Median (IQR)	Median (IQR)	Median (IQR)	Median (IQR)	Median (IQR)	Median (IQR)
Sex	Male	401	0.79 (0.13)	0.74 (0.18)	0.81 (0.13)	42.9 (40.5)	52.7 (41.8)	22.0 (18.4)
	Female	442	0.80 (0.15)	0.81 (0.12)	0.81 (0.12)	41.3 (39.7)	47.9 (44.1)	20.7 (17.2)
Age	15-19	85	0.78 (0.21)	0.71 (0.18)	0.81 (0.16)	37.1 (42.7)	39.4 (46.2)	19.1 (17.9)
	20-24	80	0.78 (0.15)	0.72 (0.20)	0.81 (0.14)	41.5 (48.1)	53.0 (46.1)	21.7 (21.7)
	25-29	107	0.80 (0.07)	0.76 (0.11)	0.82 (0.07)	51.3 (29.8)	59.5 (31.4)	26.5 (15.0)
	30-34	83	0.80 (0.11)	0.75 (0.17)	0.82 (0.07)	43.9 (34.2)	55.5 (31.4)	24.8 (16.4)
	35-39	108	0.79 (0.16)	0.74 (0.18)	0.79 (0.12)	35.2 (38.3)	38.7 (42.0)	19.2 (18.5)
	40-44	101	0.80 (0.14)	0.77 (0.19)	0.81 (0.13)	44.0 (40.6)	51.6 (40.1)	22.3 (19.0)
	45-49	97	0.79 (0.13)	0.74 (0.19)	0.81 (0.14)	35.9 (36.1)	42.9 (45.3)	19.6 (17.2)
	50-54	80	0.79 (0.15)	0.74 (0.20)	0.81 (0.13)	42.9 (42.9)	48.9 (46.1)	22.4 (19.9)
	55-60	102	0.79 (0.15)	0.75 (0.18)	0.82 (0.11)	43.2 (37.0)	53.8 (41.7)	23.0 (16.3)
Education°	Low	480	0.77 (0.15)	0.72 (0.18)	0.79 (0.13)	41.6 (36.5)	46.1 (41.0)	22.0 (16.1)
	High	363	0.75 (0.14)	0.71 (0.16)	0.78 (0.12)	44.5 (44.2)	49.8 (46.7)	23.3 (19.6)
SES	Low	422	0.78 (0.13)	0.74 (0.16)	0.80 (0.11)	44.9 (36.4)	49.9 (38.3)	23.7 (16.5)
	High	421	0.74 (0.17)	0.70 (0.18)	0.77 (0.14)	40.4 (43.8)	45.5 (47.9)	21.5 (19.2)
Residence*	West	334	0.80 (0.13)	0.76 (0.18)	0.83 (0.11)	42.3 (29.1)	48.2 (30.9)	22.5 (12.8)
	East	509	0.73 (0.18)	0.69 (0.18)	0.76 (0.15)	42.9 (50.1)	47.4 (53.1)	22.6 (23.4)

° low = not achieving general qualification for university entrance, high = achieving general qualification for university entrance; *Residence on the west or east side of the river; CB = circular buffer, NWB = street network buffer;

Table 12: Descriptive characteristics of the sample based on connectivity variables

			Three-way intersection density			**Four-way intersection density**		
			CB 1000m	NWB 1000m	NWB 1500m	CB 1000m	NWB 1000m	NWB 1500m
		No	Median (IQR)	Median (IQR)	Median (IQR)	Median (IQR)	Median (IQR)	Median (IQR)
Sex	Male	401	74.2 (27.9)	87.7 (33.0)	83.6 (27.7)	12.7 (13.2)	14.0 (15.1)	15.0 (13.9)
	Female	442	71.1 (31.6)	84.5 (33.4)	79.9 (27.0)	12.7 (14.0)	14.7 (16.1)	14.4 (14.3)
Age	15-19	85	68.8 (23.4)	78.9 (27.8)	78.2 (23.7)	9.5 (11.3)	13.0 (15.3)	12.4 (12.6)
	20-24	80	78.6 (34.8)	91.1 (33.9)	85.3 (36.1)	11.6 (18.9)	13.3 (21.8)	14.0 (17.3)
	25-29	107	76.7 (26.7)	91.0 (29.5)	85.7 (25.8)	16.2 (12.4)	19.6 (14.9)	18.0 (11.4)
	30-34	83	77.0 (28.7)	86.2 (32.2)	83.9 (25.8)	15.3 (13.4)	19.0 (16.6)	17.6 (12.4)
	35-39	108	72.4 (31.4)	84.7 (33.2)	80.2 (27.9)	9.9 (13.3)	12.2 (16.2)	11.6 (14.4)
	40-44	101	72.3 (32.5)	87.7 (39.2)	82.1 (29.9)	15.0 (17.4)	18.3 (20.2)	16.3 (14.8)
	45-49	97	71.6 (36.0)	80.9 (30.4)	79.4 (33.9)	11.8 (13.1)	13.1 (14.1)	13.3 (14.1)
	50-54	80	72.6 (31.4)	87.4 (37.9)	83.7 (32.4)	14.5 (15.9)	16.2 (19.4)	15.8 (16.6)
	55-60	102	71.1 (24.6)	78.3 (30.8)	80.7 (26.9)	11.8 (10.4)	13.1 (12.9)	13.2 (11.7)
Education°	Low	480	71.4 (27.9)	84.8 (32.0)	80.3 (26.0)	13.5 (12.7)	16.4 (14.5)	15.0 (13.6)
	High	363	75.9 (33.1)	90.1 (35.4)	84.3 (31.4)	14.9 (15.9)	17.9 (18.1)	16.0 (15.6)
SES	Low	422	73.9 (25.0)	86.8 (32.0)	82.7 (24.2)	14.9 (12.8)	17.9 (15.3)	16.4 (13.0)
	High	421	72.8 (34.4)	87.3 (33.8)	81.3 (30.4)	13.4 (14.3)	16.2 (16.2)	14.6 (15.2)
Residence*	West	334	69.7 (29.1)	84.8 (33.6)	78.9 (26.3)	13.9 (12.2)	17.2 (14.3)	15.6 (13.1)
	East	509	75.7 (33.0)	88.5 (32.5)	84.0 (31.2)	14.2 (14.6)	16.9 (16.7)	15.4 (15.4)

° low = not achieving general qualification for university entrance, high = achieving general qualification for university entrance; *Residence on the west or east side of the river; CB = circular buffer, NWB = street network buffer;

Table 13: Descriptive characteristics of the sample based on walkability indices

			IPEN walkability index$^{\#}$			**Graz walkability index^**		
			CB 1000m	NWB 1000m	NWB 1500m	CB 1000m	NWB 1000m	NWB 1500m
		No	Median (IQR)	Median (IQR)	Median (IQR)	Median (IQR)	Median (IQR)	Median (IQR)
Sex	Male	401	0.72 (3.68)	0.31 (3.00)	0.48 (4.02)	0.41 (4.78)	-0.12 (4.44)	0.10 (4.91)
	Female	442	0.46 (3.79)	0.07 (3.26)	0.38 (3.76)	-0.23 (4.55)	-0.37 (4.37)	-0.23 (4.69)
Age	15-19	85	0.17 (3.82)	-0.19 (3.30)	0.02 (3.86)	-1.07 (4.28)	-0.91 (4.33)	-0.99 (4.12)
	20-24	80	0.83 (4.76)	0.61 (3.42)	0.66 (5.17)	0.28 (5.90)	-0.08 (5.75)	0.30 (6.04)
	25-29	107	1.01 (2.89)	0.88 (2.96)	0.63 (3.04)	1.09 (3.61)	1.20 (3.56)	0.74 (4.01)
	30-34	83	0.93 (3.21)	0.80 (2.38)	0.83 (3.68)	0.85 (3.96)	1.09 (4.06)	0.81 (4.21)
	35-39	108	0.43 (3.69)	-0.39 (2.99)	0.15 (3.73)	-1.26 (4.34)	-1.22 (4.52)	-1.11 (4.43)
	40-44	101	0.60 (3.94)	0.41 (3.41)	0.41 (4.00)	0.06 (4.58)	0.38 (3.99)	0.18 (4.80)
	45-49	97	0.20 (4.44)	-0.30 (3.83)	-0.03 (4.39)	-0.96 (4.46)	-1.10 (4.51)	-0.97 (4.83)
	50-54	80	0.63 (4.83)	0.54 (3.99)	0.31 (4.52)	0.04 (5.28)	-0.07 (4.97)	0.46 (5.66)
	55-60	102	0.46 (3.80)	-0.05 (2.94)	0.41 (3.34)	-0.27 (4.21)	-0.24 (4.14)	-0.31 (4.25)
Education°	Low	480	-0.18 (3.27)	-0.18 (3.02)	-0.17 (3.55)	-0.19 (4.14)	-0.17 (4.11)	-0.17 (4.34)
	High	363	0.24 (4.53)	0.23 (3.38)	0.22 (4.63)	0.26 (5.27)	0.23 (4.90)	0.23 (5.50)
SES	Low	422	0.24 (3.01)	0.20 (2.75)	0.28 (3.21)	0.25 (4.40)	0.26 (4.12)	0.28 (4.44)
	High	421	-0.24 (4.28)	-0.20 (3.67)	-0.28 (4.21)	-0.25 (4.74)	-0.26 (4.62)	-0.28 (4.87)
Residence*	West	334	-0.11 (3.15)	0.06 (2.66)	-0.01 (2.46)	-0.14 (3.68)	-0.01 (3.64)	-0.10 (3.42)
	East	509	0.07 (4.52)	-0.04 (3.67)	0.01 (4.85)	0.09 (5.46)	0.01 (5.22)	0.06 (5.81)

° low = not achieving general qualification for university entrance, high = achieving general qualification for university entrance; *Residence on the west or east side of the river; CB = circular buffer, NWB = street network buffer; $^{\#}$ z-household unit density + z-entropy index + (2 x z-3-way intersection density); ^ z-household unit density + z-% of mixed use + z-4-way intersection density;

Overall, male respondents lived in neighbourhoods with a higher walkability than female respondents (see Table 10, Table 11, Table 12, and Table 13). Only the *entropy index* and the *four-way intersection density* did not differ by sex. Respondents in the age of 25 to 34 showed a tendency towards living in high-walkable areas compared to respondents from other age groups (see also section 5.3.2). High-educated respondents lived in neighbourhoods with a higher walkability than low-educated respondents. In contrast, respondents with a high socio-economic status lived in neighbourhoods with lower walkability than respondents with a low socio-economic status. Respondents living in the eastern part of Graz lived in areas with a higher walkability compared to respondents living in the western part of Graz.

5.2 Exploration of different measurement issues

5.2.1 Definition of neighbourhood

As discussed in section 4.3.1, the association between walkability and health-related outcomes is sensitive to the scale of the neighbourhood defined. Different scales of neighbourhood should be tested. Table 14 shows the results of the bivariate analyses of the associations between the walkability variables the author started the analyses with the health-related outcomes.

The analyses explored the associations within circular and street network buffers. Comparing the p-values of the 800m and 1,000m circular and street network buffers in Table 14 shows that the p-values for the association between walkability and health-related outcomes were more often significant and/or smaller for the circular buffers than for the street network buffers. Since street network buffers were used more often in the literature (see section 2.4), this result was surprising. The area of the street network buffers was much smaller than the area of the circular buffer using the same buffer distance (see section 4.3.1). The area of the street network buffers may have been too small to capture the characteristics of the neighbourhood.

The present study also used different buffer distances. Table 14 shows that the p-values of the 800m buffers were less often significant or larger than the p-values of the 1,000m and 1,500m buffers. The association between walkability and health-related outcomes was thus weaker in the smaller neighbourhoods than in the larger ones. Once again, the area of the 800m buffer may have been too small to capture the characteristic of the neighbourhood. Because of the results from the bivariate analyses, and because of the argumentation described in section 4.3.1, the present study focused on the 1,000m and 1,500m buffers.

5.2.2 Measuring weight-related measures

Different operationalisations of weight-related measures are used in the literature (see Table 2), but there is no clear pattern in terms of which of the investigated weight-related measures is most important in relation to walkability. Therefore, three different weight-related measures were used in the present study. As described in section 4.2 BMI was used as a continuous variable and as categorical variables. For the categorical variables, BMI was grouped in two groups (BMI ≥ 25, others) and in three groups (BMI 25.00 to 29.99, BMI ≥ 30, others).

Table 15 shows the results from the bivariate analyses. Associations between walkability and weight-related measures were rare, but BMI as a continuous variable more often showed statistically significant associations than the other variables. Consequently, the further analyses used only BMI and no categorical weight-related measure.

Table 14: Bivariate associations of different defined neighbourhoods between walkability variables and health-related outcomes (p-values < 0.250)

Walkability variable	**Buffer**	**Twalk d/m**	**Tbike d/m**	**Walk min/w**	**BMI**	**Nbh sat**	**Act trans**	**Self-rated health**	**Social env. quality**	**Social cohesion**	**Infra-structure**
Gross population density	CB 800m	--	.000	--	--	*.003*	.007	--	*.000*	*.000*	.000
	CB 1000m	--	.000	--	--	*.000*	.002	--	*.000*	*.000*	.000
	NWB 800m	--	.001	--	--	*.004*	.007	--	*.000*	*.000*	.000
	NWB 1000m	--	.001	--	--	*.000*	.010	--	*.000*	*.000*	.000
	NWB 1500m	.242	.000	--	--	*.000*	.009	--	*.000*	*.000*	.000
Household unit density	CB 800m	--	.000	--	--	*.007*	.003	--	*.000*	*.000*	.000
	CB 1000m	.094	.000	--	--	*.000*	.002	--	*.000*	*.000*	.000
	NWB 800m	--	.001	--	--	*.006*	.013	--	*.000*	*.000*	.000
	NWB 1000m	.106	.000	--	--	*.000*	.005	--	*.000*	*.000*	.000
	NWB 1500m	.229	.000	--	--	*.000*	.003	--	*.000*	*.000*	.000
Entropy index (5-types)	CB 800m	--	--	--	--	.081	--	--	*.000*	--	.003
	CB 1000m	--	.012	--	--	*.008*	.186	*.031*	*.000*	*.007*	.001
	NWB 800m	--	--	--	--	--	--	--	*.018*	--	.000
	NWB 1000m	--	.090	--	--	--	.085	--	*.015*	--	.000
	NWB 1500m	--	.033	--	--	*.000*	.042	.078	*.000*	*.011*	.001

CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (the lower the walkability, the higher the satisfaction with social-environmental quality and social cohesion) (note: direction of association only marked for statistically significant associations (p<,05)

Cont. Table 14

Walkability variable	**Buffer**	**Twalk d/m**	**Tbike d/m**	**Walk min/w**	**BMI**	**Nbh sat**	**Act trans**	**Self-rated health**	**Social env. quality**	**Social cohesion**	**Infra-structure**
3-way intersection density	CB 800m	--	.040	--	--	--	--	--	*.001*	*.002*	.000
	CB 1000m	.087	.009	--	--	.060	.000	--	*.000*	*.001*	.000
	NWB 800m	--	--	--	--	--	--	--	--	*.022*	.000
	NWB 1000m	--	.202	--	--	*.024*	--	--	*.024*	*.015*	.000
	NWB 1500m	.191	.003	--	--	.173	.002	--	*.000*	*.001*	.000
4-way intersection density	CB 800m	--	.046	--	--	*.022*	--	--	*.000*	*.000*	.000
	CB 1000m	--	.005	--	--	*.000*	.046	--	*.000*	*.000*	.000
	NWB 800m	--	--	--	--	*.021*	--	--	*.000*	*.000*	.000
	NWB 1000m	--	.069	--	--	*.000*	.207	--	*.000*	*.000*	.000
	NWB 1500m	--	.001	--	.177	*.000*	.055	--	*.000*	*.000*	.000
IPEN walkability index*	CB 800m	--	.001	--	--	*.023*	.045	--	*.000*	*.000*	.000
	CB 1000m	.131	.000	--	--	*.000*	.002	--	*.000*	*.000*	.000
	NWB 800m	--	.040	--	--	.103	.044	--	*.000*	*.000*	.000
	NWB 1000m	.144	.022	--	--	*.000*	.059	--	*.000*	*.000*	.000
	NWB 1500m	.178	.002	.223	--	*.000*	.001	--	*.000*	*.000*	.000

CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (the lower the walkability, the higher the satisfaction with social-environmental quality and social cohesion) (note: direction of association only marked for statistically significant associations (p<,05); * z-household unit density + z-entropy index + (2 x z-3-way intersection density); ° z-household unit density + z-% of mixed use + z-4-way intersection density

Table 15: Bivariate associations between walkability variables and different weight-related measures (p-values < 0.250)

Walkability variables	**Buffer**	**BMI**	**Overweight vs. obesity vs. others**	**Overweight and obesity vs. others**
Gross population density	CB 1000m	--	--	--
	NWB 1000m	--	--	--
	NWB 1500m	--	--	--
Household unit density	CB 1000m	--	--	--
	NWB 1000m	--	--	--
	NWB 1500m	--	--	--
Entropy index (5-types)	CB 1000m	--	--	--
	NWB 1000m	--	--	--
	NWB 1500m	--	--	--
% of mixed use	CB 1000m	*.050*	--	.092
	NWB 1000m	--	--	--
	NWB 1500m	*.054*	--	.131
3-way intersection density	CB 1000m	--	--	--
	NWB 1000m	--	--	--
	NWB 1500m	--	--	--
4-way intersection-density	CB 1000m	--	--	--
	NWB 1000m	--	--	.204
	NWB 1500m	.177	--	--
IPEN walkability index*	CB 1000m	.234	--	--
	NWB 1000m	--	--	--
	NWB 1500m	--	--	--
Graz walkability index°	CB 1000m	.212	--	--
	NWB 1000m	--	--	--
	NWB 1500m	--	--	--

CB = circular buffer, NWB = street network buffer; Italics: association in the unexpected direction (the lower the walkability the higher the BMI) (note: direction of association only marked for statistically significant associations (p<,05); * z-household unit density + z-entropy index + (2 x z-3-way intersection density); ° z-household unit density + z-% of mixed use + z-4-way intersection density

5.2.3 Measuring walking and biking for transport

There is a wide range of measures available for walking and biking for transport. The survey from the study project Radfreundliche Stadt provided data on walking and biking for transport as a continuous and as a binary variable (sees section 4.2). In the bivariate analysis, all four measures were tested. Table 16 shows that the association between the walkability variables and walking and biking for transport was stronger using the continuous variable than using the binary variables. Because of this performance, the present study used only the continuous variables for further analysis.

Table 16: Bivariate associations between walkability variables and different measures for walking and biking for transport (p-values < 0.250)

Walkability variables	Buffer	Twalk d/m	Twalk dicho	Tbike d/m	Tbike dicho
Gross population density	CB 1000m	--	.038	.000	.002
	NWB 1000m	--	.087	.001	.087
	NWB 1500m	.242	--	.000	.025
Household unit density	CB 1000m	.094	--	.000	.013
	NWB 1000m	.106	--	.000	.060
	NWB 1500m	.229	--	.000	.022
Entropy index (5-types)	CB 1000m	--	--	.012	.016
	NWB 1000m	--	--	.090	.062
	NWB 1500m	--	--	.033	.102
% of mixed use	CB 1000m	.222	.103	.000	.012
	NWB 1000m	.108	--	.006	.244
	NWB 1500m	.057	--	.000	.010
3-way intersection density	CB 1000m	.087	.144	.009	.231
	NWB 1000m	--	--	.202	--
	NWB 1500m	.191	--	.003	.137
4-way intersection density	CB 1000m	--	--	.005	--
	NWB 1000m	--	--	.069	--
	NWB 1500m	--	.223	.001	--
IPEN walkability index*	CB 1000m	.131	--	.000	.197
	NWB 1000m	.144	--	.022	--
	NWB 1500m	.178	--	.002	.138
Graz walkability index°	CB 1000m	--	--	.000	.116
	NWB 1000m	.146	--	.000	.075
	NWB 1500m	.222	.102	.000	.091

CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport; d/m= days per month, min/w= minutes per week, dicho= dichotomised; * z-household unit density + z-entropy index + (2 x z-3-way intersection density); ° z-household unit density + z-% of mixed use + z-4-way intersection density

5.2.4 Measuring land use mix

The literature review showed that most studies used the *entropy index* as a measure of land use mix (see Table 5). Half of the studies found a statistically significant association with walking for transport. Studies looking at weight-related outcomes and their association with the *entropy index* showed mixed results. Different studies used data from different data sources and used a different number of land use types to calculate the index. Furthermore, there are small differences in how the formula of the index was applied in different studies. To contribute to the knowledge on the performance of different *entropy* *indices*, we calculated one index based on five land use types and one index based on four land use types (see section 4.4). Additionally, a new land use mix measure, *proportion of mixed land use,* was developed that seems to be more appropriate for the zoning data of the city of Graz (see section 4.4).

The association between these three measures of land use mix and the health-related outcomes was investigated in the bivariate analyses to identify the best measures to be used for further analyses. Table 17 shows that the newly developed variable *proportion of mixed land use* was more often statistically significantly associated with health-related outcomes and also showed smaller p-values than the other measures. In particular, the *entropy index* using four land-use types was barely associated with the outcomes. The *entropy index* using five land-use types performed better than the one using four land-use types. Even though the *entropy index* using five land-use types performed worse than the newly developed measure *proportion of mixed use*, the present study used both for further analyses. Because of its widespread use in the literature, the *entropy index* should be included.

5.2.5 Measuring connectivity

Almost all studies reviewed used *three-way intersection density* as a measure of connectivity. All studies found an association between *three-way intersection density* and walking for transport, but results for the association with weight-related measures were inconsistent (see Table 5). Nevertheless, to contribute to the knowledge about the best connectivity measure for a European setting, the present study also included *four-way intersection density* in the analyses (see also section 4.4). Table 18 shows that the associations between *four-way intersection density* and health-related outcomes were slightly stronger and more frequent than between *three-way intersection density* and the outcomes. Consequently both measures were included for further analysis. Because of the slightly better performance of *four-way intersection density,* the present study included this measure in the *Graz walkability index*.

Table 17: Bivariate associations between different measures of land use mix and health-related outcomes (p-values < 0.250)

Walkability variable	**Buffer**	**Twalk d/m**	**Tbike d/m**	**Walk min/w**	**BMI**	**Nbh sat**	**Act trans**	**Self-rated health**	**Social env. quality**	**Social cohesion**	**Infra-structure**
Entropy index (5-types)	CB 1000m	--	.012	--	--	*.008*	.186	*.031*	*.000*	*.007*	.001
	NWB 1000m	--	.090	--	--	--	.085	--	*.015*	--	.000
Entropy index (4-types)	CB 1000m	.161	--	--	--	.139	.055	--	*.053*	--	--
	NWB 1000m	--	.154	--	--	*.003*	.102	--	*.002*	.239	--
% of mixed use	CB 1000m	.222	.000	.190	.044+	*.000*	.004	.089	*.000*	*.000*	.001
	NWB 1000m	.108	.006	.149	.291	*.000*	.029	.098	*.000*	*.000*	.001

CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (the lower the walkability, the higher the satisfaction with social-environmental quality and social cohesion) (note: direction of association only marked for statistically significant associations (p<0,05)); + respondents living in areas of medium walkability (quartile 2 and 3 out of 4) have a higher BMI than respondents living in high and low walkability areas.

Table 18: Bivariate associations between different measures of connectivity and health-related outcomes (p-values < 0.250)

Walkability variable	**Buffer**	**Twalk d/m**	**Tbike d/m**	**Walk min/w**	**BMI**	**Nbh sat**	**Act trans**	**Self-rated health**	**Social env. quality**	**Social cohesion**	**Infra-structure**
3-way intersection density	CB 1000m	.087	.009	--	--	.060	.000	--	*.000*	*.001*	.000
	NWB 1000m	--	.202	--	--	*.024*	--	--	*.024*	*.015*	.000
	NWB 1500m	.191	.003	--	--	.173	.002	--	*.000*	*.001*	.000
4-way intersection-density	CB 1000m	--	.005	--	--	*.000*	.046	--	*.000*	*.000*	.000
	NWB 1000m	--	.069	--	--	*.000*	.207	--	*.000*	*.000*	.000
	NWB 1500m	--	.001	--	.177	*.000*	.055	--	*.000*	*.000*	.000

CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (the lower the walkability, the higher the satisfaction with social-environmental quality and social cohesion) (note: direction of association only marked for statistically significant associations (p<0,05))

5.2.6 Constructing walkability indices

As described in section 4.4, most studies computed z-scores to normalise the variables used as a basis for the walkability index. In the PLACE study, deciles were used for standardisation (Owen et al., 2007). In the bivariate analyses, the present study therefore tested percentiles and deciles to find the most suitable way of standardisation. Table 19 shows the results of the different computations of the walkability indices. The indices based on the z-scores most frequently delivered statistically significant p-values and the smallest p-values compared to the indices based on deciles or percentiles. Consequently, the present study used the indices based on z-scores in the further analysis.

Table 19: Bivariate associations between different walkabilty indices and health-related outcomes (p-values < 0.250)

Walkability variable	**Buffer**	**Twalk d/m**	**Tbike d/m**	**Walk min/w**	**BMI**	**Nbh sat**	**Act trans**	**Self-rated health**	**Social env. quality**	**Social cohesion**	**Infra-structure**
IPEN walkability index* (z-scores)	CB 1000m	.131	.000	--	--	*.000*	.002	--	*.000*	*.000*	.000
	NWB 1000m	.144	.022	--	--	*.000*	.059	--	*.000*	*.000*	.000
	NWB 1500m	.178	.002	.223	--	*.000*	.001	--	*.000*	*.000*	.000
IPEN walkability index* (deciles)	CB 1000m	.225	.000	--	.201	--	.005	--	*.000*	*.000*	*.000*
	NWB 1000m	--	.008	--	--	.000	.102	--	*.000*	*.000*	*.000*
	NWB 1500m	.161	.001	--	--	.000	.004	--	*.000*	*.000*	*.000*
IPEN walkability index* (percentiles)	CB 1000m	--	.001	--	.179	.000	.002	--	*.000*	*.000*	.000
	NWB 1000m	.168	.027	--	--	.193	.082	--	*.000*	*.000*	.000
	NWB 1500m	.102	.013	--	--	.000	.004	.066	*.000*	*.000*	.000
Graz walkability index° (z-scores)	CB 1000m	--	.000	--	.124	*.000*	.003	*.025*	*.000*	*.000*	.000
	NWB 1000m	.146	.000	.190	--	*.000*	.013	--	*.000*	*.000*	.000
	NWB 1500m	.222	.000	--	.115	*.000*	.010	.100	*.000*	*.000*	.000
Graz walkability index° (deciles)	CB 1000m	--	.000	--	--	*.004*	.004	.165	*.000*	*.000*	.000
	NWB 1000m	--	.000	--	--	*.021*	.029	.182	*.000*	*.000*	.000
	NWB 1500m	--	.000	--	--	*.027*	.007	.177	*.000*	*.000*	.000
Graz walkability index° (percentiles)	CB 1000m	--	.000	--	--	*.007*	.003	.098	*.000*	*.000*	.000
	NWB 1000m	--	.000	--	--	*.011*	.009	.228	*.000*	*.000*	.000
	NWB 1500m	--	.000	--	--	*.022*	.011	.142	*.000*	*.000*	.000

CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (the lower the walkability, the higher the satisfaction with social-environmental quality and social cohesion) (note: direction of association only marked for statistically significant associations (p<0,05)); * household unit density + entropy index + (2 x 3-way intersection density); ° household unit density + % of mixed use + 4-way intersection density

5.3 Exploration of differences by potential confounders

5.3.1 Place of residence on the west or east side of the river

In the sample of the present study, the proportion of respondents achieving general qualification for university entrance residing on the east side of the river was statistically significantly higher than among the respondents residing on the west side of the river (p=000) (data not shown). In addition, the socio-economic status among the respondents residing on the west side was significantly lower than the socio-economic status among the respondent residing on the east side of the river (p=000). Therefore, it was necessary to investigate the strength of the confounding effect of the place of residence on the association between walkability and health-related outcomes. The study first investigated differences between walkability variables and health-related outcomes based on the place of residence of the respondents. Second, it analysed differences in the bivariate associations between walkability variables and health-related outcomes in general and stratified by education. Finally, the study reports on the strength of confounding of the place of residence on the bivariate associations.

Table 20 shows that most walkability variables were slightly lower in the western part of Graz than in the eastern part of the city. Only the *entropy index* and the *four-way intersection density* were slightly higher in the western part than in the eastern part of the city. The difference between the West and the East was statistically significant for the *entropy index* in all buffers, for the *three-way intersection density,* for the 1,000m circular buffer and the 1,500m street network buffer and for the *household unit density* for the circular buffer. The *entropy index* was significantly higher in the West. This does not necessarily mean that the land use was more mixed in the West than in the East. As described in section 4.4 the zoning data already included two land use types that are mixed use. Therefore, it is more likely that more area in the eastern part of the city was already classified as mixed use, which kept the *entropy index* low, even though the land use mix was high. This assumption is supported by the fact that the *proportion of mixed land use* (as shown in Table 20) was higher in the East than in the West. Overall, Table 20 shows that the walkability in the West was not significantly lower than in the East.

Almost all health-related outcomes (see Table 21 and Table 22) were significantly worse in the West than in the East. Only walking for transport and use of active transport were not statistically significantly different.

To summarize, there were differences in education, socio-economic status and health-related outcomes between respondents residing on the east and the west sides of the river, but no differences in walkability. Consequently, the results of a bivariate analyses stratified by place of residence are presented next. To ensure that age and sex did not confound the analyses, the analyses controlled for these variables. Furthermore, the author stratified by education to see if there were differences in associations in different educational groups.

Table 20: Descriptive statistics of the walkability variables stratified by place of residence

Walkability variable	**Buffer**	**West**				**East**				
		Median	**IQR**	**Min**	**Max**	**Median**	**IQR**	**Min**	**Max**	**p-value#**
Gross population density	CB 1000	3802.15	3928.98	187.84	8716.20	4364.22	4776.48	101.93	9019.60	.212
	NWB 1000	4702.15	4184.42	172.61	10294.90	4312.90	5113.62	106.22	10168.10	.920
	NWB 1500	3904.58	3377.88	157.37	8663.19	4427.70	4869.00	102.52	8830.27	.259
Household unit density	CB 1000	1703.41	1957.49	73.66	4022.80	1985.24	2511.27	28.45	4401.81	.050
	NWB 1000	2056.39	2117.63	62.46	4586.56	2047.96	2677.18	29.12	5100.21	.395
	NWB 1500	1704.60	1653.88	56.60	3992.45	2082.20	2565.65	27.98	4288.53	.069
Entropy index (5-types)	CB 1000	0.8079	0.13	0.12	1.00	0.7803	0.18	0.05	0.95	.000
	NWB 1000	0.7655	0.18	0.11	0.98	0.7283	0.18	0.12	0.95	.000
	NWB 1500	0.8403	0.11	0.23	0.99	0.7876	0.15	0.07	1.09	.000
% of mixed use	CB 1000	41.51	29.07	0.86	83.72	43.95	50.07	0.00	85.86	.824
	NWB 1000	48.84	30.86	0.00	87.00	53.54	53.12	0.00	90.25	.985
	NWB 1500	20.57	12.79	0.00	39.12	23.19	23.41	0.00	42.85	.980
3-way intersection dens.	CB 1000	70.03	29.05	3.50	131.78	74.80	32.95	8.59	137.83	.001
	NWB 1000	84.11	33.59	8.79	156.08	87.34	32.53	9.12	171.30	.149
	NWB 1500	79.46	26.26	15.02	119.63	83.62	31.23	13.20	126.73	.001
4-way intersection-dens.	CB 1000	13.69	12.18	0.00	31.83	12.41	14.64	0.32	38.83	.440
	NWB 1000	16.46	14.25	0.00	40.75	13.30	16.70	0.00	47.04	.173
	NWB 1500	15.40	13.10	0.00	29.94	14.05	15.40	0.52	34.75	.340
IPEN walkability index*	CB 1000	0.4909	3.15	-11.74	5.20	0.6331	4.52	-11.91	5.80	.126
	NWB 1000	0.4893	2.66	-11.41	5.60	0.0477	3.67	-11.24	5.86	.641
	NWB 1500	0.3786	2.46	-12.48	5.19	0.5016	4.85	-13.95	7.84	.160
Graz walkability index°	CB 1000	-0.1099	3.68	-4.79	5.25	-0.2187	5.46	-4.79	6.12	.111
	NWB 1000	-0.2210	3.64	-4.83	5.02	-0.2861	5.22	-4.82	5.83	.474
	NWB 1500	0.0837	3.42	-5.10	4.66	-0.2133	5.81	-5.33	5.61	.816

#Mann-Whitney U

CB = circular buffer, NWB = street network buffer; * household unit density + entropy index + (2 x 3-way intersection density); ° household unit density + % of mixed use + 4-way intersection density

Table 21: Descriptive statistics of the continuous health-related outcome variables stratified by place of residence

Outcome	**West**				**East**				
	Median	**IQR**	**Min**	**Max**	**Median**	**IQR**	**Min**	**Max**	**p-value#**
Twalk d/m	24	18	00	24	24	12	00	24	.851
Tbike d/m	6	24	00	24	12	21	00	24	.006
Walk min/w	121	180	15	4800	120	210	14	4250	.052
BMI	23.67	5.01	16.33	46.49	22.49	4.21	15.94	34.69	.000
Nbh sat	2.3	0.9	1.0	4.40	2.0	0.70	1.0	4.10	.000

#Mann-Whitney U

twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction; d/m= days per month, min/w= minutes per week;

Table 22: Descriptive statistics of the binary health-related outcome variables stratified by place of residence

Outcome	**West**		**East**		
	Users / low	**Non-Users / high**	**Users / low**	**Non-Users / high**	**p-value***
Act trans (non-users vs. users)	15.3%	84.7%	12.0%	88.0%	.169
Self-rated health (low vs. high)	22.8%	77.2%	15.1%	84.9%	.000
Social env. quality (low vs. high)	65.3%	34.7%	40.3%	59.7%	.000
Social cohesion (low vs. high)	56.6%	43.4%	46.0%	54.0%	.003
Infrastructure (low vs. high)	52.7%	47.3%	45.4%	54.6%	.038

*Pearson Chi-Square

Act trans= active transport;

Bivariate Analyses

Table 23 shows that walking and biking for transport and active transport were consistently positively associated with walkability in the East but not in the West. Satisfaction with social cohesion and satisfaction with local infrastructure were associated with walkability in the West but not in the East. For the outcomes neighbourhood satisfaction and satisfaction with the social environmental quality, no such clear pattern emerged. Nevertheless, negative associations between walkability and neighbourhood satisfaction were slightly stronger in the West, while negative associations between walkability and satisfaction with social environmental quality were slightly stronger in the East. BMI was positively associated with connectivity in the West, but not for all neighbourhood scales. General walking and self-rated health were not associated with walkability in the East or the West. However, these results were confounded by education.

Table 24 and Table 25 show the results stratified by education. In the group of respondents achieving general qualification for university entrance (Table 24), differences between residing east or west of the river were less pronounced than in the whole sample and than they were among respondents not achieving general qualification for university entrance. Nevertheless, the positive association between walkability and biking for transport and satisfaction with local infrastructure were stronger for respondents living on the east side of the river than for respondents living on the west side of the river among the highly educated group.

The associations between walkability and walking for transport and active transport and the differences between East and West, which were observed in the whole sample, almost disappeared in the highly educated group. Walking for transport was mainly in the western part of the city associated with walkability. Additionally these associations were negative, so walking was lower in high-walkable neighbourhoods than in low-walkable neighbourhoods. In both parts of the city, active transport was associated with single measures of walkability, but the association was often not linear. Highly educated respondents living in areas of medium walkability used active transport less than highly educated respondents living in areas of low or high walkability.

The associations between walkability and general walking were different among the highly educated group than in the whole sample. General walking was not associated with walkability in the whole sample. Among the highly educated respondents, it was positive, and mainly in the eastern part of the city associated with walkability. Overall the place of residence was less important for the association between walkability and physical activity for transport among highly educated respondents than among the whole sample.

However, there were differences by place of residence for the neighbourhood satisfaction factors. The negative association between walkability and neighbourhood satisfaction and satisfaction with social environmental quality and with social cohesion was stronger among highly educated respondents residing in the West than in the East. The reason could be that neighbourhood satisfaction was high in the East anyway, regardless of the walkability of the neighbourhood. This reasoning is supported by the descriptive statistics in Table 21, which show that mean neighbourhood satisfaction was higher in the East than in the West.

Among highly educated respondents, BMI was negatively associated with walkability in the West, but not in the East. Self-rated health was not associated with walkability, regardless of place of residence.

Comparing the results of the whole sample (Table 23) with the results of the respondents not achieving general qualification for university entry (Table 25), the positive associations between walking for transport and walkability in the East and satisfaction with local infrastructure and walkability in the West almost disappeared.

Among the low-educated respondents, biking for transport and use of active transport were positively associated with walkability in the East, but not in the West.

In the whole sample, there were negative associations between satisfaction with social cohesion and walkability in the West, while among the low-educated respondents, there was mainly a negative association in the East. Among low-educated respondents, mean neighbourhood satisfaction and the satisfaction with social environmental quality were negatively associated with walkability in both parts of the city. Satisfaction with local infrastructure was only positively associated with a couple of walkability variables.

Self-rated health and general walking were not at all associated, and BMI was almost not associated with walkability among the lower-educated respondents.

In summary, in the whole sample, walkability was more frequently and strongly related to physical activity for transport in the East than in the West. The neighbourhood satisfaction factors, in contrast, were more frequently and strongly related to walkability in the West than in the East. Among the low-educated respondents, we observed a similar pattern. Among highly educated respondents, differences were overall less frequent and less pronounced, but there were differences between the two parts of the city. These results and the results of the descriptive statistics suggest that the composition of the population differs by place of residence and that this difference has an impact on the association between walkability and health-related outcomes.

The question remained if in the entire bivariate analyses of the present study should be controlled for place of residence as a confounder. Therefore, the author did first a bivariate analysis on the whole sample, controlling for age, sex, socio-economic status and place of residence. A cross check if place of residence would reach statistical significance as a confounder in the association between walkability variables and health-related outcomes was necessary.

Table 26 shows that place of residence was a statistically significant confounder in the bivariate association between walkability and biking for transport, BMI and all neighbourhood satisfaction factors. It was not significant in the association between walkability and walking for transport and general walking and use of active transport. In the association between walkability and self-rated health, place of residence only reached statistical significance for a few connectivity variables and the *IPEN walkability inde*x. Nevertheless, Table 26 shows that place of residence played an important role in the association between walkability and health-related outcomes.

Therefore, the entire bivariate analysis was controlled for place of residence, in addition to sex, age and socio-economic status.

Table 23: Bivariate associations between walkability and health-related outcomes (p-values < 0.250) stratified by place of residence controlled for age and sex

Walkability variable	**Buffer**	**Twalk d/m**		**Tbike d/m**		**Walk min/w**		**BMI**		**Nbh sat**		**Act trans**		**Self-rated health**		**Social env. quality**		**Social cohesion**		**Infra-structure**	
		W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E
Gross population density	CB 1000m	--	.017^	--	.000	--	--	--	.168	*.000*	*.000*	.129	.000	--	--	*.000*	*.000*	*.010*	--	.017^	--
	NWB 1000m	--	.047	--	.000	--	--	--	--	*.000*	*.000*	.208	.000	--	--	*.000*	*.000*	*.018*	--	.047	--
	NWB 1500m	--	.054	--	.000	--	--	--	.061	*.000*	*.000*	--	.001	--	--	*.000*	*.000*	*.012*	--	.054	--
Household unit density	CB 1000m	--	.018	--	.000	--	--	--	--	*.000*	*.000*	.110	.000	--	--	*.000*	*.000*	*.006*	--	.018	--
	NWB 1000m	--	.024	--	.000	--	.181	--	--	*.000*	*.000*	.183	.000	--	--	*.000*	*.000*	*.014*	--	.024	--
	NWB 1500m	--	.032	--	.000	--	--	--	.240	*.000*	*.000*	.175	.000	--	--	*.000*	*.000*	*.012*	--	.032	--
Entropy index (5 types)	CB 1000m	--	--	.112	.041	--	.102	--	--	--	.244	--	.237	--	.209	*.101*	*.003*	--	--	--	.112
	NWB 1000m	--	--	--	.035	--	--	.232	*.012*	.222	--	.236	.229	--	--	--	--	--	--	--	--
	NWB 1500m	--	--	.085	.090	.079	.060	--	--	.110	.073	.051	--	--	.196	*.005*	*.001*	.083	--	--	.085
% of mixed use	CB 1000m	--	.016	.063	.000	--	--	.189	--	*.000*	*.000*	.217	.000	--	--	*.000*	*.000*	*.003*	--	.016	.063
	NWB 1000m	--	.090	--	.000	--	--	--	--	*.000*	*.000*	--	.010	--	.055	*.000*	*.000*	*.002*	--	.090	--
	NWB 1500m	--	.026	.192	.000	--	--	.077	--	*.000*	*.000*	--	.001	--	--	*.000*	*.000*	*.015*	--	.026	.192
3-way intersection density	CB 1000m	--	.007	--	.004	--	--	*.044*	--	*.000*	--	.156	.000	--	--	*.000*	*.016*	*.023*	--	.007	--
	NWB 1000m	--	--	.209	.010	--	.223	--	--	--	*.000*	.149	.078	.239	--	*.032*	*.028*	.215	--	--	.209
	NWB 1500m	--	.024	--	.002	--	--	*.002*	--	*.001*	.212	.152	.002	.222	--	*.000*	*.019*	.082	--	.024	--
4-way intersection density	CB 1000m	.179	.047	--	.000	--	--	.055	--	*.000*	*.036*	.172	.003	.207	.122	*.000*	*.000*	*.000*	.179	.047	--
	NWB 1000m	--	.027	--	.000	.248	--	.069	--	*.000*	.072	--	.003	.243	--	*.000*	*.000*	*.002*	--	.027	--
	NWB 1500m	--	.049	--	.000	--	--	*.003*	--	*.000*	*.004*	.154	.004	--	--	*.000*	*.000*	*.015*	--	.049	--
IPEN walkability index*	CB 1000m	.049	.079	--	.001	--	--	--	--	*.000*	.101	.023	.001	--	--	*.000*	*.000*	*.006*	.049	.079	--
	NWB 1000m	--	.029	.095	.000	--	--	--	--	*.000*	--	.153	.007	--	--	*.000*	*.000*	*.004*	--	.029	.095
	NWB 1500m	--	.014	--	.000	--	--	.210	--	*.000*	.068	.054	.000	--	--	*.000*	*.000*	*.002*	--	.014	--
Graz walkability index°	CB 1000m	--	.034	--	.000	--	--	.094	--	*.000*	*.001*	.088	.000	.063	--	*.000*	*.000*	*.002*	--	.034	--
	NWB 1000m	--	.007	--	.000	--	--	--	--	*.000*	*.000*	.124	.010	--	--	*.000*	*.000*	*.002*	--	.007	--
	NWB 1500m	--	.032	--	.000	--	--	.094	--	*.000*	*.000*	--	.003	--	--	*.000*	*.000*	*.003*	--	.032	--

W=West, E=East; CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (the lower the walkability, the higher the satisfaction with social-environmental quality and social cohesion) (note: direction of association only marked for statistically significant associations (p<0,05)); * z-household unit density + z-entropy index + (2 x z-3-way intersection density); ° z-household unit density + z-% of mixed use + z-4-way intersection density; ^ respondents living in areas of medium walkability (quartile 2 and 3 out of 5) walk less than respondents living in high and low walkability areas.

Table 24: Bivariate associations between walkability and health-related outcomes (p-values < 0.250) stratified by place of residence controlled for age and sex for respondents achieving general qualification for university entrance

Walkability variable	**Buffer**	**Twalk d/m**		**Tbike d/m**		**Walk min/w**		**BMI**		**Nbh sat**		**Act trans**		**Self-rated health**		**Social env. quality**		**Social cohesion**		**Infra-structure**	
		W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E
Gross population density	CB 1000m	.219	--	.092	.021	--	--	.083	.223	*.012*	.201	.057	.056	--	--	*.001*	*.003*	.113	.163	--	.000
	NWB 1000m	.141	.151	.185	.001	--	.105	.138	--	*.013*	.128	.157	.070	--	--	*.000*	*.001*	.110	.219	--	.001
	NWB 1500m	--	--	.212	.015	--	--	.122	.169	*.012*	.160	.212	.082	--	--	*.001*	*.002*	.060	.131	--	.001
Household unit density	CB 1000m	--	.182	.113	.015	--	--	.082	--	*.012*	.252	.053^	.061	--	--	*.001*	*.003*	.112	.182	--	.000
	NWB 1000m	.240	.119	.137	.001	--	.032	.088	--	*.013*	.194	.130	.026	--	--	*.000*	*.001*	.120	.094	--	.000
	NWB 1500m	--	.202	--	.022	--	.116	.155	.132	*.024*	.091	--	.066	--	--	*.001*	*.001*	.087	.125	--	.001
Entropy index (5 types)	CB 1000m	--	--	.001	.029	.217	.219	--	--	.072	.242	.121	--	.128	.082	.230	*.015*	--	.223	--	.009
	NWB 1000m	--	--	.049	.068	--	--	*.044*	--	.127	--	.062	--	.111	--	.055	--	--	--	--	.038
	NWB 1500m	--	--	.002	.239	--	.041	--	--	.061	*.043*	.026	--	.142	.237	*.029*	*.003*	.201	.133	--	.011
% of mixed use	CB 1000m	*.015*	--	.106	.008	--	.239	.030	--	*.001*	*.020*	.076	.033	--	.207	*.000*	*.000*	.056	.085	--	.000
	NWB 1000m	.190	.198	--	.072	--	--	.002	--	*.023*	.054	.154	.249	--	.004^	*.000*	*.000*	.169	.065	--	.004
	NWB 1500m	.128	--	--	.013	--	.234	.012	--	*.010*	*.024*	.193	.084	--	.162	*.000*	*.000*	.176	*.027*	--	.000
3-way intersection density	CB 1000m	*.046*	.026^	.014	--	--	.034	.091	--	*.002*	--	.034^	.025^	.150	--	*.000*	.205	.107	--	--	.000
	NWB 1000m	--	--	.106	--	--	--	.082	--	--	*.000*	.174	.203	--	.248	*.001*	.057	--	--	--	.000
	NWB 1500m	.106	.085	.014	.188	--	.101	.023	--	*.000*	*.048*	.099	.064	--	--	*.000*	.164	*.030*	--	--	.000
4-way intersection density	CB 1000m	.110	.165	--	.002	--	.091	.120	--	.000^	--	.159	.136	--	--	*.000*	*.014*	*.017*	.204	--	.000
	NWB 1000m	.097	.080	--	.003	*.017*	.203	.066	--	*.001*	--	--	.044	--	--	*.000*	*.035*	*.045*	--	--	.000
	NWB 1500m	.193	.241	--	.001	--	.089	.025	--	.000^	.223	--	.030^	--	.162	*.000*	*.005*	*.028*	.059	--	.000
IPEN walkability index*	CB 1000m	*.000*	.208	.202	.025	--	.066	.072	--	*.006*	--	.009^	.097	--	--	*.000*	*.002*	*.053*	.116	--	.000
	NWB 1000m	*.008*	.078	.046	.118	--	.103	--	--	*.018*	--	.023	.078	--	--	*.000*	.094	*.046*	--	--	.000
	NWB 1500m	.184	.155	.046	.044	--	.051	.041	--	.068	--	.012^	.063	--	--	*.001*	*.010*	.153	.122	--	.000
Graz walkability index°	CB 1000m	.137	.159	--	.009	--	.201	.084	--	*.000*	--	--	.054	--	--	*.000*	*.009*	*.025*	.242	--	.000
	NWB 1000m	.073	.129	--	.023	--	.169	.036	--	*.020*	.157	--	.244	--	.194	*.000*	*.002*	.094	.134	--	.004
	NWB 1500m	.181	.149	--	.018	--	--	.081	--	*.011*	.132	--	.102	--	--	*.000*	*.000*	.125	.073	--	.000

W=West, E=East; CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (e.g. the lower the walkability, the higher the satisfaction with social-environmental quality) (note: direction of association only marked for statistically significant associations (p<0,05)); * z-household unit density + z-entropy index + (2 x z-3-way intersection density); ° z-household unit density + z-% of mixed use + z-4-way intersection density; ^ respondents living in areas of medium walkability (quartile 2 and 3 out of 4) walk less / are less satisfied / use active transport less / rate their health worse than respondents living in high and low walkability areas.

Table 25: Bivariate associations between walkability and health-related outcomes (p-values < 0.250) stratified by place of residence controlled for age and sex for respondents not achieving general qualification for university entrance

Walkability variable	**Buffer**	**Twalk d/m**		**Tbike d/m**		**Walk min/w**		**BMI**		**Nbh sat**		**Act trans**		**Self-rated health**		**Social env. quality**		**Social cohesion**		**Infra-structure**	
		W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E
Gross population density	CB 1000m	--	.076	--	.005	--	--	--	--	*.009*	*.001*	--	.006	--	--	*.003*	*.000*	.083	*.006*	--	.237
	NWB 1000m	--	--	--	.009	--	--	--	--	*.003*	*.001*	--	.006	--	--	*.007*	*.000*	.221	*.010*	.095	.124
	NWB 1500m	--	.169	--	.009	--	--	--	--	*.017*	*.000*	--	.026	--	--	*.007*	*.000*	.176	*.006*	.152	.206
Household unit density	CB 1000m	--	.147	--	.005	--	--	--	--	*.000*	*.001*	--	.007	--	--	*.001*	*.000*	.084	*.010*	.224	--
	NWB 1000m	.238	.131	--	.004	--	--	--	--	*.003*	*.002*	--	.008	--	--	*.015*	*.000*	.167	*.012*	.150	.194
	NWB 1500m	--	.122	--	.009	--	--	--	--	*.033*	*.001*	--	.016	--	--	*.009*	*.000*	.223	*.007*	.193	.183
Entropy index (5 types)	CB 1000m	--	--	--	.101	--	--	--	.134	--	--	--	.200	--	--	*.022*	.167	--	.130	--	.074
	NWB 1000m	--	--	--	--	--	.248	*.040*	*.006*	.114	--	--	--	--	--	.148	--	--	--	.044	.003
	NWB 1500m	--	.243	--	--	.136	--	--	--	--	--	--	--	--	--	*.011*	.059	--	--	--	.011
% of mixed use	CB 1000m	--	.088	--	.020	--	--	--	--	*.000*	*.003*	--	.018	--	--	*.001*	*.000*	.096	*.030*	--	--
	NWB 1000m	.137	.230	--	.013	--	--	--	--	*.000*	*.000*	--	.115	.060	--	*.000*	*.000*	*.047*	*.013*	--	--
	NWB 1500m	--	.103	--	.015	--	--	--	--	*.000*	*.000*	--	.048	--	--	*.001*	*.000*	.108	*.021*	--	--
3-way intersection density	CB 1000m	--	.138	--	.006	.204	--	.081	.068	*.026*	--	--	.007	--	--	*.024*	.099	--	.169	--	--
	NWB 1000m	--	.165	--	.022	--	.072	--	--	--	.230	--	.022	--	--	--	--	--	*.027*	--	.014
	NWB 1500m	--	.235	--	.004	--	--	*.052*	--	*.033*	--	--	.016	--	--	.081	.055	--	.088	--	.178
4-way intersection density	CB 1000m	.206	--	--	.010	.154	--	.191	--	*.020*	*.003*	.147	.034	--	--	*.009*	*.000*	*.021*	*.020*	.155	.124
	NWB 1000m	--	--	--	.065	--	--	.096	--	.121	*.034*	.167	.126	--	--	*.022*	*.000*	*.030*	*.022*	--	.025
	NWB 1500m	--	.213	--	.014	--	--	*.037*	--	.135	*.005*	.082	.066	--	--	*.042*	*.000*	.225	*.024*	--	.018
IPEN walkability index*	CB 1000m	.145	--	--	.030	--	--	--	--	*.000*	.089	--	.027	--	--	*.003*	*.000*	--	*.048*	--	--
	NWB 1000m	--	--	--	.004	--	--	--	--	*.012*	.230	--	.071	--	--	*.015*	*.002*	.161	*.041*	.228	.008
	NWB 1500m	--	.109	--	.009	--	--	--	--	*.003*	*.022*	--	.017	--	--	*.004*	*.000*	*.032*	*.002*	--	.194
Graz walkability index°	CB 1000m	--	.251	--	.008	--	--	--	--	*.000*	*.002*	--	.025	.106	--	*.003*	*.000*	.098	*.021*	.251	--
	NWB 1000m	--	.047	.195	.016	.189	--	--	--	*.001*	*.002*	--	.103	--	--	*.016*	*.000*	*.008*	*.018*	.128	.249
	NWB 1500m	--	.169	--	.017	.247	--	.253	--	*.000*	*.000*	--	.091	.221	--	*.005*	*.000*	*.022*	*.016*	--	--

W=West, E=East; CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (the lower the walkability, the higher the satisfaction with social-environmental quality and social cohesion) (note: direction of association only marked for statistically significant associations (p<0,05)); * z-household unit density + z-entropy index + (2 x z-3-way intersection density); ° z-household unit density + z-% of mixed use + z-4-way intersection density

Table 26: P-values of the variable place of residence in the bivariate analyses on the association between walkability and health-related outcomes controlled for age, sex, socio-economic status and place of residence

Walkability variable	**Buffer**	**Twalk d/m**	**Tbike d/m**	**Walk min/w**	**BMI**	**Nbh sat**	**Act trans**	**Self-rated health**	**Social env. quality**	**Social cohesion**	**Infrastructure**
Gross population density	CB 1000m	--	.027	.137	.001	.000	.250	.060	.000	.001	.046
	NWB 1000m	--	.011	.149	.001	.000	.140	.068	.000	.003	.020
	NWB 1500m	--	.023	.152	.001	.000	.206	.062	.000	.002	.037
Household unit density	CB 1000m	--	.036	.154	.001	.000	--	.070	.000	.001	.049
	NWB 1000m	--	.013	.146	.001	.000	.162	.080	.000	.002	.020
	NWB 1500m	--	.039	.131	.001	.000	--	.080	.000	.001	.039
Entropy index (5 types)	CB 1000m	--	.011	.127	.001	.000	.210	.143	.000	.008	.012
	NWB 1000m	--	.019	.093	.003	.000	.165	.105	.000	.004	.008
	NWB 1500m	--	.008	.104	.001	.000	--	--	.000	.020	.013
% of mixed use	CB 1000m	--	.042	.094	.001	.000	.165	.145	.000	.001	.010
	NWB 1000m	--	.022	.195	.001	.000	.235	.179	.000	.002	.008
	NWB 1500m	--	.015	.195	.001	.000	.182	.150	.000	.005	.007
3-way intersection density	CB 1000m	--	.037	.153	.001	.000	--	.039	.000	.001	.086
	NWB 1000m	--	.017	.136	.001	.000	.159	.054	.000	.002	.046
	NWB 1500m	--	.046	.142	.001	.000	--	.055	.000	.001	.079
4-way intersection density	CB 1000m	--	.008	.131	.001	.000	.133	.062	.000	.003	.035
	NWB 1000m	--	.006	.112	.001	.000	.115	.069	.000	.008	.015
	NWB 1500m	--	.007	.136	.001	.000	.138	.047	.000	.005	.021
IPEN walkability index*	CB 1000m	--	.038	.148	.001	.000	--	.078	.000	.002	.049
	NWB 1000m	--	.017	.132	.001	.000	.203	.054	.000	.003	.010
	NWB 1500m	--	.022	.170	.001	.000	--	.085	.000	.005	.030
Graz walkability index°	CB 1000m	--	.028	.147	.002	.000	--	.139	.000	.004	.023
	NWB 1000m	--	.016	.162	.001	.000	.221	.085	.000	.004	.020
	NWB 1500m	--	.019	.170	.003	.000	--	.156	.000	.004	.018

CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; * z-household unit density + z-entropy index + (2 x z-3-way intersection density); ° z-household unit density + z-% of mixed use + z-4-way intersection density

5.3.2 Age

A systematic review of the association between environmental variables and physical activity among older adults found inconsistent evidence. In most studies, environmental variables were not related to physical activity (Van Cauwenberg et al., 2011). However, associations between walkability and health-related outcomes may differ by age. Therefore, we also took a closer look at differences by age in the sample. Table 27 shows the descriptive statistics of the walkability variables stratified by the median age of the sample. Almost all walkability variables were slightly higher for the younger age group. This would indicate that younger respondents lived in neighbourhoods with higher walkability than older respondents. The difference between the two age groups did not reach statistical significance.

We observed the same pattern when looking at the median age stratified by the quartiles of the walkability variables (see Table 28). Respondents living in the low-walkability neighbourhoods (quartile 1 and 2) were slightly older than the respondents living in the high-walkability neighbourhoods. These differences also did not reach statistical significance. Among the health-related outcomes, statistically significant differences between the two age groups were also rare (see Table 29 and Table 30). BMI and satisfaction with social cohesion were statistically significantly higher among older respondents than among younger respondents. Self-rated health was statistically significantly lower among older respondents than among younger respondents.

Nevertheless, further investigation if there were differences between different younger and older respondents was necessary. Therefore, the author performed a binary analysis controlled for age, sex and socio-economic status stratified by younger than 55, older than 55, and by the median age. In Austria, 55 years of age is roughly the age where people actually retire, even though the official age for retiring is higher.

Table 27: Descriptive statistics of the walkability variables stratified by median age

Walkability variable	**Buffer**	**< 37 years of age**				**>37 years of age**				
		Median	**IQR**	**Min**	**Max**	**Median**	**IQR**	**Min**	**Max**	**p-value#**
Gross population density	CB 1000	4198.15	4366.74	203.84	9019.60	3712.26	4369.25	101.93	8997.13	.125
	NWB 1000	4858.31	4354.40	207.51	10038.42	4189.58	5012.22	106.22	10294.9	.123
	NWB 1500	4211.03	4220.70	200.30	8777.75	3888.97	4388.72	102.52	8830.27	.162
Household unit density	CB 1000	1882.87	2269.31	70.86	4401.81	1653.02	2224.18	28.45	4383.82	.137
	NWB 1000	2242.54	2382.67	75.91	4963.87	1920.76	2522.66	29.12	5100.21	.155
	NWB 1500	1893.82	2110.12	73.13	4259.82	1716.21	2117.03	27.98	4288.53	.166
Entropy index (5 types)	CB 1000	0.7898	0.14	0.19	0.98	0.7942	0.14	0.05	1.00	--
	NWB 1000	0.7450	0.17	0.11	0.98	0.7407	0.18	0.12	0.97	--
	NWB 1500	0.8121	0.74	0.23	0.97	0.8120	1.02	0.07	1.10	--
% of mixed use	CB 1000	42.14	40.93	0.00	85.86	42.18	37.88	0.00	85.50	.247
	NWB 1000	51.74	45.29	0.00	90.25	48.18	43.11	0.00	90.03	.153
	NWB 1500	21.06	18.09	0.00	41.88	20.70	17.33	0.00	42.85	.215
3-way intersection dens.	CB 1000	74.00	28.65	6.37	136.24	71.94	31.35	3.50	137.83	.168
	NWB 1000	87.27	31.65	13.64	166.87	84.52	33.48	8.79	171.30	--
	NWB 1500	82.62	26.14	15.02	126.73	81.27	28.33	13.20	126.64	.139
4-way intersection dens.	CB 1000	13.37	14.40	0.00	37.56	12.41	13.53	0.00	38.83	.140
	NWB 1000	15.03	16.17	0.00	45.80	13.99	15.35	0.00	47.04	.161
	NWB 1500	15.33	13.82	0.00	34.69	14.05	14.59	0.00	34.75	.158
IPEN walkability index*	CB 1000	0.7131	3.44	-11.06	5.78	0.4675	3.98	-11.91	5.80	.100
	NWB 1000	0.3542	2.84	-11.41	5.84	0.0694	3.53	-11.24	5.86	.197
	NWB 1500	0.5010	4.04	-12.48	5.29	0.2691	3.99	-13.95	7.84	.101
Graz walkability index°	CB 1000	0.2112	4.87	-4.74	6.10	-0.2279	4.40	-4.79	6.12	.141
	NWB 1000	0.0000	4.42	-4.74	5.75	-0.4530	4.32	-4.83	5.83	.111
	NWB 1500	0.2693	5.01	-5.11	5.55	-0.3652	4.61	-5.33	5.61	.163

#Mann-Whitney U

CB = circular buffer, NWB = street network buffer; * z-household unit density + z-entropy index + (2 x z-3-way intersection density); ° z-household unit density + z-% of mixed use + z-4-way intersection density

Table 28: Median age (IQ-range) by the walkability variables in quartiles

Walkability variable	**Buffer**	**1 (low)**	**2**	**3**	**4 (high)**	**p-value#**
Gross population density	CB 1000	39 (22)	38 (21)	37 (21)	37 (20)	--
	NWB 1000	39 (21)	38 (21)	36 (22)	37 (21)	--
	NWB 1500	38.5 (24)	38 (21)	37 (22)	37 (20)	--
Household unit density	CB 1000	38.5 (24)	38.5 (21)	35.5 (21)	37 (20)	--
	NWB 1000	38.5 (24)	39 (21)	35 (21)	37 (20)	--
	NWB 1500	39 (24)	38 (20)	37 (23)	36 (19)	--
Entropy index (5 types)	CB 1000	37 (25)	37 (22)	38 (22)	38 (19)	--
	NWB 1000	38.5 (24)	37 (21)	37 (21)	38 (20)	--
	NWB 1500	38 (24)	37 (21)	36 (22)	39 (20)	--
% of mixed use	CB 1000	37 (24)	37 (20)	39 (23)	36 (21)	--
	NWB 1000	37.5 (23)	39 (21)	37 (22)	36 (21)	--
	NWB 1500	39 (24)	37 (20)	39 (22)	36 (22)	--
3-way intersection density	CB 1000	39 (19)	37 (22)	37 (23)	36 (20)	--
	NWB 1000	39 (21)	37 (20)	37 (23)	37 (21)	--
	NWB 1500	39 (19)	37 (21)	37 (23)	37 (20)	--
4-way intersection density	CB 1000	39 (21)	36.5 (22)	37.5 (21)	36 (20)	--
	NWB 1000	39 (24)	37 (21)	37 (21)	37 (19)	--
	NWB 1500	39 (22)	37 (22)	37 (21)	36 (20)	--
IPEN walkability index*	CB 1000	39.5 (22)	37 (21)	37 (20)	36 (22)	--
	NWB 1000	40 (20)	37 (21)	36 (21)	38 (21)	--
	NWB 1500	38.5 (23)	38 (21)	37 (22)	36 (20)	--
Graz walkability index°	CB 1000	39 (21)	37 (21)	37 (22)	36 (21)	--
	NWB 1000	38 (24)	38 (20)	37 (22)	36 (22)	--
	NWB 1500	38.5 (24)	38 (20)	37 (22)	36 (21)	--

#Kruskal-Wallis

CB = circular buffer, NWB = street network buffer; * z-household unit density + z-entropy index + (2 x z-3-way intersection density); ° z-household unit density + z-% of mixed use + z-4-way intersection density

Table 29: Descriptive statistics of the continuous health-related outcome variables stratified by median age

Outcome	**< 37 years of age**				**>37 years of age**				
	Median	**IQR**	**Min**	**Max**	**Median**	**IQR**	**Min**	**Max**	**p-value#**
Twalk d/m	24	12	0.00	24	24	12	0.00	24	--
Tbike d/m	6	21	0.00	24	6	21	0.00	24	--
Walk min/w	120	180	15	4200	150	240	14	4800	.070
BMI	21.70	4.29	15.94	38.75	24.31	4.28	17.26	41.97	.000
Nbh sat	2	0.80	1	4.10	2.10	0.80	1.00	4.40	--

#Mann-Whitney U

twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction; d/m= days per month, min/w= minutes per week;

Table 30: Descriptive statistics of the binary health-related outcome variables stratified by median age

Outcome	**< 37 years of age**		**>37 years of age**		
	Users / **low**	**Non-Users** / **high**	**Users** / **low**	**Non-Users** / **high**	**p-value#**
Act trans (non-users vs. users)	86.9%	13.1%	86.6%	13.4%	.903
Self-rated health (low vs. high)	13.4%	86.6%	23.1%	76.9%	.000
Social env. quality (low vs. high)	50.0%	50.0%	50.4%	49.6%	.917
Social cohesion (low vs. high)	53.5%	46.5%	46.8%	53.2%	.050
Infrastructure (low vs. high)	46.2%	53.8%	50.4%	49.6%	.232

#Pearson Chi-Square

act trans = active transport;

Bivariate Analyses

Table 31 shows the results of the bivariate analysis stratified by less than 55 years of age and more than 55 years of age, controlled for age, sex and socio-economic status. Differences between age groups seem quite clear in this table. For respondents younger than 55 years of age, the results showed associations between walkability and walking and cycling for transport, use of active transport, mean neighbourhood satisfaction and satisfaction with social cohesion. In addition, the associations between walkability and the factors satisfaction with social environmental quality and local infrastructure were stronger and more frequent among younger respondents. Almost no associations for both age groups were observed for general walking, BMI and self-rated health. It seems that there was only an association between walkability and health-related outcomes for younger population groups. Since the group of respondents older than 55 years of age was rather small (n=88) and covered only an age group of five years, the results have to be interpreted with caution.

These results were supported by the results of the analysis stratified by the median age. Once again, among younger respondents we observed that biking for transport, use of active transport and the neighbourhood satisfaction factors were more frequently and strongly associated with walkability than among older respondents (see Table 32).

Walking for transport was positively related to walkability among the respondents younger than 55 years of age and among the respondents older than 37 years of age. Thus, the positive association between walkability and walking for transport may be strongest for a medium age group. Among the group above median age, walking for transport was positively associated with connectivity, while biking for transport was positively associated with population density and land use mix (see Table 32). Connectivity is assumed to be related to short connections, but may also be related to lower traffic security. There was no association between connectivity and biking for transport among the older population group. Traffic security may play a role in the association between walkability and biking for transport among older respondents. We observed no noteworthy association – neither for younger nor for older respondents –

between the walkability variables and general walking, BMI and self-rated health.

To summarize, since there were clear differences between different age groups, the present study controlled for age across all further analyses.

Table 31: Bivariate associations between walkability variables and health-related outcomes (p-values < 0.250) stratified by younger and older than 55 years of age controlled for sex, age and socio-economic status

Walkability variable	**Buffer**	**Twalk d/m**		**Tbike d/m**		**Walk min/w**		**BMI**		**Nbh sat**		**Act trans**		**Self-rated health**		**Social env. quality**		**Social cohesion**		**Infra-structure**	
		<55	>55	<55	>55	<55	>55	<55	>55	<55	>55	<55	>55	<55	>55	<55	>55	<55	>55	<55	>55
Gross population density	CB 1000m	.127	--	.002	.018	--	--	--	--	*.000*	--	.001	--	--	--	*.000*	*.005*	*.000*	.249	.003	.104
	NWB 1000m	.190	--	.003	.013	--	--	--	--	*.000*	--	.005	--	--	--	*.000*	*.001*	*.000*	--	.001	.060
	NWB 1500m	.190	--	.002	.023	--	.162	--	--	*.000*	--	.007	--	--	--	*.000*	*.013*	*.000*	.253	.001	.244
Household unit density	CB 1000m	.031	--	.001	.049	--	--	--	--	*.000*	--	.000	--	--	--	*.000*	*.009*	*.000*	--	.003	.079
	NWB 1000m	.058	--	.001	.021	--	--	--	--	*.000*	--	.002	--	--	--	*.000*	*.003*	*.000*	--	.000	.069
	NWB 1500m	.124	--	.001	.024	--	--	--	.198	*.000*	.078	.002	--	--	--	*.000*	*.002*	*.000*	.188	.001	.039
Entropy index (5 types)	CB 1000m	--	--	.021	.211	--	.208	--	--	*.041*	--	.062	--	.063	--	*.000*	*.004*	*.016*	--	.007	.052
	NWB 1000m	--	.186	.100	.076	--	.035	.222	--	--	--	.099	--	--	--	.133	.113	--	--	.001	.094
	NWB 1500m	--	--	.033	--	--	.075	--	--	*.004*	.235	.052	--	.247	--	*.000*	*.019*	*.026*	--	.007	.182
% of mixed use	CB 1000m	.126	--	.000	--	--	--	--	--	*.000*	--	.001	--	--	--	*.000*	*.021*	*.000*	--	.012	.115
	NWB 1000m	.013	--	.016	--	--	--	--	--	*.000*	.129	.009	--	--	--	*.000*	*.017*	*.000*	--	.003	--
	NWB 1500m	.037	--	.001	.235	--	--	--	--	*.000*	.180	.001	--	.182	--	*.000*	*.012*	*.000*	.055	.020	--
3-way intersection density	CB 1000m	.009	--	.014	.127	--	--	--	*.041*	.191	.165	.000	--	--	.240	*.000*	*.026*	*.009*	--	.000	--
	NWB 1000m	--	--	.169	--	--	--	--	--	*.007*	.236	--	--	--	.209	*.001*	*.026*	.065	--	.000	--
	NWB 1500m	.070	--	.004	--	--	--	--	--	.081	--	.002	--	--	--	*.000*	*.005*	*.007*	--	.000	--
4-way intersection-density	CB 1000m	.135	--	.016	.203	--	.204	--	--	*.000*	--	.019	--	--	.223	*.000*	.210	*.000*	.121	.000	.021
	NWB 1000m	--	--	.072	.189	--	--	--	--	*.002*	--	.130	--	--	--	*.000*	.153	*.000*	--	.000	.038
	NWB 1500m	--	--	.003	--	--	.127	--	--	*.000*	--	.043	--	--	--	*.000*	*.042*	*.000*	--	.000	.054
IPEN walkability index*	CB 1000m	.026	--	.002	.087	--	--	--	--	*.002*	.167	.001	--	--	.077	*.000*	.084	*.000*	*.022*	.000	.172
	NWB 1000m	.071	--	.082	.107	--	--	--	--	*.022*	--	.039	--	--	.177	*.000*	.200	*.001*	--	.000	.025
	NWB 1500m	.116	--	.003	--	--	--	--	--	*.000*	--	.002	--	--	--	*.000*	*.054*	*.000*	.118	.000	.165
Graz walkability index°	CB 1000m	.197	--	.001	.226	--	.173	.141	--	*.000*	--	.002	--	.018	--	*.000*	*.070*	*.000*	.073	.005	.237
	NWB 1000m	.051	--	.002	.241	--	--	--	--	*.000*	.211	.007	--	--	--	*.000*	*.008*	*.000*	--	.002	.021
	NWB 1500m	.129	--	.001	.187	--	--	.124	--	*.000*	--	.005	--	--	--	*.000*	*.024*	*.000*	.209	.001	.135

CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (the lower the walkability, the higher the satisfaction with social-environmental quality and social cohesion) (note: direction of association only marked for statistically significant associations (p<0,05)); * z-household unit density + z-entropy index + (2 x z-3-way intersection density); ° z-household unit density + z-% of mixed use + z-4-way intersection density

Table 32: Bivariate associations between walkability variables and health-related outcomes (p-values < 0.250) stratified by median age controlled for sex, age and socio-economic status

Walkability variable	**Buffer**	**Twalk d/m**		**Tbike d/m**		**Walk min/w**		**BMI**		**Nbh sat**		**Act trans**		**Self-rated health**		**Social env. quality**		**Social cohesion**		**Infra-structure**	
		<55	>55	<55	>55	<55	>55	<55	>55	<55	>55	<55	>55	<55	>55	<55	>55	<55	>55	<55	>55
Gross population density	CB 1000m	--	.105	.008	.010	--	.102	--	--	*.000*	*.007*	.011	.027	.107	--	*.000*	*.016*	*.000*	--	.001	--
	NWB 1000m	--	.131	.012	.004	--	.128	--	--	*.000*	*.004*	.037	.083	--	.195	*.000*	*.003*	*.000*	--	.000	.246
	NWB 1500m	--	.138	.009	.016	--	.105	--	--	*.000*	*.013*	.015	.028	.121	--	*.000*	*.053*	*.000*	--	.001	--
Household unit density	CB 1000m	--	.059	.002	.008	--	.086	--	--	*.000*	*.017*	.011	.017	.118	--	*.000*	*.031*	*.000*	--	.001	--
	NWB 1000m	--	.121	.007	.007	--	.153	--	--	*.000*	*.013*	.015	.090	--	.192	*.000*	*.010*	*.000*	--	.000	--
	NWB 1500m	--	.194	.007	.014	--	--	--	--	*.000*	*.031*	.012	.018	--	--	*.000*	*.015*	*.000*	--	.000	--
Entropy index (5 types)	CB 1000m	--	--	.233	.052	--	--	--	--	.070	.245	.073	.234	.163	.180	*.000*	*.005*	*.020*	--	.006	.124
	NWB 1000m	--	--	.069	--	--	--	.075	--	--	--	.068	--	--	.222	.142	.149	--	--	.000	--
	NWB 1500m	--	--	.193	.020	--	--	--	--	*.049*	*.010*	.044	--	--	.167	*.000*	*.009*	*.039*	.071	.005	--
% of mixed use	CB 1000m	.107	.186	.002	.041	.124	.055			*.000*	*.001*	.002	.018	--	.247	*.000*	*.000*	*.000*	*.043*	--	.002
	NWB 1000m	.068	.063	.092	.055	--	.165			*.000*	*.001*	.038	.058	--	.134	*.000*	*.000*	*.000*	*.021*	.169	.003
	NWB 1500m	.042	.144	.013	.009	--	.159			*.000*	*.000*	.001	.068	--	.211	*.000*	*.000*	*.000*	*.012*	--	.014
3-way intersection density	CB 1000m	--	.014^	.021	.252	--	--	--	--	.191	.058	.003	.031	.154	.119	*.000*	.208	*.003*	--	.000	--
	NWB 1000m	--	--	.022	--	--	--	--	--	*.004*	--	--	--	.249	--	*.001*	.145	.080	--	.000	--
	NWB 1500m	--	.047	.007	.249	.221	--	--	.160	*.011*	--	.026	.024	.220	.214	*.000*	.104	*.003*	--	.000	--
4-way intersection-density	CB 1000m	--	.121	.029	.098	--	--	--	--	*.030*	*.003*	.027	.126	--	.252	*.000*	.092	*.000*	--	.000	.143
	NWB 1000m	--	.141	.017	--	--	--	--	--	.092	*.006*	.071	.239	--	--	*.000*	.055	*.000*	--	.000	.212
	NWB 1500m	--	.107	.006	.032	--	--	--	--	*.011*	*.008*	.198	.052	.140	--	*.000*	.057	*.000*	--	.000	--
IPEN walkability index*	CB 1000m	--	.010^	.006	.080	--	.220	--	--	*.003*	.088	.029	.007	*.036*	.010^	*.000*	.115	*.000*	--	.000	--
	NWB 1000m	.246	--	.046	--	--	.110	.164	--	*.025*	.204	.119	.079	--	.046^	*.000*	.079	*.000*	--	.000	.145
	NWB 1500m	.198	.023	.006	.168	--	.248	--	--	*.006*	*.021*	.035	.007	.176	.124	*.000*	.090	*.000*	--	.000	--
Graz walkability index°	CB 1000m	--	.015	.001	.050	--	.201	--	--	*.000*	*.002*	.004	*.008*	.266	.115	*.000*	*.000*	*.000*	*.019*	.084	.024
	NWB 1000m	--	.059	.002	.052	--	.083	--	--	*.000*	*.002*	.033	.086	--	--	*.000*	*.000*	*.000*	*.040*	.028	.006
	NWB 1500m	--	.048	.003	.025	--	.186	--	--	*.000*	*.001*	.018	*.018*	--	--	*.000*	*.000*	*.000*	*.020*	.055	.004

CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (the lower the walkability, the higher the satisfaction with social-environmental quality and social cohesion) (note: direction of association only marked for statistically significant associations (p<0,05)); * z-household unit density + z-entropy index + (2 x z-3-way intersection density); ° z-household unit density + z-% of mixed use + z-4-way intersection density; ^ respondents living in areas of medium walkability (quartile 2 and 3 out of 4) report worse self-rated health than respondents living in high and low walkability areas.

5.4 Density

5.4.1 Gross population density

Table 33 and Table 34 show the associations between *gross population density* and the investigated health-related outcomes. No association was found between *gross population density* and walking for transport and general walking, BMI and self-rated health in the uncontrolled and in the controlled analyses.

Gross population density was positively associated with biking for transport among men and women, younger and older respondents, but only among respondents with a high socio-economic status and respondents residing on the east side of the river. *Gross population density* was also positively related to active transport, especially among women and among respondents residing in the east part of the city.

Furthermore, the data showed a clear negative relationship between measures of neighbourhood satisfaction and *gross population density*. *Gross population density* was negatively associated with mean neighbourhood satisfaction, satisfaction with social environmental quality and satisfaction with social cohesion. Respondents living in low-density neighbourhoods were more satisfied with their neighbourhood, especially with the social environmental quality and the social cohesion, than respondents living in high-density neighbourhoods. However, there was a positive association between *gross population density* and satisfaction with infrastructure. In the controlled analysis, this association was less pronounced among younger respondents, respondents with a low socio-economic status and among respondents residing in the West.

Buffer type and size did not have a clear impact on the results. There was a light tendency towards results being more often significant in the 1,500m street network buffer than in the 1,000m street network buffer.

Table 33: Bivariate associations between gross population density and health-related outcomes (p-values < 0.250)

	Twalk d/m		**Tbike d/m**		**Walk min/w**		**BMI**		**Nbh sat**		**Act trans**		**Self-rated health**		**Social env. quality**		**Social cohesion**		**Infra-structure**	
CB 1000m	--		.000		--		--		*.000*		.002		--		*.000*		*.000*		.000	
NWB 1000m	--		.001		--		--		*.000*		.010		--		*.000*		*.000*		.000	
NWB 1500m	.242		.000		--		--		*.000*		.009		--		*.000*		*.000*		.000	
By sex	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**
CB 1000m	.158	--	.017	.028	.251	--	--	--	*.038*	*.000*	.038	.032	.097	--	*.000*	*.000*	*.010*	*.000*	.002	.020
NWB 1000m	--	--	.030	.024	.223	--	--	--	*.011*	*.000*	.212	.020	.169	--	*.000*	*.000*	*.039*	*.000*	.002	.004
NWB 1500m	--	--	.004	.069	--	--	.069		.057	*.000*	.071	.076	.075		*.000*	*.000*	*.010*	*.000*	.005	.006
By age	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**
CB 1000m	--	.132	.018	.009	--	.117	--	--	*.000*	*.015*	.060	.024	.191	--	*.000*	*.000*	*.000*	.077	.053	.003
NWB 1000m	--	.111	.054	.003	--	.099	--	--	*.000*	*.007*	.121	.077	--	--	*.000*	*.000*	*.000*	.085	.023	.001
NWB 1500m	--	.141	.024	.014	--	.121	--	--	*.000*	*.022*	.060	.015	--	--	*.000*	*.000*	*.000*	.103	.068	.002
By education[&]	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**
CB 1000m	.129	--	.160	.005	--	--	--	--	*.000*	*.005*	.027	.018	--	--	*.000*	*.000*	*.000*	*.004*	.056	.001
NWB 1000m	--	--	.101	.006	--	--	--	--	*.000*	*.000*	.031	.204	--	--	*.000*	*.000*	*.005*	*.005*	.005	.003
NWB 1500m	.155	--	.147	.007	--	--	--	--	*.000*	*.003*	.094	.121	--	--	*.000*	*.000*	*.001*	*.002*	.026	.001
By pop.density	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**
CB 1000m	--	--	--	--	--	--	.138	--	--	*.021*	--	.174	--	--	.092	*.026*	.082	--	--	--
NWB 1000m	--	.151	--	--	--	--	--	--	.232	*.002*	--	--	--	--	*.006*	*.002*	--	--	.104	--
NWB 1500m	--	--	.112	.051	--	--	--	--	--	*.021*	.184	--	.150	.072	.162	.006	.151	--	.246	--

CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (the lower the walkability, the higher the satisfaction with social-environmental quality and social cohesion) (note: direction of association only marked for statistically significant associations (p<0,05)); [&]low = not achieving general qualification for university entrance, high = achieving general qualification for university entrance

Table 34: Controlled bivariate associations between gross population density and health-related outcomes (p-values < 0.250)

	Twalk d/m		**Tbike d/m**		**Walk min/w**		**BMI**		**Nbh sat**		**Act trans**		**Self-rated health**		**Social env. quality**		**Social cohesion**		**Infra-structure**	
CB 1000m	.121		.000		--		--		*.000*		.000		--		*.000*		*.000*		.000	
NWB 1000m	.204		.000		--		--		*.000*		.003		--		*.000*		*.000*		.000	
NWB 1500m	.172		.000		--		--		*.000*		.003		--		*.000*		*.000*		.000	
By sex	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**
CB 1000m	.152	--	.013	.023	--	--	.205	--	*.031*	*.000*	.024	.032	.113	--	*.000*	*.000*	*.014*	*.000*	.002	.039
NWB 1000m	--	--	.012	.009	.234	--	--	--	*.017*	*.000*	.141	.019	.227	--	*.000*	*.000*	*.017*	*.000*	.002	.007
NWB 1500m	--	--	.004	.053	--	--	.047	--	*.067*	*.000*	.062	.084	.078	--	*.000*	*.000*	*.018*	*.001*	.004	.011
By age	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**
CB 1000m	--	.091	.009	.013	--	.121	--	--	*.000*	*.001*	.012	.026	--	--	*.000*	*.000*	*.000*	*.038*	.067	.008
NWB 1000m	--	.125	.011	.003	--	.143	--	--	*.000*	*.001*	.030	.083	--	.219	*.000*	*.000*	*.001*	*.044*	.021	.004
NWB 1500m	--	.114	.010	.019	--	.126	--	--	*.000*	*.002*	.016	.028	--	--	*.000*	*.000*	*.000*	.073	.075	.005
By SES	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**
CB 1000m	--	.081	.097	.004	--	--	--	--	*.000*	*.009*	.035	.017	--	.134	*.000*	*.000*	*.001*	*.006*	.169	.001
NWB 1000m	--	.157	.060	.003	.193	--	--	--	*.000*	*.006*	.070	.067	--	.159	*.000*	*.000*	*.009*	*.007*	.011	.002
NWB 1500m	--	.112	.073	.002	--	--	--	--	*.000*	*.006*	.068	.069	--	.216	*.000*	*.000*	*.002*	*.002*	.058	.002
By place of residence	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**
CB 1000m	--	.018	--	.000	--	--	--	.138	*.000*	*.000*	.130	.000	--	--	*.000*	*.000*	*.008*	*.001*	--	.000
NWB 1000m	--	.049	--	.000	--	--	--	--	*.000*	*.001*	.218	.000	--	--	*.000*	*.000*	*.015*	*.002*	.166	.000
NWB 1500m	--	.056	--	.000	--	--	--	.039	*.000*	*.000*	--	.000	--	--	*.000*	*.000*	*.010*	*.001*	.235	.001

CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (the lower the walkability, the higher the satisfaction with social-environmental quality and social cohesion) (note: direction of association only marked for statistically significant associations (p<0,05))

5.4.2 Household unit density

Household unit density can be considered as a proxy for population density. Usually, urban policies rather regulate housing units than population (Forsyth et al., 2007). The analyses using *household unit density* as a measure of walkability showed similar results as the analyses using *gross population density*. But *household unit density* was somewhat more often related to health-related outcomes than *gross population density*.

Table 35 shows the bivariate associations between *household unit density* and health-related outcomes. *Household unit density* was not at all associated with general walking, BMI and self-rated health and only minimally associated with walking for transport. When controlling for potential confounders, there were some significant positive associations with walking for transport (see Table 36). The positive association was borderline significant at a 5% level in the circular 1,000m buffer, but not in the other buffers. In particular, residents living on the east side of the river reported more walking for transport in neighbourhoods with a high *household unit density* than in neighbourhoods with a low *household unit density.* Among respondents with a high socio-economic status, *household unit density* and walking for transport were also positively associated. However, the association was not entirely linear. Respondents in neighbourhoods of high *household unit density* walked more for transport than respondents living in neighbourhoods of middle *household unit density.*

There was a clear positive relationship between *household unit density* and biking for transport. Respondents biked more for transport in high-density neighbourhoods than in low-density neighbourhoods, independent of sex, age and socio-economic status. However, there was a difference between respondents residing in the West and in the East. Among respondents living in the East, there was a clear positive relationship between biking for transport and *household unit density;* but no such relationship existed among respondents living in the West.

In both the uncontrolled and controlled analyses, *household unit density* was positively associated with active transport. Without controlling for sex, age, socio-economic status and place of residence, *household unit density* was not always associated with active transport among female, younger and highly educated respondents. These differences almost disappeared in the controlled analyses. Only among respondents residing in the western part of the city were *household unit density* and active transport not positively associated.

Household unit density was negatively associated with the measures of neighbourhood satisfaction, except for satisfaction with infrastructure, which was positively associated with *household unit density.* Respondents residing in high-density areas were less satisfied with their neighbourhood overall, with the social-environmental quality and social cohesion, and more satisfied with the infrastructure than respondents residing in low-density areas, independent of sex, age, socio-economic status and place of residence and in all sub-groups. The only exception was that there was no positive association between *household unit density* and satisfaction with infrastructure among respondents living in the western part of the city.

Regarding the different buffer types, associations were less frequently significant in the 1,000m street network buffer than in the 1,000m circular buffer and the 1,500m street network buffer.

Table 35: Bivariate associations between household unit density and health-related outcomes (p-values < 0.250)

	Twalk d/m		**Tbike d/m**		**Walk min/w**		**BMI**		**Nbh sat**		**Act trans**		**Self-rated health**		**Social env. quality**		**Social cohesion**		**Infra-structure**	
CB 1000m	.094		.000		--		--		*.000*		.002		--		*.000*		*.000*		.000	
NWB 1000m	.106		.000		--		--		*.000*		.005		--		*.000*		*.000*		.000	
NWB 1500m	.229		.000		--		--		*.000*		.003		--		*.000*		*.000*		.000	
By sex	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**
CB 1000m	.113	--	.007	.028	.170	--	.205	--	*.018*	*.000*	.023	.057	.075	--	*.000*	*.000*	*.003*	*.000*	.004	.015
NWB 1000m	--	.211	.016	.019	.194	--	--	--	*.016*	*.000*	.112	.018	.173	--	*.000*	*.000*	*.011*	*.000*	.003	.006
NWB 1500m	--	--	.001	.052	--	--	.138	--	.083	*.000*	.027	.102	.169	--	*.000*	*.000*	*.009*	*.000*	.003	.009
By age	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**
CB 1000m	--	.063	.006	.007	--	.101	--	--	*.000*	*.015*	.076	.013	--	--	*.000*	*.000*	*.000*	.064	.070	.003
NWB 1000m	--	.109	.026	.007	--	.133	--	--	*.000*	*.024*	.072	.073	--	--	*.000*	*.000*	*.000*	*.050*	.015	.002
NWB 1500m	--	.210	.017	.013	--	--	--	--	*.000*	.055	.057	.008	--	--	.000	.000	.000	.060	.021	.002
By education$^{\&}$	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**
CB 1000m	.112	--	.080	.003	--	--	--	--	*.000*	*.014*	.019	.011	--	--	*.000*	*.000*	*.001*	*.005*	.056	.005
NWB 1000m	.086	--	.064	.004	--	--	--	--	*.000*	*.013*	.037	.154	--	--	*.000*	*.000*	*.003*	*.003*	.020	.000
NWB 1500m	.192	--	.037	.014	--	--	--	--	*.000*	*.008*	.036	.107	--	--	*.000*	*.000*	*.001*	*.003*	.034	.000
By pop.density	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**
CB 1000m	--	.144	--	.168	--	.009	.118	.129	--	*.048*	--	.064	--	--	--	*.052*	.082	--	--	--
NWB 1000m	--	.034	.108	.226	--	--	--	--	.245	*.006*	--	--	--	--	*.015*	*.005*	.152	--	.190	.095
NWB 1500m	--	--	.229	.055	--	--	--	.246	--	--	.184	.124	--	*.019*	.240	.064	.081	--	.059	--

CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (the lower the walkability, the higher the satisfaction with social-environmental quality and social cohesion) (note: direction of association only marked for statistically significant associations (p<0,05)); $^{\&}$low = not achieving general qualification for university entrance, high = achieving general qualification for university entrance

Table 36: Controlled bivariate associations between household unit density and health-related outcomes (p-values < 0.250)

	Twalk d/m		Tbike d/m		Walk min/w		BMI		Nbh sat		Act trans		Self-rated health		Social env. quality		Social cohesion		Infra-structure	
CB 1000m	.044		.000		--		--		*.000*		.000		--		*.000*		*.000*		.000	
NWB 1000m	.076		.000		--		--		*.000*		.001		--		*.000*		*.000*		.000	
NWB 1500m	.151		.000		--		--		*.000*		.001		.155		*.000*		*.000*		.000	
By sex	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**
CB 1000m	.114	--	.007	.027	.145	--	.120	--	*.009*	*.000*	.017	.047	.082	--	*.000*	*.000*	*.005*	*.000*	.005	.036
NWB 1000m	--	.202	.008	.008	.194	--	.255	--	*.016*	*.000*	.072	.017	--	--	*.000*	*.000*	*.016*	*.000*	.003	.010
NWB 1500m	.252	--	.001	.042	--	--	.206	--	.067	*.000*	.026	.105	.194	--	*.000*	*.000*	*.016*	*.000*	.002	.015
By age	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**
CB 1000m	--	.047^	.002	.013	--	.108	--	--	*.000*	*.000*	.013	.016	--	--	*.000*	*.000*	*.000*	*.026*	.093	.008
NWB 1000m	--	.110	.006	.007	--	.170	--	--	*.000*	*.002*	.012	.090	--	--	*.000*	*.000*	*.000*	*.023*	.013	.004
NWB 1500m	--	.141	.009	.025	--	--	--	--	*.000*	*.007*	.013	.016	--	--	*.000*	*.000*	*.000*	*.042*	.020	.006
By SES	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**
CB 1000m	--	.025^	.038	.002	--	--	--	--	*.000*	*.013*	.023	.013	--	.145	*.000*	*.000*	*.001*	*.005*	.180	.001
NWB 1000m	--	.062	.017	.003	--	--	--	--	*.000*	*.013*	.063	.039	--	.176	*.000*	*.000*	*.008*	.002	.043	.000
NWB 1500m	--	.031^	.025	.005	--	--	--	--	*.000*	*.009*	.036	.042	--	--	*.000*	*.000*	*.002*	*.004*	.041	.002
By place of residence	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**
CB 1000m	--	.019	--	.000	--	--	--	--	*.000*	*.000*	.101	.000	--	--	*.000*	*.000*	*.005*	*.001*	--	.000
NWB 1000m	--	.025	--	.000	--	.186	--	--	*.000*	*.001*	.178	.000	--	--	*.000*	*.000*	*.011*	*.001*	--	.000
NWB 1500m	--	.034	--	.000	--	--	--	.177	*.000*	*.000*	.130	.000	--	--	*.000*	*.000*	*.011*	*.001*	--	.000

CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (the lower the walkability, the higher the satisfaction with social-environmental quality and social cohesion) (note: direction of association only marked for statistically significant associations (p<0,05)); ^ respondents living in areas of medium walkability (quartile 2 or/and 3 out of 4) walk less for transport than respondents living in high (quartile 4) walkability areas.

5.5 Land use mix

5.5.1 Entropy index

The *entropy index* as a measure of diversity and of the heterogeneous distribution of different land use types was not very often associated with health-related outcomes in the uncontrolled analyses, and some of the associations disappeared in the controlled analyses (see Table 37 and Table 38). The *entropy index* was overall not associated with walking for transport, walking in general, BMI and self-rated health.

The *entropy index* was associated with biking for transport in the whole sample and among the older respondents, the respondents with high socio-economic status and the respondents living in the eastern part of the city in the controlled analyses. The single positive association between the *entropy index* and active transport found in the bivariate analysis (see Table 37) disappeared almost entirely when controlled for potential confounders.

A similar pattern was observed for the association with mean neighbourhood satisfaction. In the bivariate analysis, the *entropy index* was associated with mean neighbourhood satisfaction in the whole sample and to some extent in some sub-groups. The negative association between the *entropy index* and mean neighbourhood satisfaction remained significant after controlling for confounders in the whole sample. In the sub-groups, the associations disappeared almost entirely.

The *entropy index* was negatively associated with satisfaction with social environmental quality in the uncontrolled analyses in the whole sample and in all sub-groups. This association remained in the adjusted analyses, but not for all sub-groups. Women, respondents with a high socio-economic status and respondents residing on the east side of the river more often reported being satisfied with their social environmental quality when living in areas with a low *entropy index* than when living in areas with a high *entropy index.* In the controlled analysis, associations between the *entropy index* and satisfaction with environmental quality were only found when measured in the 1,000m circular buffer and in the 1,500m street network buffer, but not in the 1,000m street network buffer.

A negative association between the *entropy index* and the satisfaction with social cohesion was found in the whole sample and among women in the uncontrolled and controlled analyses, and only within the circular buffer and the 1,500m street network buffer, but not for other sub-groups or within the 1,000m street network buffer.

There was a positive association between the *entropy index* and the satisfaction with infrastructure for all sub-groups in the uncontrolled analysis. In the controlled analysis, there was no association among respondents with a low socio-economic status and among respondents living on the west side of river.

Overall, the *entropy index* and health-related outcomes were clearly more often associated when the neighbourhood was defined as a 1,000m circular buffer or a 1,500m street network buffer than when the neighbourhood was defined as a 1,000m street network buffer.

Table 37: Bivariate associations between entropy index and health-related outcomes (p-values < 0.250)

	Twalk d/m		**Tbike d/m**		**Walk min/w**		**BMI**		**Nbh sat**		**Act trans**		**Self-rated health**		**Social env. quality**		**Social cohesion**		**Infra-structure**	
CB 1000m	--		.012		--		--		*.008*		.186		*.031*		*.000*		*.007*		.001	
NWB 1000m	--		.090		--		--		--		.085		--		*.015*		--		.000	
NWB 1500m	--		.033		--		--		*.000*		.042		.078		*.000*		*.011*		.001	
By sex	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**
CB 1000m	--	--	.138	.116	--	--	--	--	--	*.021*	--	--	--	*.021*	*.040*	*.000*	--	*.014*	.062	.008
NWB 1000m	.200	.208	.137	.206	.046	--	.141	--	.112	--	.077	--	--	--	.131	.074	--	.156	.009	.005
NWB 1500m	--	--	.102	--	--	--	.149	--	*.013*	*.013*	--	--	--	--	*.040*	*.000*	--	*.014*	.062	.008
By age	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**
CB 1000m	--	--	.176	.067	--	--	--	--	*.044*	.157	.167	--	.215	.098	*.001*	*.000*	*.012*	.253	.018	.068
NWB 1000m	--	--	.059	--	--	.159	--	--	--	--	.131	--	--	.155	--	*.029*	--	.098	.005	.048
NWB 1500m	--	--	.187	.018	--	--	--	.248	*.026*	*.009*	.093	--	--	*.028*	*.000*	*.000*	.060	*.028*	.014	.117
By education[&]	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**
CB 1000m	--	--	--	.000	--	--	--	--	*.024*	--	--	.192	*.034*	--	*.000*	*.009*	.079	.072	.027	.013
NWB 1000m	--	--	--	.013	--	--	.179	--	--	--	--	.016	.127	--	*.051*	.252	--	--	.003	.045
NWB 1500m	--	--	--	.017	--	--	--	--	*.012*	*.049*	--	.011	.058	--	*.000*	*.000*	.108	.123	.003	.092
By pop.density	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**
CB 1000m	--	--	.113	.008	--	--	--	--	*.007*	.140	--	*.037*	.072	.188	*.000*	*.015*	.098	--	.079	--
NWB 1000m	.204	--	--	.070	--	--	--	--	.139	*.016*	--	.021	--	--	*.000*	*.004*	--	--	.000	.058
NWB 1500m	--	--	--	--	--	--	--	--	*.004*	*.036*	--	*.014*	.238	.242	*.000*	*.001*	.242	--	.040	--

CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (the lower the walkability, the higher the satisfaction with social-environmental quality and social cohesion) (note: direction of association only marked for statistically significant associations (p<0,05)); [&]low = not achieving general qualification for university entrance, high = achieving general qualification for university entrance

Table 38: Controlled bivariate associations between entropy index and health-related outcomes (p-values < 0.250)

	Twalk d/m		**Tbike d/m**		**Walk min/w**		**BMI**		**Nbh sat**		**Act trans**		**Self-rated health**		**Social env. quality**		**Social cohesion**		**Infra-structure**	
CB 1000m	--		.008		--		--		*.000*		.094		--		*.002*		*.044*		.001	
NWB 1000m	--		.126		--		--		*.000*		.068		--		.222		--		.000	
NWB 1500m	--		.020		--		--		*.000*		.040		--		*.000*		.056		.001	
By sex	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**
CB 1000m	--	--	.104	.125	--	--	--	--	--	--	--	--	--	.101	--	*.001*	--	*.038*	.040	.011
NWB 1000m	.255	.246	--	.197	*.034*	--	--	--	.154	--	.062	--	--	--	--	--	--	--	.018	.002
NWB 1500m	--	.160	.075	--	--	--	--	--	.196	--	.062	--	--	--	*.015*	*.001*	--	*.022*	.102	.005
By age	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**
CB 1000m	--	--	--	.023	--	--	--	--	--	--	.081	.235	--	--	*.054*	*.008*	*.044*	--	.026	.048
NWB 1000m	--	--	.105	--	--	--	.197	--	--	--	.112	--	--	--	--	.183	--	.070	.005	.037
NWB 1500m	--	--	--	.004	--	--	--	--	--	--	.073	--	--	.217	*.015*	*.001*	.150	.090	.027	.078
By SES	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**
CB 1000m	--	--	--	.003	--	--	--	--	--	--	--	--	.220	.219	.117	*.025*	.211	.171	.091	.001
NWB 1000m	--	--	--	.060	--	--	--	--	*.048*	--	--	*.050*	--	--	--	--	--	--	.013	.002
NWB 1500m	--	--	--	.019	--	--	--	--	--	.145	.150	--	.147	--	.089	*.000*	.212	*.017*	.061	.003
By place of residence	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**
CB 1000m	--	--	.118	.031	--	.099	--	--	--	--	--	.229	--	--	.127	*.005*	--	.064	.082	.002
NWB 1000m	--	--	.563	.035	--	--	.252	.013	.227	--	--	.234	--	.070	--	--	--	--	.088	.000
NWB 1500m	--	--	.083	.068	.112	.057	--	--	.111	.108	.057	--	--	--	*.005*	*.001*	.083	.136	--	.001

CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (the lower the walkability, the higher the satisfaction with social-environmental quality and social cohesion) (note: direction of association only marked for statistically significant associations (p<0,05))

5.5.2 Proportion of mixed land use

Proportion of mixed land use describes the share of area in the neighbourhood that is devoted to mixed use according to the zoning data. We developed this indicator to capture mixed land use more adequately based on the Austrian zoning data, since the Austrian zoning data provides different information than the zoning data described in the literature. The results indicate that the indicator *proportion of mixed land use* may describe land use mix better than the *entropy index. Proportion of mixed land use* was consistently related to health-related outcomes, while the *entropy index* only occasionally showed statistically significant associations with health-related outcomes.

Table 39 and Table 40 show that *proportion of land use mix* was not related to general walking, BMI and self-rated health. In the uncontrolled analyses, there was also no association with walking for transport. However, in the controlled analysis, the association between *proportion of mixed land use* and walking for transport occasionally became significant, but only marginally. Only among respondents residing on the east side of the river there was a clear significantly positive association between *proportion of mixed land use* and walking for transport.

Biking for transport was also positively associated with *proportion of mixed land use* in the whole sample. In the controlled analysis, there was more often a positive association among men and younger respondents than among women and older respondents. *Proportion of mixed land use* was positively associated with biking for transport among low and highly educated respondents, but only among respondents living in the eastern part of the city. The association was statistical significant for all sub-groups (except respondents residing in the western part of the city) in the controlled analyses when using the 1,500m street network buffer to define neighbourhoods.

Proportion of land use mix was also positively associated with active transport. Especially among men, younger respondents, respondents with a low socio-economic status and respondents residing in the eastern part of the city, active transport was associated with *proportion of mixed land use.*

There was also a clear association between *proportion of mixed land use* and neighbourhood satisfaction measures. Mean neighbourhood satisfaction, satisfaction with social environmental quality and satisfaction with social cohesion were lower among respondents living in areas with a higher land use mix than among respondents living in areas with a lower land use mix. This was true for all sub-groups when confounders were taken into account. Satisfaction with infrastructure was also associated with *proportion of mixed land use,* but the association was in the expected direction and did not exist for all sub-groups. Among men and women, older respondents, respondents with a high socio-economic status and respondents living in the eastern part of the city, *proportion of mixed land use* was positively associated with satisfaction with infrastructure when potential confounders were taken into account (seeTable 40).

Table 39: Bivariate associations between proportion of mixed land use and health-related outcomes (p-values < 0.250)

	Twalk d/m		**Tbike d/m**		**Walk min/w**		**BMI**		**Nbh sat**		**Act trans**		**Self-rated health**		**Social env. quality**		**Social cohesion**		**Infra-structure**	
CB 1000m	.222		.000		--		.044+		*.000*		.004		.089		*.000*		*.000*		.001	
NWB 1000m	.108		.006		--		.291		*.000*		.029		.098		*.000*		*.000*		.001	
NWB 1500m	.057		.000		--		.070		*.000*		.005		.080		*.000*		*.000*		.002	
By sex	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**
CB 1000m	--	--	.138	.116	--	--	--	--	--	*.021*	--	--	--	*.021*	*.040*	*.000*	--	*.014*	.062	.008
NWB 1000m	.200	.208	.137	.206	.046	--	.141	--	.112	--	.077	--	--	--	.131	.074	--	.156	.009	.005
NWB 1500m	--	--	.102	--	--	--	.149	--	*.013*	*.013*	--	--	--	--	*.040*	*.000*	--	*.014*	.062	.008
By age	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**
CB 1000m	.151	.241	.003	.038	--	.089	.104	.175	*.000*	*.001*	.012	.015	--	.121	*.000*	*.000*	*.000*	.056	--	.001
NWB 1000m	.095	.080	.148	.055	--	.167	.120		*.000*	*.001*	.127	.051	--	.095	*.000*	*.000*	*.000*	*.026*	.179	.002
NWB 1500m	.077	.156	.030	.009	--	.181	.125	.201	*.000*	*.000*	.003	.057	.231	.200	*.000*	*.000*	*.000*	*.012*	--	.006
By education[&]	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**
CB 1000m	.173	.120	.068	.006	.203	--	.226	--	*.000*	*.001*	.005	.127	.227	--	*.000*	*.000*	*.003*	*.002*	--	.001
NWB 1000m	.093	--	--	.040	--	--	--	--	*.000*	*.001*	.092	.243	.201	.042	*.000*	*.000*	*.000*	*.002*	.252	.000
NWB 1500m	.119	.142	.063	.009	--	--	.143	--	.000	.001	.048	.070	--	.226	*.000*	*.000*	*.005*	*.003*	--	.000
By pop.density	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**
CB 1000m	--	--	--	.119	--	--	.233	.186	*.021*	.177	--	.119	*.038*	.114	*.001*	--	*.033*	--	--	--
NWB 1000m	.197	.145	--	--	--	--	--	--	.061	*.049*	*.053*	.198	--	--	*.000*	.060	.100	--	.138	--
NWB 1500m	--	--	--	.224	--	--	--	.207	*.023*	.100	.077	.235	--	--	*.000*	*.019*	.063	--	.075	--

CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (the lower the walkability, the higher the satisfaction with social-environmental quality and social cohesion) (note: direction of association only marked for statistically significant associations (p<0,05)); [&]low = not achieving general qualification for university entrance, high = achieving general qualification for university entrance; + respondents living in areas of medium walkability (quartile 2 and 3 out of four) have a higher BMI than respondents living in high and low walkability areas.

Table 40: Controlled bivariate associations between proportion of mixed land use and health-related outcomes (p-values < 0.250)

	Twalk d/m		**Tbike d/m**		**Walk min/w**		**BMI**		**Nbh sat**		**Act trans**		**Self-rated health**		**Social env. quality**		**Social cohesion**		**Infra-structure**	
CB 1000m	.194		.000		--		--		*.000*		.001		--		*.000*		*.000*		.001	
NWB 1000m	.056		.004		--		--		*.000*		.009		--		*.000*		*.000*		.000	
NWB 1500m	.050		.000		--		--		*.000*		.002		.219		*.000*		*.000*		.002	
By sex	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**
CB 1000m	.117	--	.000	.125	.058	--	--	--	*.005*	*.000*	.015	.101	--	.223	*.000*	*.000*	*.011*	*.000*	.005	.051
NWB 1000m	.050	--	.003	--	.017	--	--	--	*.046*	*.000*	.055	.208	--	--	*.000*	*.000*	*.011*	*.000*	.003	.049
NWB 1500m	.120	--	.001	.031	.075	--	.113	--	*.004*	*.000*	.041	.049	.236	.246	*.000*	*.000*	*.007*	*.001*	.009	.058
By age	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**
CB 1000m	.112	.130	.002	.073	.145	.085	--	--	*.000*	*.000*	.001	.016	--	--	*.000*	*.000*	*.000*	*.009*	--	.001
NWB 1000m	.077	.042^	.089	.057	--	.203	--	--	*.000*	*.000*	.025	.057	--	--	*.000*	*.001*	*.000*	*.021*	.155	.001
NWB 1500m	.051	.092	.017	.009	--	.199	--	--	*.000*	*.000*	.001	.062	--	--	*.001*	--	*.000*	*.020*	--	.007
By SES	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**
CB 1000m	--	.056	.018	.005	--	--	--	--	*.000*	*.001*	.001	.075	--	--	*.000*	*.000*	*.003*	*.002*	--	.000
NWB 1000m	.192	.101	.179	.009	--	--	--	--	*.000*	*.002*	.116	.117	--	.047	*.000*	*.000*	*.004*	*.002*	--	.000
NWB 1500m	--	.112	.037	.007	--	--	--	--	*.000*	*.000*	.047	.092	--	.097	*.000*	*.000*	*.003*	*.006*	--	.001
By place of residence	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**
CB 1000m	--	.017	.073	.000	--	--	--	--	*.000*	*.001*	.161	.000	--	--	*.000*	*.000*	*.003*	*.002*	.082	.000
NWB 1000m	--	.041	--	.000	--	--	--	--	*.000*	*.000*	.231	.001	--	.048^	*.000*	*.000*	*.003*	*.001*	--	.000
NWB 1500m	--	.029	.195	.000	--	--	.192	--	*.000*	*.000*	--	.000	--	--	*.000*	*.000*	*.005*	*.002*	.217	.000

CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (the lower the walkability, the higher the satisfaction with social-environmental quality and social cohesion) (note: direction of association only marked for statistically significant associations (p<0,05); ^ respondents living in areas of medium walkability (quartile 2 or/and 3 out of 4) walk less for transport respondents living in high (quartile 4) walkability areas.

5.6 Connectivity

5.6.1 Three-way intersection density

Three-way intersection density measures the number of intersections with more than three legs per area. A large number of three-way intersections per area means that the distance to get from place to place is short, and connectivity and permeability are high.

Three-way intersection density was not associated with general walking, BMI or self-rated health (see Table 41 and Table 42).

There were some positive associations between *three-way intersection density* and walking for transport. For the whole sample and among men, *three-way intersection density* was positively associated with walking for transport after controlling for confounders, but only in the 1,000m circular buffer. Overall, associations between *three-way intersection density* and walking for transport were observed in the 1,000m circular and in the 1,500m street network buffers, but not in the 1,000m street network buffer. This was also the case for the positive association between *three-way intersection density* and walking for transport among older respondents, respondents with a high socio-economic status and respondents living in the eastern part of the city.

There was a clear positive association between *three-way intersection density* and biking for transport, but not for all sub-groups. This association was observed among men, younger respondents, respondents with a high socio-economic status and among respondents residing on the east side of the river.

A similar pattern can be observed for the positive association between *three-way intersection density* and active transport. The association reached statistical significance among men, respondents with a high socio-economic status and respondents living in the eastern part of the city, but also among younger and older respondents.

Three-way intersection density was negatively associated with all neighbourhood satisfaction measures except satisfaction with infrastructure. Mean neighbourhood satisfaction was most often negatively associated with *three-way intersection density* among women, younger respondents,

respondents with a low socio-economic status and respondents living on the west side of the river. *Three-way intersection density* was negatively associated with satisfaction with social-environmental quality in the whole sample and in all sub-groups. The negative association between *three-way intersection density* and satisfaction with social cohesion was mainly observed among men and women, respondents with a high socio-economic status and respondents residing in the eastern part of the city.

The same pattern was seen for the association between *three-way intersection density* and satisfaction with infrastructure, even though this association was positive. Neighbourhood satisfaction with infrastructure was higher among respondents living in areas with a high *three-way intersection density* than among respondents living in areas with a low *three-way intersection density*. This association was found for all sub-groups, except respondents with a low socio-economic status and respondents living in the West.

Table 41: Bivariate associations between three-way intersection density and health-related outcomes (p-values < 0.250)

	Twalk d/m		**Tbike d/m**		**Walk min/w**		**BMI**		**Nbh sat**		**Act trans**		**Self-rated health**		**Social env. quality**		**Social cohesion**		**Infra-structure**	
CB 1000m	.087		.009		--		--		.060		.000		--		*.000*		*.001*		.000	
NWB 1000m	--		.202		--		--		*.024*		--		--		*.024*		*.015*		.000	
NWB 1500m	.191		.003		--		--		.173		.002		--		*.000*		*.001*		.000	
By sex	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**
CB 1000m	.020	--	.012	--	--	--	--	--	.238	.120	.000	.095	--	--	*.007*	*.000*	*.071*	*.027*	.008	.001
NWB 1000m	--	--	.187	--	--	--	--	--	--	*.016*	--	--	.229	--	.222	.088	.208	.091	.008	.000
NWB 1500m	.083	--	.004	.154	--	--	.092	--	--	.098	.018	.073	--	--	*.063*	*.005*	*.107*	*.007*	.000	.000
By age	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**
CB 1000m	--	.033	.033	.216	--	--	.175	.241	.074	.075	.007	.044	--	--	*.000*	*.005*	*.020*	*.044*	.003	.002
NWB 1000m	--	--	.036	--	--	--	.160	--	*.003*	--	--	--	--	--	*.000*	--	.100	.224	.001	.001
NWB 1500m	--	.102	.013	--	.240	.229	--	--	*.009*	--	.066	.039	--	--	*.000*	*.025*	*.009*	.170	.000	.005
By education[&]	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**
CB 1000m	--	.020	.097	.071	--	.188	--	--	.056	--	.050	.000	--	--	*.005*	*.000*	*.043*	*.033*	.105	.000
NWB 1000m	--	--	--	.251	--	--	--	--	--	*.016*	--	.184	--	--	--	*.012*	*.022*	--	.022	.000
NWB 1500m	--	.057	.246	.022	--	--	--	.229	*.042*	--	.132	.002	--	--	*.041*	*.005*	*.031*	*.027*	.090	.000
By pop.density	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**
CB 1000m	.063	--	--	--	--	--	--	.225	.064	*.046*	.005	--	.206	--	.233	--	.145	--	.053#	.012
NWB 1000m	--	--	--	--	--	--	--	--	*.003*	.221	--	--	.091	--	--	--	--	--	.001	--
NWB 1500m	.158	--	--	.192	--	--	--	--	*.014*	--	.094	.016	--	--	--	--	.222	--	.001#	.194

CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (the lower the walkability, the higher the satisfaction with social-environmental quality and social cohesion) (note: direction of association only marked for statistically significant associations (p<0,05)); [&]low = not achieving general qualification for university entrance, high = achieving general qualification for university entrance; # respondents living in areas of medium walkability (quartile 2 and 3 out of four) are more often satisfied with the infrastructure than respondents living in high and low walkability areas.

Table 42: Controlled bivariate associations between three-way intersection density and health-related outcomes (p-values < 0.250)

	Twalk d/m		**Tbike d/m**		**Walk min/w**		**BMI**		**Nbh sat**		**Act trans**		**Self-rated health**		**Social env. quality**		**Social cohesion**		**Infra-structure**	
CB 1000m	.027		.020		--		--		*.017*		.000		--		*.000*		*.001*		.000	
NWB 1000m	--		.244		--		--		*.023*		--		--		*.015*		*.047*		.000	
NWB 1500m	.076		.007		--		.248		*.015*		.001		--		*.000*		*.001*		.000	
By sex	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**
CB 1000m	.016	--	.043	--	--	--	--	--	.121	*.017*	.001	.082	.232	--	*.000*	*.000*	*.033*	*.013*	.018	.002
NWB 1000m	--	--	.251	--	--	--	.085	--	--	.025^	--	--	--	--	.090	.061	--	--	.017	.000
NWB 1500m	.064	--	.016	.154	--	--	.009	--	.201	*.011*	.019	.074	.150	--	*.004*	*.001*	*.050*	*.005*	.000	.001
By age	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**
CB 1000m	--	.012^	.029	--	--	--	--	--	.062	*.036*	.006	.031	--	.227	*.000*	*.011*	.070	*.012*	.005	.005
NWB 1000m	--	--	.021	--	--	--	--	--	*.005^*	--	--	--	--	--	*.000*	*.000*	--	.135	.001	.003
NWB 1500m	--	.043^	.012	--	.180	--	--	.190	*.002^*	--	.048	.023	--	--	*.000*	*.000*	*.031*	.059	.000	.013
By SES	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**
CB 1000m	--	.000^	.103	.051	--	--	--	--	*.027*	.059	.094	.000#	--	--	*.013*	*.000*	.080	*.003*	.130	.000
NWB 1000m	--	--	--	--	--	--	--	--	.114	.126	--	--	--	.178	--	*.046*	.106	.167	.051	.000
NWB 1500m	--	.001^	.067	.022	--	--	--	.180	*.011*	--	.125	.001	--	.076	*.011*	*.001*	.073	*.004*	.090	.000
By place of residence	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**
CB 1000m	.127	.007	--	.004	--	--	.088	.255	*.000*	.842	.125	.000	--	--	*.000*	*.015*	*.017*	*.041*	--	.000
NWB 1000m	--	--	.231	.012	--	.223	--	--	--	*.000*	.153	.082	--	--	*.036*	*.025*	--	*.052*	--	.000
NWB 1500m	--	.024	--	.002	--	--	.013	--	*.002*	.191	.114	.002	--	--	*.000*	*.018*	.065	*.026*	.158	.000

CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (the lower the walkability, the higher the satisfaction with social-environmental quality and social cohesion) (note: direction of association only marked for statistically significant associations (p<0,05)); ^ respondents living in areas of medium-walkability (quartile 2 or/and 3 out of 4) walk less for transport / are more satisfied with their neighbourhood than respondents living in high (quartile 4) walkability areas; # = respondents living in areas of quartile 2 were significantly less likely to use active transport than respondents living in high-walkability (quartile 4) areas.

5.6.2 Four-way intersection density

Four-way intersection density is meant to reflect the grid street pattern that should be supportive for walking (Forsyth et al., 2006). In the present analysis, statistically significant associations between connectivity and health-related outcomes were more frequent when using *four-way intersection density* than when using *three-way intersection density*. However, patterns of association were relatively similar.

There was no association between *four-way intersection density* and general walking, BMI and self-rated health (see Table 43 and Table 44). After adjusting for potential confounders, the positive association between *four-way intersection density* and walking for transport was only statistically significant among residents of the eastern part of the city.

Biking for transport was positively associated with *four-way intersection density,* especially among men, younger respondents, respondents with a high socio-economic status and respondents residing on the east side of the river. This is basically the same pattern as observed for *three-way intersection density.* When connectivity is measured using *four-way intersection density,* and when the neighbourhood is defined as 1,500m street network buffer, connectivity was also positively associated with biking for transport among women, older respondents and respondents with a low socio-economic status.

Respondents living in areas with a higher *four-way intersection density* reported using modes of active transport more often than respondents living in areas with lower *four-way intersection density*. This positive association was especially true for younger respondents, respondents with a high socio-economic status and respondents living on the east side of the city.

Using *four-way intersection density* as an indicator of connectivity, the associations with measures of neighbourhood satisfaction were more frequent and reached a higher level of statistical significance than when using *three-way intersection density* as an indicator of connectivity*. Four-way intersection density* was negatively associated with mean neighbourhood satisfaction, satisfaction with social-environmental quality and satisfaction with social cohesion in all sub-groups after controlling for potential confounders.

Satisfaction with infrastructure was also positively associated with *four-way intersection density* among all sub-groups; however the positive association was less frequent among respondents with a low socio-economic status and among respondents residing in the western part of the city.

Overall, in this analysis, associations were also more often statistically significant when neighbourhood was defined as a 1,000m circular buffer or a 1,500m street network buffer.

Table 43: Bivariate associations between four-way intersection density and health-related outcomes (p-values < 0.250)

	Twalk d/m		Tbike d/m		Walk min/w		BMI		Nbh sat		Act trans		Self-rated health		Social env. quality		Social cohesion		Infrastructure	
CB 1000m	--		.005		--		--		*.000*		.046		--		*.000*		*.000*		.000	
NWB 1000m	--		.069		--		--		*.000*		.207		--		*.000*		*.000*		.000	
NWB 1500m	--		.001		--		.177		*.000*		.055		--		*.000*		*.000*		.000	
By sex	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**
CB 1000m	--	--	.021	.114	--	--	.149	--	*.005*	*.004*	.232	--	.079	--	*.000*	*.000*	*.005*	*.003*	.000	.004
NWB 1000m	--	--	--	.091	--	--	--	--	*.010*	*.013*	--	.195	.212	--	*.000*	*.000*	*.002*	*.001*	.001	.001
NWB 1500m	--	--	.008	.079	--	--	*.046*	--	*.015*	*.001*	.147	.250	--	--	*.000*	*.000*	*.003*	*.004*	.001	.000
By age	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**
CB 1000m	--	.181	.084	.076	--	--	.154	--	*.006*	*.003*	.098	.148	--	--	*.000*	*.000*	*.000*	.068	.001	.000
NWB 1000m	--	.246	.068	--	--	--	.223	--	*.022*	*.007*	.106	--	--	--	*.000*	*.000*	*.000*	*.031*	.001	.000
NWB 1500m	--	.189	.022	.034	--	--	.060	--	*.002*	*.012*	--	.079	.064	--	*.000*	*.000*	*.000*	*.046*	.011	.001
By education[&]	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**
CB 1000m	--	--	.092	.007	--	.162	.153	--	*.000*	.090	.030	.223	--	--	*.000*	*.000*	*.001*	*.010*	.039	.000
NWB 1000m	.166	--	--	.024	--	--	--	--	*.011*	*.013*	.096	--	--	--	*.000*	*.000*	*.001*	*.002*	.012	.000
NWB 1500m	--	--	.135	.005	--	.178	.194	--	*.002*	*.006*	.079	.218	--	--	*.000*	*.000*	*.003*	*.001*	.010	.000
By pop.density	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**
CB 1000m	.148	--	.151	--	--	--	--	--	*.050*	--	--	--	--	--	*.002*	--	*.012*	--	.003	.017
NWB 1000m	--	--	--	--	--	--	--	--	--	--	.211	--	--	--	*.012*	--	.071	--	.014	--
NWB 1500m	--	--	--	--	--	--	.191	--	--	--	*.017*	--	--	--	*.014*	--	.186	--	.006	--

CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (the lower the walkability, the higher the satisfaction with social-environmental quality and social cohesion) (note: direction of association only marked for statistically significant associations (p<0,05)); [&]low = not achieving general qualification for university entrance, high = achieving general qualification for university entrance

Table 44: Controlled bivariate associations between four-way intersection density and health-related outcomes (p-values < 0.250)

	Twalk d/m		**Tbike d/m**		**Walk min/w**		**BMI**		**Nbh sat**		**Act trans**		**Self-rated health**		**Social env. quality**		**Social cohesion**		**Infra-structure**	
CB 1000m	.288		.001		--		--		*.000*		.017		--		*.000*		*.000*		.000	
NWB 1000m	--		.020		--		--		*.004*		.112		--		*.000*		*.000*		.000	
NWB 1500m	--		.000		--		--		*.000*		.021		--		*.000*		*.000*		.000	
By sex	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**
CB 1000m	--	--	.010	.079	--	--	.130	--	.019	*.004*	.121	.247	.182	--	*.000*	*.000*	*.006*	*.002*	.000	.019
NWB 1000m	--	--	.155	.057	.148	--	--	--	.076	*.019*	--	.179	--	--	*.000*	*.000*	*.007*	*.002*	.002	.006
NWB 1500m	--	--	.001	.051	--	--	.079	--	.065	*.000*	.049	.188	--	--	*.000*	*.000*	*.007*	*.004*	.001	.002
By age	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**
CB 1000m	--	.096	.023	.087	--	--	--	--	*.038*	*.006*	.021	.124	--	--	*.000*	*.000*	*.003*	*.009*	.003	.000
NWB 1000m	.244	.127	.010	--	--	--	--	--	.181	*.023*	.032	.240	--	--	*.000*	*.000*	*.000*	.086	.001	.001
NWB 1500m	--	.094	.005	.022	--	--	--	--	*.018*	*.012*	.164	.052	.150	--	*.000*	*.000*	*.000*	*.024*	.001	.001
By SES	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**
CB 1000m	--	.125	.080	.006	--	--	--	--	*.001*	*.002*	.112	.048#	--	.181	*.000*	*.000*	*.006*	*.002*	.100	.000
NWB 1000m	--	--	--	.045	.231	--	--	--	*.021*	.079	--	--	--	--	*.001*	*.000*	*.001*	*.017*	.020	.001
NWB 1500m	--	--	.019	.005	--	--	--	--	*.002*	*.022*	.150	.038#	--	--	*.001*	*.000*	*.005*	*.004*	.068	.000
By place of residence	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**
CB 1000m	.102	.049	--	.000	.230	--	.111	--	*.000*	*.044*	.134	.003	--	.110	*.000*	*.000*	*.000*	*.012*	.031	.000
NWB 1000m	--	.028	--	.000	--	--	.111	--	*.000*	.081	.204	.003	--	--	*.000*	*.000*	*.001*	*.008*	.211	.000
NWB 1500m	.145	.051	--	.000	--	--	*.018*	--	*.000*	*.005*	.070	.001	--	--	*.000*	*.000*	*.010*	*.002*	--	.000

CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (the lower the walkability, the higher the satisfaction with social-environmental quality and social cohesion) (note: direction of association only marked for statistically significant associations (p<0,05)); # = respondents living in areas of quartile 2 were significantly less likely to use active transport than respondents living in high-walkability (quartile 4) areas.

5.7 Walkability indices

5.7.1 IPEN walkability index

The *IPEN walkability index* provides a summary score on the walkability based on the indicators *three-way intersection density, household unit density* and *entropy index. Three-way intersection density* as a measure of connectivity is given twice as much weight as the other variables.

As in the analyses of the individual walkability measures, no association was found between walkability and general walking, BMI or self-rated health (see Table 45 and Table 46).

There were some associations between the *IPEN walkability index* and walking for transport in the controlled analyses, especially among older respondents, respondents with a high socio-economic status and respondents living in the eastern part of the city. The association was not always linear, but there was a trend towards a positive association between the *IPEN walkability index* and walking for transport.

Walkability measured by the *IPEN walkability index* was also positively associated with cycling for transport, but not in all sub-groups. Among male and younger respondents, respondents with a high socio-economic status and respondents living on the east side of the river, the association reached statistical significance.

After controlling for confounders, the *IPEN walkability index* and active transport were also positively associated in almost all sub-groups, except women and respondents residing in the western part of the city.

Walkability and neighbourhood satisfaction were associated in all cases using the *IPEN walkability index* as a measure of walkability. Mean neighbourhood satisfaction was lower among respondents living in high-walklable areas than among respondents living in low-walkable areas in the uncontrolled analaysis in the whole sample and among men and women, younger respondents and low-educated respondents (seeTable 45). This pattern remained when controlling for potential confounders (see Table 46). However, among older respondents and respondents living in the West, the negative association was also statistically significant in the controlled analyses.

Neighbourhood satisfaction with social environmental quality and social cohesion were negatively associated with the *IPEN walkability index* in the whole sample and also in the sub-groups.

The positive association between the *IPEN walkability index* and satisfaction with infrastructure was also observed in all groups, except among respondents with a low socio-economic status and among respondents living in the western part of the city.

Table 45: Bivariate associations between IPEN walkability index and health-related outcomes (p-values < 0.250)

	Twalk d/m		Tbike d/m		Walk min/w		BMI		Nbh sat		Act trans		Self-rated health		Social env. quality		Social cohesion		Infra-structure	
CB 1000m	.048		.001		--		--		*.000*		.001		--		*.000*		*.000*		.000	
NWB 1000m	.122		.021		--		--		*.003*		.036		--		*.000*		*.000*		.000	
NWB 1500m	.071		.001		--		--		*.000*		.000		--		*.000*		*.000*		.000	
By sex	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**
CB 1000m	.116	--	.006	.097	--	--	--	--	*.029*	*.001*	.017	.057	.216	--	*.000*	*.000*	*.002*	*.006*	.002	.002
NWB 1000m	--	--	.107	.241	--	--	--	--	*.051*	.200	--	.091	.073	--	*.000*	*.000*	*.020*	*.003*	.001	.000
NWB 1500m	.140	--	.014	.161	--	--	.137	--	*.036*	*.001*	.003	.072	--	--	*.000*	*.000*	*.002*	*.002*	.001	.007
By age	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**
CB 1000m	--	.027	.009	.072	--	--	.090	--	*.001*	.114	.107	.007	.134	--	*.000*	*.000*	*.000*	*.046*	.011	.001
NWB 1000m	.196	--	.078	--	--	.078	*.029*	--	*.000*	--	.167	.093	--	.078	*.000*	*.000*	*.001*	*.026*	.000	.000
NWB 1500m	--	.029	.018	.150	--	--	--	--	*.001*	*.037*	.128	.004	--	--	*.000*	*.000*	*.000*	*.010*	.009	.001
By education$^{\&}$	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**
CB 1000m	.252	.078	.200	.014	--	.154	--	--	*.002*	.122	.027	.015	--	--	*.000*	*.000*	*.008*	*.002*	.129	.000
NWB 1000m	--	.056	--	.166	.124	--	--	--	*.025*	--	.224	.016	--	--	*.000*	*.000*	*.004*	*.010*	.002	.000
NWB 1500m	.229	--	--	.015	--	--	--	--	*.000*	.205	.034	.003	--	--	*.000*	*.000*	*.001*	*.005*	.183	.000
By pop.density	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**
CB 1000m	--	.208	--	.059	--	--	--	--	--	--	--	.093	*.050*	.117	.059	--	*.019*	--	.060	.205
NWB 1000m	--	--	--	--	--	--	.192	--	.206	*.034*	--	--	*.021*	--	*.016*	--	.168	--	.000	.016
NWB 1500m	--	.254	--	--	--	--	--	--	--	--	--	.127	--	--	.059	--	*.038*	--	.097	.069

CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (the lower the walkability, the higher the satisfaction with social-environmental quality and social cohesion) (note: direction of association only marked for statistically significant associations (p<0,05)); $^{\&}$low = not achieving general qualification for university entrance, high = achieving general qualification for university entrance

Table 46: Controlled bivariate associations between IPEN walkability index and health-related outcomes (p-values < 0.250)

	Twalk d/m		**Tbike d/m**		**Walk min/w**		**BMI**		**Nbh sat**		**Act trans**		**Self-rated health**		**Social env. quality**		**Social cohesion**		**Infra-structure**	
CB 1000m	.048		.001		--		--		*.000*		.001		--		*.000*		*.000*		.000	
NWB 1000m	.122		.021		--		--		*.003*		.036		--		*.000*		*.000*		.000	
NWB 1500m	.071		.001		--		--		*.000*		.000		--		*.000*		*.000*		.000	
By sex	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**
CB 1000m	.087	--	.015	.071	--	--	.232	--	*.025*	*.000*	.013	.063	--	--	*.000*	*.000*	*.003*	*.008*	.003	.004
NWB 1000m	--	--	.134	.188	--	--	--	.227	.115	*.003*	--	.079	*.053*	--	*.000*	*.000*	*.024*	*.006*	.001	.000
NWB 1500m	.138	--	.015	.127	.229	--	.198	.235	*.045*	*.000*	.003	.083	--	--	*.000*	*.000*	*.004*	*.002*	.001	.007
By age	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**
CB 1000m	--	.007^	.008	.132	--	.252	--	--	*.001*	*.036*	.037	.006	--	--	*.000*	*.000*	*.001*	*.025*	.017	.004
NWB 1000m	.202	.227	.051	--	--	.095	--	--	*.006^*	.131	.087	.077	--	.104	*.000*	*.000*	*.005*	*.014*	.000	.000
NWB 1500m	.184	.016^	.007	.201	--	--	--	--	*.001*	*.018*	.031	.006	--	--	*.000*	*.000*	*.002*	*.010*	.012	.003
By SES	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**
CB 1000m	--	.006^	.056	.007	--	--	--	--	*.000*	*.015*	.028	.006	--	--	*.000*	*.000*	*.031*	*.001*	--	.000
NWB 1000m	--	.009^	--	.051	.154	--	--	--	*.004*	--	.136	.016#	--	.233	*.000*	*.000*	*.017*	*.002*	.033	.000
NWB 1500m	--	.033^	--	.014	--	--	--	--	*.000*	.110	.035	.011	--	--	*.000*	*.000*	*.007*	*.004*	.179	.000
By place of residence	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**
CB 1000m	.021	.076	--	.000	--	--	--	--	*.000*	.124	.021	.007	--	--	*.000*	*.000*	*.005*	*.007*	.246	.000
NWB 1000m	.243	.030	.105	.000	--	--	--	--	*.000*	--	.143	.000	--	--	*.000*	*.000*	*.003*	*.042*	.185	.000
NWB 1500m	--	.014	--	.000	--	--	--	--	*.000*	.083	.055	.000	--	--	*.000*	*.000*	*.002*	*.002*	.242	.000

CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (the lower the walkability, the higher the satisfaction with social-environmental quality and social cohesion) (note: direction of association only marked for statistically significant associations (p<0,05)); ^ respondents living in areas of medium walkability (quartile 2 or/and 3 out of four) walk less for transport / are more satisfied with their neighbourhood than respondents living in high (quartile 4) walkability areas; # = respondents living in areas of quartile 2 were significantly less likely to use active transport than respondents living in high-walkability (quartile 4) areas.

5.7.2 Graz walkability index

The *Graz walkability index* was based on the measures of *household unit density, proportion of mixed land use* and *four-way intersection density,* giving the same weight to each indicator. The index is a summary score of walkability using the indicators that most frequently showed statistically significant associations with health-related outcomes among the respondents in the present study. As a consequence, statistically significant associations between the *Graz walkability index* and health-related outcomes were more frequent than between the *IPEN walkability index* and health-related outcomes, even though patterns were rather similar overall.

Once again, there was no association between the *Graz walkability index* and general walking, BMI or self-rated health (see Table 47 and Table 48). Only among men did the positive association between walkability and BMI reach statistical significance.

The *Graz walkability index* was also positively associated with walking for transport in the controlled analyses among older respondents, respondents with a high socio-economic status and respondents living in the eastern part of the city, even though this association was not always linear.

Biking for transport was positively associated with the *Graz walkability index* in all sub-groups, except among residents of the western part of the city. Unlike the *IPEN walkability index,* the *Graz walkability index* was also positively associated with biking for transport among women and older respondents.

The *Graz walkability index* was also associated with all neighbourhood satisfaction measures. Mean neighbourhood satisfaction, satisfaction with social-environmental quality and satisfaction with social cohesion were negatively associated with the *Graz walkability index* in all sub-groups. Thus, neighbourhood satisfaction was lower among respondents living in high-walkable neighbourhoods compared to respondents living in low-walkable neighbourhoods.

The opposite was the case for satisfaction with infrastructure. Respondents living in high-walkable areas reported a high satisfaction with infrastructure, and respondents living in low-walkable areas reported a low satisfaction with infrastructure. This was not the case in all sub-groups. Among respondents with a low socio-economic status and among respondents living in the western part of the city, this association was not observed after controlling for potential confounders.

Nevertheless, as in the analysis using the single walkability indicators, associations more often reached statistical significance when neighbourhood was defined as a 1,000m circular buffer or a 1,500m street network buffer than when defined as a 1,000m street network buffer.

Table 47: Bivariate associations between Graz walkability index and health-related outcomes (p-values < 0.250)

	Twalk d/m		**Tbike d/m**		**Walk min/w**		**BMI**		**Nbh sat**		**Act trans**		**Self-rated health**		**Social env. quality**		**Social cohesion**		**Infra-structure**	
CB 1000m	--		.000		--		.124		*.000*		.003		*.025*		*.000*		*.000*		.000	
NWB 1000m	.146		.000		--		--		*.000*		.013		--		*.000*		*.000*		.000	
NWB 1500m	.222		.000		--		.115		*.000*		.010		.100		*.000*		*.000*		.000	
By sex	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**
CB 1000m	.125	--	.007	.060	.232	--	*.017*	--	*.014*	*.000*	.046	.043	.005	--	*.000*	*.000*	*.013*	*.000*	.001	.018
NWB 1000m	.095	--	.007	.067	.129	.234	*.054*	--	*.004*	*.000*	.074	.167	.126	--	*.000*	*.000*	*.002*	*.000*	.002	.027
NWB 1500m	.170	--	.006	.065	--	--	*.005*	--	*.027*	*.000*	.120	.074	.120	.106	*.000*	*.000*	*.011*	*.001*	.001	.041
By age	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**
CB 1000m	--	.027^	.002	.044	--	.223	.072	--	*.000*	*.004*	.023	.004	.222	.072	*.000*	*.000*	*.000*	*.026*	.077	.010
NWB 1000m	--	.067	.005	.046	--	.045	.099	--	*.000*	*.003*	.082	.093	--	--	*.000*	*.000*	*.000*	*.047*	.022	.002
NWB 1500m	--	.058	.010	.023	--	.216	.138	--	*.000*	*.002*	.073	.012	--	--	*.000*	*.000*	*.000*	*.021*	.055	.002
By education&	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**
CB 1000m	.166	--	.212	.004	--	--	.232	--	*.000*	*.004*	.027	.085	.060	--	*.000*	*.000*	*.001*	*.003*	.117	.001
NWB 1000m	.066	--	.064	.014	.091	--	--	--	*.000*	*.001*	.024	--	--	--	*.000*	*.000*	*.000*	*.002*	.042	.000
NWB 1500m	.132	--	.124	.019	.123	--	.125	--	*.000*	*.005*	.062	.128	.170	--	*.000*	*.000*	*.000*	*.003*	.065	.000
By pop.density	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**
CB 1000m	--	--	--	.119	--	--	.233	.186	*.021*	.177	--	.119	*.038*	.114	*.001*	--	*.033*	--	--	--
NWB 1000m	.197	.145	--	--	--	--	--	--	.061	*.049*	*.053*	.198	--	--	*.000*	.060	.100	--	.138	--
NWB 1500m	--	--	--	.224	--	--	--	.207	*.023*	.100	.077	.235	--	--	*.000*	*.019*	.063	--	.075	--

CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (the lower the walkability, the higher the satisfaction with social-environmental quality and social cohesion) (note: direction of association only marked for statistically significant associations (p<0,05)); &low = not achieving general qualification for university entrance, high = achieving general qualification for university entrance; ^ respondents living in areas of medium walkability (quartile 2 and 3 out of four) walk less for recreation than respondents living in high and low-walkability areas.

Table 48: Controlled bivariate associations between Graz walkability index and health-related outcomes (p-values < 0.250)

	Twalk d/m		**Tbike d/m**		**Walk min/w**		**BMI**		**Nbh sat**		**Act trans**		**Self-rated health**		**Social env. quality**		**Social cohesion**		**Infra-structure**	
CB 1000m	.163		.000		--		--		*.000*		.001		.068		*.000*		*.000*		.001	
NWB 1000m	.102		.000		--		--		*.000*		.007		--		*.000*		*.000*		.000	
NWB 1500m	.124		.000		--		--		*.000*		.006		.236		*.000*		*.000*		.000	
By sex	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**	**m**	**f**
CB 1000m	.116	--	.008	.040	.240	--	.028	--	*.022*	*.000*	.044	.054	*.013*	--	*.000*	*.000*	*.026*	*.001*	.001	.030
NWB 1000m	.143	--	.004	.035	.128	--	.246	--	*.011*	*.000*	.076	.106	.203	--	*.000*	*.000*	*.008*	*.000*	.002	.046
NWB 1500m	.174	--	.004	.055	--	--	.017	--	*.039*	*.000*	.115	.084	.199	.203	*.000*	*.000*	*.024*	*.001*	.001	.054
By age	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**	**<37y**	**>37y**
CB 1000m	--	.010^	.001	.046	--	.249	--	--	*.000*	*.000*	.003	.006	--	.200	*.000*	*.000*	*.000*	*.019*	.077	.022
NWB 1000m	--	.041^	.002	.042	--	.106	--	--	*.000*	*.000*	.027	.083	--	--	*.000*	*.000*	*.000*	*.024*	.020	.007
NWB 1500m	--	.031^	.005	.019	--	.236	--	--	*.000*	*.000*	.013	.015	--	--	*.000*	*.000*	*.000*	*.021*	.045	.004
By SES	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**	**low**	**high**
CB 1000m	--	.021^	.027	.007	--	.236	--	--	*.000*	*.000*	.031	.061	.242	.092	*.000*	*.000*	*.011*	*.001*	.083	.002
NWB 1000m	--	.092	.025	.008	.134	--	--	--	*.000*	*.002*	.097	.108	--	.216	*.000*	*.000*	*.002*	*.003*	.133	.001
NWB 1500m	--	.032^	.047	.007	.175	--	--	--	*.000*	*.003*	.070	.103	--	.168	*.000*	*.000*	*.002*	*.005*	.062	.001
By place of residence	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**	**West**	**East**
CB 1000m	.172	.034	--	.000	--	--	--	--	*.000*	*.001*	.089	.000	.128	--	*.002*	*.003*	.002	.003	--	000
NWB 1000m	.157	.011	--	.000	--	--	--	--	*.000*	*.001*	.163	.001	--	--	*.004*	*.001*	*.004*	*.001*	--	.000
NWB 1500m	--	.033	--	.000	--	--	--	.195	*.000*	*.000*	--	.001	--	--	*.003*	*.002*	*.003*	*.002*	.121	.000

CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (the lower the walkability, the higher the satisfaction with social-environmental quality and social cohesion) (note: direction of association only marked for statistically significant associations (p<0,05)); ^ respondents living in areas of medium walkability (quartile 2 or/and 3 out of four) walk less for transport than respondents living in high (quartile 4) walkability areas.

5.8 Multiple associations

Table 49 shows the results of the ANCOVA and multiple regression analyses. For each outcome, one model was conducted controlling for sex, age, socio-economic status and place of residence. Exposure variables were walkability variables that were from different data sets. Each model included one density, one land use mix and one connectivity measure. Based on the results of the controlled bivariate analyses the models included *household unit density*, *proportion of mixed land use* and *four-way intersection density.* These indicators were more strongly associated with the outcomes than the other measures of density, land use mix and connectivity, respectively.

The covariates covering a range of individual characteristics were more often significantly associated with health-related outcomes than the walkability variables. In particular, place of residence was significantly associated with a range of the health-related outcomes, except walking for transport, general walking, use of active transport and self-reported health status.

Among the walkability variables, *four-way intersection density* was most frequently associated with health-related outcomes. *Proportion of mixed land use* was significantly associated with the outcomes almost as frequently as connectivity. *Household unit density* was the least important walkability variable in relation to the outcomes.

Walking for transport, general walking and self-rated health were not significantly associated with walkability.

Biking for transport was positively and strongly associated with walkability in the controlled bivariate analyses. In the ANOVA including multiple exposure variables, it was only positively associated with *household unit density* within the 1,000m street network buffer.

BMI was positively associated with land use mix within the circular buffer, but not with other walkability variables or within the two other buffers. BMI was strongly associated with the covariates. The covariates as individual characteristics explained about 30% of the variance in BMI.

Active transport was positively associated with density and negatively associated with connectivity within the 1,500m street network buffer.

Based on the results of the controlled bivariate analyses, one would expect that walkability was negatively and strongly associated with mean neighbourhood satisfaction. In the multiple regression models, mean neighbourhood satisfaction was negatively associated with land use mix within the street network buffers, but not within the circular buffer. Within the circular buffer, neighbourhood satisfaction was positively associated with connectivity. Nevertheless, the model explained about 14% of the variance in neighbourhood satisfaction.

Neighbourhood satisfaction with social environmental quality and local infrastructure were among the health-related outcomes most frequently associated with the three examined walkability variables in the full models.

In all buffers, neighbourhood satisfaction with social environmental quality was significantly negatively associated with *proportion of mixed land use*. It was also significantly associated with *four-way intersection density* within the circular and the 1,000m street network buffer. However, a significant association was almost reached within the 1,500m street network, with a p-value of 0.062. The model explained about 25% of the variance in satisfaction with social environmental quality.

Neighbourhood satisfaction with local infrastructure was significantly positively associated with all included walkability variables within the 1,500m street network buffer, but only positively associated with *four-way intersection density* within the other buffers. However, about 10% of the variance in satisfaction with local infrastructure was explained by the included variables.

Unlike the results of the bivariate analyses, neighbourhood satisfaction with social cohesion was only negatively associated with *four-way intersection density* within the circular buffer, but not with other walkability variables or within the other buffers. The 10% variance explained by the model was mainly due to sex and place of residence.

Table 49: Multiple associations (p-values < 0.250) controlled for sex, age, socio-economic status and place of residence

	Buffer	Sex	Age	Socio-economic status	Place of residence	Household unit density	% mixed use	4-way inter-section density	r^2
Twalk d/m	CB 1000	.004	.122	.256	--	--	--	--	.042
	NWB 1000	.004	.138	.250	--	--	--	--	.038
	NWB 1500	.004	.161	.204	--	--	--	--	.041
Tbike d/m	CB 1000	--	--	.045	.044	--	--	--	.045
	NWB 1000	--	--	.032	.020	.013	--	--	.047
	NWB 1500	--	--	.053	.013	.179	.173	.233	.052
Walk min/w	CB 1000	--	.028	--	.093	--	.137	--	.034
	NWB 1000	--	.017	--	--	--	--	--	.030
	NWB 1500	--	.014	--	.167	--	.136	--	.033
BMI	CB 1000	.000	.000	.000	.001	.062	*.045*	--	.293
	NWB 1000	.000	.000	.000	.002	.166	--	--	.288
	NWB 1500	.000	.000	.000	.001	--	.248	--	.291
Nbh sat	CB 1000	--	--	--	.000	.150	.091	.018	.142
	NWB 1000	--	--	--	.000	.122	*.033*	.201	.135
	NWB 1500	.192	--	--	.000	--	*.000*	--	.139
Act trans	CB 1000	.000	.211	--	.195	.182	--	--	.102
	NWB 1000	.001	--	--	--	.059	--	--	.092
	NWB 1500	.000	--	--	.209	.011	.058	*.011*	.120
Self-rated health	CB 1000	.097	.002	.001	.127	--	--	--	.103
	NWB 1000	.069	.002	.001	.253	--	--	--	.103
	NWB 1500	.068	.002	.000	.165	--	.121	.108	.114
Social environmental quality	CB 1000	--	--	.128	.000	*.040*	*.022*	*.007*	.244
	NWB 1000	--	--	.131	.000	.200	*.000*	*.019*	.248
	NWB 1500	--	--	.152	.000	.115	*.000*	.062	.256
Social cohesion	CB 1000	.000	--	--	.000	--	.169	*.051*	.113
	NWB 1000	.001	--	--	.005	--	--	--	.103
	NWB 1500	.000	.242	--	.002	--	--	--	.101
Infrastructure	CB 1000	--	.182	--	.011	--	.145	.003	. 091
	NWB 1000	--	.221	--	.003	.179	--	.021	.088
	NWB 1500	--	.214	--	.021	.011	.007	.012	.103

CB = circular buffer, NWB = street network buffer; twalk= walking for transport, tbike= biking for transport, walk= general walking, nbh sat= mean neighbourhood satisfaction, act trans = active transport; d/m= days per month, min/w= minutes per week; Italics: association in the unexpected direction (the lower the walkability, the higher the satisfaction with social-environmental quality and social cohesion) (note: direction of association only marked for statistically significant associations (p<0,05))

6 Discussion

The aim of this thesis was to develop GIS-based walkability indicators relevant to public health for surveillance and planning purposes in Graz.

To achieve this aim, the discussion will first deepen the understanding of the results and issues related to the health-related outcomes.

Then, the author will discuss which walkabililty indicators are consistently associated with health-related outcomes in the literature and among the population in Graz and are therefore relevant to public health surveillance and planning in Graz. This section will also discuss methodologial and conceptual issues related to the walkability indicators and further research questions.

The following discussion section debates the definition of neighbourhood and the impact of confounding sub-group characteristics in the context of the current scientific discourse.

Finally, the discussion describes the implications of the results and the recommendations for surveillance and planning and policy.

6.1 Issues related to health-related outcomes

Walking

The empirical results of the present study show no associations between the walkability measures and general walking and hardly any association between walkability and walking for transport. Giles-Corti et al. (2005) argued that behaviour-specific environmental measures need to be determined. The results on general walking support this argument. Walkability measures that were developed to understand the association between the built environment and active modes of transport were more related to walking for transport than to general walking.

Nevertheless, an association between walkability and walking for transport was also barely found. One possible explanation is that respondents overestimated their walking for transport. Table 9 showed that the median days per month walked for transport and the median minutes per week walked in general are rather high. Respondents were asked how many times they walked on average at least for ten minutes. In the situation of the telephone interview, respondents may not have understood properly that the question was asking not about walking in general, but rather about walking for at least ten minutes. Additionally, walking times per se may be estimated incorrectly. Dewulf et al. (2012) found that on average 34% of all respondents overestimated walking times, while only about half of the respondens estimated walking times correctly (Dewulf et al., 2012). Furthermore, they have shown that misperception of walking times was related to physical activity status. Physically active respondents could better estimate walking times than physically inactive respondents. Insufficiently active people overestimated walking times, and active people underestimated walking times. For the results of the present study, this could mean that differences between walkers and non-walkers were leveled off by misperception of walking times.

Additionally, the misperception of high-walkable neighbourhoods as low could also affect the association between walkability and walking for transport in Graz. Studies have shown that about one third of individuals misperceive their objectivley high-walkable neighbourhood as low (Arvidsson et al., 2012, Gebel, Bauman and Owen, 2009). Since the objective environment and its perception probably contribute to walking for transport (Gebel, Bauman and Owen, 2009, Gebel et al., 2011), this may also have played a role.

There could also be simply no association between walkability and walking for transport in Graz. Since most of the evidence on the association between walkability and walking for transport was found in the US, it may not be transferable to European cities. However, in Belgium and Sweden, investigators also found associations between walkability and walking for transport (Van Dyck et al., 2010, Arvidsson et al., 2012, Sundquist et al., 2011). Therefore, it is assumed that there is also a positive association between walkability and walking for transport, but research design needs to be improved to measure this association.

Cycling for transport and active transport

In the present study, all included walkability measures were consistently positively associated with cycling for transport and active transport. As the literature review of the present study has shown, good quality evidence from other studies on these associations is scarce. Nevertheless, the present and other reviews support the results of the present study. Fraser et al. (2010) found population density and land use mix positively associated with cycling. The evidence of other reviews suggests that walkability is related to cycling and active transportation (Saelens et al., 2003, Sallis et al., 2004).

Self-rated health

In the present study, it was hypothesised that walkability was positively related to self-rated health. Other investigators have found positive associations between walkability and different measures of physical and mental health (Rohrer, Pierce and Deninson, 2004, Tomey et al., 2013, Sallis et al., 2009). In the literature review, no study was found that investigated the association between GIS-measured walkability and self-rated general health. The analysis of the present study found no association. The causation of good self-rated health is very complex, and the neighbourhood environment may be one factor, but presumably not a very important factor determining self-rated health. However, since other research has suggested that self-rated health may be associated with walkability, further research should be conducted.

Weight-related measures

No association was found between walkability and BMI in the present study. The literature shows mixed findings. Feng et al. (2010) conducted a systematic review of the association between the built environment and obesity. They concluded that the evidence was too heterogeneous to draw conclusions. Further research using comparable measures would be desirable. More recent longitudinal evidence from the US and Canada indicates that BMI may not be associated with objectively measured walkability (Berry et al., 2010a, Berry et al., 2010b, Michael et al., 2013, Michael et al., 2014). Recent European cross-sectional studies found almost no association between walkability measures and BMI (Ball et al., 2012, Burgoine, Alvanides and Lake, 2011). Sarkar, Gallacher and Webster (2013) conducted a longitudinal study in the UK and also found no association between density, connectivity and BMI. Land use mix and BMI were even inversely related. One study in Belgium also found no direct association between walkability and BMI (Van Dyck et al., 2010a). Physical activity mediated the association between walkability and BMI. Thus, the association between walkability and BMI is probably more complex than hypothesised in the present study. Improved walkability may have a positive and indirect impact on BMI through physical activity, but not directly.

Neighbourhood satisfaction

Based on the theory of walkability outlined above (see section 2.1), it was hypothesised that high walkability would be associated with high social cohesion. Contrary to these expectations, the walkability factors investigated in the present study were negatively associated with mean neighbourhood satisfaction, satisfaction with social environmental quality and satisfaction with social cohesion. Neighbourhood satisfaction was lower among respondents living in high-walkable areas than among respondents living in low-walkable areas. This association also remained rather consistently statistically significant in the multiple models.

Van Dyck et al. (2011) also found a negative association between residential density and the walkability index and neighbourhood satisfaction in Belgium. These negative associations were mediated by perceived environmental characteristics, such as aesthetics and safety (Van Dyck et al., 2011). The association between land use mix and connectivity and neighbourhood satisfaction was not statistically significant in Belgium. One similar study undertaken with data from Australia also found a negative association between a destination's connectivity score and social cohesion in the neighbourhood (Van Dyck et al., 2013). A study in Japan found walkability negatively associated with individual items of a social capital scale (Hanibuchi et al., 2012). Based on data from the PLACE study, du Toit et al. (2007) found a modest positive association between walkability and a sense of community, but no association between walkability and social cohesion and informal social control. This modest positive association was mediated by walking for transport (du Toit et al., 2007). Thus, the scarce available evidence on all socio-economic groups indicates a negative association rather than a positive association or no association between objectively assessed walkability measures and neighbourhood satisfaction. Sallis et al. (2009) investigated the difference in associations between walkability and neighbourhood satisfaction by neighbourhood income. They found a positive association between walkability and neighbourhood satisfaction, but only among respondents living in high income neighbourhoods. This difference by neighbourhood income should also be investigated for Graz, and the results may look different. In Graz, most high-walkable neighbourhoods are considered to be low-income neighbourhoods. Neighbourhood income could have an impact on the results of the present study. However, the consistent negative association between walkability and neighbourhood satisfaction probably cannot be entirely explained by neighbourhood income. More research is needed to investigate how walkability and neighbourhood satisfaction and social cohesion are related to each other.

The results of the present study are not surprising when looking at the questions asked in more detail and when considering the preferences of the population of Graz. Neighbourhood satisfaction with general social environmental quality included aspects such as reputation and appearance, location, safety, recreational walking opportunities and environmental quality of the neighbourhood. The typical low walkable neighbourhood in Graz is a residential area with single-family detached houses on the outskirts surrounded by green area. Most people and families prefer to live there or aim to move there. These neighbourhoods usually have a good reputation, plenty of recreational walking opportunities and a high environmental quality. Safety is also considered to be higher than in the high-walkable areas in the city centre. Consequently, it is no surprising that respondents living in low-walkable areas reported being more satisfied with social environmental quality than respondents living in high-walkable areas.

Furthermore, these single family detached houses, usually found in low walkable but green areas, are private property. In Austria, people usually buy a house and live there for their whole lives. Thus, these low-walkable areas are characterised by a constant population that builds up social ties within the neighbourhood over time. In the typical high-walkable areas, the share of people who rent their home is high. Consequently fluctuation over time is higher than in the low walkable residential areas on the outskirt of Graz. Fluctuation hinders the development of close relationships to neighbours. Considering these facts, it is not surprising that satisfaction with social cohesion was negatively associated with walkability in Graz.

As expected, based on the theoretical approach, walkability was positively associated with satisfaction with local infrastructure. In terms of the walkability measures, high-walkable neighbourhoods have a higher land use mix. Therefore, local infrastructure measured objectively should be better than in low-walkable, more residential areas. Consequently, respondents living in low-walkable areas were less satisfied with the local infrastructure than respondents living in high-walkable areas.

6.2 Issues related to walkability

6.2.1 Issues related to density

High residential density is considered to be related to traffic congestions and parking problems. As a result of these factors, it is supposed to directly promote walking for transport, since it is more convenient to walk than to go by car (Forsyth et al., 2007). The literature showed that density, especially measured as *gross population density*, is related to walking for transport. McCormack and Shiell (2011) also found that population density was not only positively associated with walking behaviour in cross-sectional studies, but also in quasi-experimental studies. In the present empirical study, we were unable to find a clear association between the two density measures and walking for transport. However, density was related to walking for transport among respondents residing in the eastern part of the city. Therefore, there may be an association between density and walking for transport among the population of Graz when the validity of the walking measurement is improved.

Density was also positively associated with biking for transport and physically active transport in the present study. The association with biking for transport was more frequent, and in most cases the p-value was smaller than for the associations with active transport. Furthermore, in the model including multiple outcomes, *household unit density* was positively associated with biking for transport and active transport. As shown in the literature review, scientific evidence on the association between density and biking for transport and active transport is scarce. One cross-sectional study on potential determinants of bike commuting found that bike commuting increases as density increases (Zahran et al., 2008). Another review found a positive association between density and cycling for transport among school children, but a negative association between density and active travel to school (Fraser and Lock, 2011).

Nevertheless, the association between density and biking for transport and active travel was consistently observed in the present study. An association for the population of the city of Graz can therefore be assumed.

The density measures in the present study were not related to BMI. The literature review in the present study and the results of Feng et al. (2010) showed mixed findings. This pattern is found in more recent studies. McDonald et al. (2012) found no association between *gross population density* and BMI in the Twin Cities Walking Study, a result which was supported by longitudinal evidence from the UK (Sarkar, Gallacher and Webster, 2013). Similar to Brown et al. (2009), Wen and Kowaleski-Jones (2012) found an association between density and BMI for men, but not for women. Wen and Kowaleski-Jones (2012) even found a positive association between *gross population density* and BMI. In northeastern England, investigators found an increased risk for overweight in the lowest density study area compared to the highest density study area (Burgoine, Alvanides and Lake, 2011). Due to these mixed findings, the association between density and BMI needs further investigation (McDonald et al., 2012, Wen and Kowaleski-Jones, 2012).

Density could also indirectly influence walkability (Forsyth et al., 2007). It can also be seen as a proxy for good transit infrastructure, land use mix, sights and aesthetics. In the present study, density was positively associated with satisfaction with infrastructure, which indicates that density is also a proxy measure for land use mix (Gebel, Bauman and Petticrew, 2007).

Furthermore, density was negatively associated with mean neighbourhood satisfaction, neighbourhood satisfaction with social environmental quality and social cohesion. Van Dyck et al. (2011) reported similar findings from Ghent, Belgium. In their study, density was associated with perceived aesthetic, environmental and safety-related problems, and the association between density and neighbourhood satisfaction was mediated by these perceptions (Van Dyck et al., 2011). Therefore, the negative association between density and neighbourhood satisfaction in the present study may also be explained by negative perceptions of high-density neighbourhoods.

Although the two density measures used in the present study are related to each other, they measure slightly different things. *Gross population density* measures the number of people living in an area, while *household unit density* measures the household units. Thus, in areas with a high *gross population density*, if the share of families with children is high, the *household unit density* can still be low. On the other hand, areas with a high proportion of single households or even vacant apartments, which is more often the case in high-walkable areas, can have a high *household unit density* but a low *gross population density* (Forsyth et al., 2007). Thus, it is important to be clear about what should be measured.

Feng et al. (2010) argued that there is no consensus on which density measures should be used. How population density is measured is of relevance. In the present study, gross density was measured. The number of people or households in an area was related to the total area of the neighbourhood. The entire land area was used as the denominator of the calculation. The literature analysis has shown that almost all studies investigating *population* or *household unit density* as a stand-alone measure (not in an index) have used gross density measures. For the calculation of the walkability index, most studies have used net density measures. In this case, certain land uses are excluded. Most net density measures used the area devoted to residential use as a denominator.

Net density measures are typically higher than gross density measures. Since non-residential areas, which have a *population* or *household unit density* of zero, are included in the denominator for the gross density measure, the overall figure is lower than for the net density. However, people walk in the total neighbourhood, and not only in the residential area. Therefore, gross density is considered to be the better measure for walkability (Forsyth et al., 2007). Gross density measures were used in the present study because they were the most prevalent measures in the literature, were associated with health-related outcomes in the literature, and are considered better density measures for walkability.

Furthermore, in the present study, the zoning data did not allow to calculate net density measures. The zoning data for Graz only differentiates between 'purely residential', 'mainly residential' and other land uses (see section 4.4). The 'mainly residential' areas are defined as residential, but buildings with commercial, social, religious and cultural services are allowed (Steiermärkische Landesregierung, 2007). For example, the area around the Karl-Franzens-University in Graz (e.g. Zinsendorfgasse) is categorized as 'mainly residential'. However, this area offers many services and is considered to be very walkable. Due to cases like these, the category 'mainly residential' was included as mixed use and not as residential in the present analysis (see section 4.4). To calculate net density measures the area categorized as 'pure residential' in the zoning data remained. From the 843 respondents included in the analysis, 49 had no pure residential area in the 1,500m street network buffer. For the 1,500m street network buffer, the median *net household unit density* was twice as high as the median *gross household unit density*. The median *net population density* was even 11 times higher than the median *gross population density*. Since the area devoted to pure residential use was very low for many cases, the resulting data and net density measures did not make sense.

To summarize, the association between density and biking for transport and active transport in the present study was clear and consistent. Although there was no clear association between density and walking, it can be concluded that density and active transport modes are associated among the population in Graz. Density was also associated with neighbourhood satisfaction.

Since density can be considered as a determinant of health-related outcomes among the population in Graz, it is recommended to integrate it into surveillance and planning instruments. For surveillance and planning purposes, *gross population density* is important when infrastructures such as medical services are planned. However, it is usually not possible for public agents to regulate household size or *gross population density. Housing unit density*, on the other hand, is easier to measure and to regulate (Forsyth, 2003, Forsyth et al., 2007). In the present study, the measure *household unit density* was more strongly and more frequently associated with health-related outcomes. Since it is also easier to regulate, it is recommended to use *housing unit density* as one indicator to monitor walkability.

6.2.2 Issues related to land use mix

Land use mix measures the variety of activities in the neighbourhood. Residents move to get to different destinations. Large destination variety is considered to increase visual and architectural diversity and to increase interest for pedestrians. Furthermore, the increase in pedestrian traffic should also improve perceived crime safety (Forsyth et al., 2006). A greater variety of activities and destinations in the neighbourhood is meant to promote physically active travel. Physically active travel is again meant to stimulate social contacts among neighbourhoods and to increase social cohesion and neighbourhood satisfaction.

In the present study, two measures of land use mix were used. The *entropy index* measured the heterogeneity of land use types in the neighbourhood. Neighbourhoods with a great number of different land use types were classified as highly mixed, while neighbourhoods with only one land use type were classified as perfectly homogenous. Since the zoning data already included categories which were mixed by definition, the *entropy index* did not seem to be the most appropriate measure to capture land use mix in Graz. These doubts are reflected in the results of the analysis. The *entropy index* was only minimally associated with the health-related outcomes investigated.

The second measure of land use mix was *proportion of mixed land use*. This measure captures the proportion of the area in the neighbourhood that is dedicated to a mixed use category in the zoning data. The present study showed that this measure of land use mix showed associations between land use mix and health-related outcomes, especially modes of active transport and neighbourhood satisfaction.

Reviews also found that land use mix was associated with physical activity (Durand et al., 2011, McCormack and Shiell, 2011). McCormack and Shiell (2011) reported positive and consistent associations between land use mix and physical activity in studies with a quasi-longitudinal design. In their relocation study, Mumford et al. (2011) found that walking for transport increased almost twofold after moving to a mixed use area. Even though these results were exploratory due to methodological issues related to the study (Mumford et al., 2011), they indicate that land use mix and walking for transport are positively associated.

The literature review of the present study yielded mixed results on the association between the *entropy index* and BMI, and the present empirical study found no association between land use mix and BMI. The result of the present study is supported by a cross-sectional study in northeastern England (Burgoine, Alvanides and Lake, 2011). Feng et al. (2010) found negative associations between the *entropy index* and BMI. Longitudinal evidence from the UK, in contrast, found a positive association between the *entropy index* and BMI (Sarkar, Gallacher and Webster, 2013). Thus, no clear pattern for the association between the *entropy index* and BMI emerges. One reason may be the different detailed methods of computing the *entropy index*. Another reason may be that the *entropy index* is not the best way to capture land use mix.

The present study found land use mix negatively associated with mean neighbourhood satisfaction, neighbourhood satisfaction with social-environmental quality and neighbourhood satisfaction with social cohesion. The study of Wood, Frank and Giles-Corti (2010) also found that land use mix was negatively associated with sense of community. In another study, Wood et al. (2008) used different walkability measures and got mixed results. They found a negative association between land use mix and social capital when land use mix was operationalized as number of destinations (Wood et al., 2008). However, when using the perceived adequacy of destinations as a measure of land use mix, they found a positive association between walkability and social capital. Leyden (2003) found that respondents perceiving their neighbourhoods as walkable and mixed use reported higher levels of social capital than respondents not perceiving their neighbourhoods as walkable and mixed use (Leyden, 2003).

The method of measuring land use mix seems to be a key issue. Although the present literature review and empirical study have shown, that the *entropy index* is one way to measure land use mix, it may not be the best available measure to capture land use mix.

Brown et al. (2009) discussed a wide range of problems related to the *entropy index*. They investigated the association between *entropy indices* using two, three and six different land use types and BMI. Furthermore, they calculated the square kilometres of each land use type and used them as measures for land use. Using these last very simple measures of land use, they derived better results than with the *entropy indices.* They concluded that components of the *entropy index* need to be chosen carefully, and that the *entropy index* should be complemented by other simple mixed use and walkability measures. Cerin et al. (2007) followed this conclusion by conducting a study using the *entropy index* and a second measure. They identified groups of neighbourhoods with similar land use profiles, such as residential, commercial and recreational. They found no association between the *entropy index* and walking for transport. However, residents living in commercial areas walked 39.6 more minutes per week for transport than residents living in recreational areas. These findings are also supported by the meta-analysis of Ewing and Cervero, who concluded that other measures of land use mix were stronger correlates of walking than the *entropy index* (Ewing and Cervero, 2010). Following the results of Brown et al.

(2009), Cerin et al. (2007) und Ewing and Cervero (2010), a simple measure of the total area of walkable land use may capture land use mix better than the *entropy index*. This was also the case in the present empirical study, where the rather simple measure *proportion of mixed land use* was more often associated with active modes of transport and other health-related outcomes.

Brown et al. (2009) stressed the importance of choosing the components of the *entropy index* carefully. This follows the call for a more behaviour-specific measurement of land use mix. Duncan, Spence and Mummery (2010) aimed to increase the specificity of measurement of land use mix. They used the *entropy index* and a *revised entropy index*. For the *revised entropy index,* they included only land uses that are theoretically relevant to walking for transport, and excluded land use types that are not typical destinations for utilitarian walking. They found no association between the *entropy index* and a positive association between the *revised entropy index* and walking for transport (Duncan, Spence and Mummery, 2010). Christian et al. (2011) reached a similar conclusion when they used data from the RESIDE study project to calculate five different *entropy indices*. For each index, they used a different number and composition of land use types. They found that an *entropy index* that included the land use types retail, office, residential, health, welfare, community, entertainment, culture and recreation showed the strongest associations with walking for transport. Using this *entropy index,* participants living in high-walkable neighbourhoods reported being almost twice as likely to walk for transport than participants living in low-walkable neighbourhoods (Christian et al., 2011). Including land use types such as public open space, sporting infrastructure and rural areas in the *entropy index* showed stronger associations with walking for leisure. These results support the request for more behaviour-specific measures of land use mix.

The present study explored the associations between two different *entropy indices* and health-related outcomes. One *entropy index* included four land use types and one included five land use types. However, since a wide range of health-related outcomes was used, none of the *entropy indices* used was behaviour specific. Further research should use a more behaviour-specific *entropy index* (e.g. excluding the land use type ‘green area’) and should investigate its association with walking for transport, in particular. In the present study, the indicator *proportion of mixed land use* was a more specific measure of land use mix than the *entropy index.* While the *entropy index* included all land use types (also ‘green area’ or ‘industrial area’) the indicator *proportion of mixed land use* captured only the area devoted to mixed use including destinations people usually walk to frequently. Consequently, it seems plausible that the association between land use mix and health-related outcomes is better assessed with the indicator *proportion of mixed land use*.

Another more practical issue related to the composition of the *entropy index* is the different categorization of land uses in different localities (Brown et al., 2009, Hirsch et al., 2013). The zoning data in the present study area had roughly 90 slightly different land uses for about 8,600 polygons. Salt Lake County, for example, differentiates between 167 land uses (Brown et al., 2009). The land use categories used in studies are determined more by the available data and land use codes than by the research question (Hirsch et al., 2013). However, in the present study only a few land use codes were assigned to the overwhelming majority of polygons. These land use codes do not differentiate well between the different categories necessary for health research. A clear distinction between residential area and mixed use was not possible. Therefore, comparisons between studies and between different study areas can be problematic and have to be made with caution.

Brown et al. (2009) discussed the problem that an *entropy index* of one (i.e. representing perfect heterogeneity) does not necessarily mean a wide variety of land uses in the neighbourhood. This is the case if the ‘number of land use types’ in the formula is defined as the ‘number of land use types present in the neighbourhood’. As Brown et al. (2009) pointed out, a neighbourhood can score a one on the *entropy index* when there are six different land use types present and the land use types are equally distributed, but another neighbourhood could receive the same score if there are only two different land use types present and these are equally distributed. In this case, the *entropy index* captures the evenness of the distribution of different land use types in the neighbourhood more than the actual variety of different land use types.

To overcome this problem, the present study used the ‘number of land use types defined in the study’ as a constant number. Using this approach, only a few associations between the *entropy index* and health-related outcomes were found. Bodea et al. (2008), Cerin et al. (2007) and Forsyth et al. (2008) used the same approach and also found no association between the *entropy index* and walking for transport or BMI. Li et al. (2008), Frank et al. (2004) and Frank et al. (2005) used ‘number of land use types present in the neighbourhood’ and found an association between the *entropy index* and walking for transport or physical activity and BMI. Brown et al. (2009) used the same approach and found mixed results on the association between different *entropy indices* and BMI, overweight and obesity. The approach used in the present study (median score: 0.7942) delivers statistically significant ($p<0.000$) smaller *entropy indices* than the approach using ‘the number of land use types present in the neighbourhood’ (median score: 0.8174) for the 1,500m street network buffer (data not shown). Further investigation is required to determine whether or not this could be one of the reasons why the present study and the studies of Cerin et al. (2007) and Forsyth et al. (2008) did not find associations between the *entropy index* and walking for transport. Unfortunately, in a wide range of studies such details are not reported, therefore reporting should be improved. Further research should explore the impact of this difference in the formula on the association between the *entropy index* and health-related outcomes. In addition, such research should also be conducted in Graz in order to obtain further insights into the performance of the *entropy index* and its use for surveillance and planning.

Another possible variation in the formula of the *entropy index* is the “missing land problem”, as Brown et al. (2009, p. 1132) called it. Land use types that are not included in the *entropy index* may have an impact on the land use mix and on the walkability of an area, but may not be captured by the *entropy index*. In most studies – as described above – not all land use types are included in the *entropy index*. Land use types that seem to be irrelevant are excluded. For example, the land use type industrial land can be excluded because it seems to be an irrelevant destination and an irrelevant land use type for walking. However, in cases where a large proportion of the neighbourhood is covered by industrial land, this alters the land use mix and the walkability of the neighbourhood. Furthermore, it may be an important destination in terms of walking to work if there is a large employer on the industrial land. To overcome the ‘missing land problem’, some studies have used ‘the total area of the neighbourhood’ instead of ‘the area covered by the land use types included in the study’. The prior approach delivers lower *entropy indices* than the latter one. Bodea et al. (2008) and Frank et al. (2004) used the first approach, and Brown et al. (2009), Cerin et al. (2007), Li et al. (2008), Pouliou and Elliot (2010) and Christian et al. (2010) used the second approach. When looking at the results of these studies, no clear pattern emerges. With both approaches, associations between the *entropy index* and health-related outcomes were found.

The present study categorized the whole zoning data and included it in the *entropy index*. Therefore, this difference in formula was not relevant. However, the present study excluded areas covered by water and streets, as outlined in the GIS protocol of Forsyth et al. (2006). So the exclusion of areas covered by water and streets could cause a ‘missing land problem’ in cases where a large area of the neighbourhood is covered by water or streets. This also may have an impact on the walkability of a neighbourhood, but not on the *entropy index* in the present study. For example, for the 1,500m street network buffer, on average 17% of the area was excluded because it was covered by water or streets. The *entropy index* using the total area of the neighbourhood (including areas covered by water or streets) (median score: 0.7534) delivers a statistically significantly ($p<0.000$) lower *entropy index* than the *entropy index* used in the present study (excluding areas covered by water or streets) (median score: 0.7942) for the 1,500m street network buffer (data not shown). Consequently, further research should investigate if the association between the *entropy index* and health-related outcomes is altered if the ‘missing land area problem’ is solved in the formula of *entropy index* in different ways.

Christian et al. (2011) conclude that future research should explore the association between the *entropy index* and walking with different sizes and configurations of neighbourhoods. In the present study, the *entropy index* showed almost no association with health-related outcomes, regardless of the size and configuration of the neighbourhood. Like most of the other walkability measures, it was slightly more likely that the *entropy index* was associated with health-related outcomes if the neighbourhood was defined as a 1,000m circular or a 1,500m street network buffer. Based on the results of the present study, it seems that the size and shape of the neighbourhood has only a small effect on the association between the *entropy index* and health-related outcomes.

Even though some measurement issues are involved, it can be concluded that land use mix is associated with health-related outcomes, especially with different modes of active travel. Consequently, it is recommended to include measures of land use mix in surveillance and planning. However, the question remains which indicator should be used to measure land use mix. The results of the present study show a pattern similar to the one found in the studies of Cerin et al. (2007) and Duncan, Spence and Mummery (2010). The *entropy index* was only minimally related to health-related outcomes, while the simpler and more specific measure of land use, *proportion of mixed land use*, was associated with modes of active travel and neighbourhood satisfaction. In the model including multiple outcomes, *proportion of mixed land use* was also a rather important correlate. The indicator *proportion of mixed land use* may be more appropriate to use for surveillance and planning in the city of Graz than the *entropy index*. Nevertheless, future research on the use of the *entropy index* should be monitored, and further research on the use of the indicator *proportion of mixed land use* should be conducted to ensure the validity of the indicator.

6.2.3 Issues related to connectivity

People use streets to move around the environment. Therefore, the number and directness of routes are measured to investigate the pedestrian friendliness of the neighbourhood (Forsyth et al., 2006). In the present study, the connectivity of the street network was measured by the density of three-way and four-way intersections per area in the residential neighbourhood. High intersection density indicates directness of path, small block sizes and more options for a direct route.

Three-way intersection density was positively associated with walking for transport among older respondents, respondents with a high socio-economic status and respondents residing east of the river when the neighbourhood was defined as a 1,000m circular or a 1,500m street network buffer. However, the association was not linear for most sub-groups. Respondents living in areas of medium connectivity reported walking less for transport than respondents living in highly connected neighbourhoods. The literature review of the present study showed that studies investigating the association between *three-way intersection density* and walking for transport reported a positive association. This result is supported by more recent studies (Saelens et al., 2012). Most of the studies were cross-sectional. One study with a longitudinal design also found a positive association between *three-way intersection density* and walking for transport. Li et al. (2008) reported that walking for transport increased by 20% and walking for errands by 11% with each unit increase in street connectivity. Research results show a clear pattern of a positive association between *three-way intersection density* and walking for transport. So it has to be assumed, that this association could also be observed in Graz more clearly, if the measurement of walking for transport were improved.

This association between connectivity and walking for transport was not found for *four-way intersection density* (only for residents of the eastern part of the city) in the present study. Since there were some measurement issues involved with walking for transport (see section 6.1), the question of which connectivity measure is more relevant in relation to walking for transport in Graz is still to be determined. *Four-way intersection density* as a potential correlate of walking for transport has barely been used in other studies. Ewing and Cevero (2010) used *three-way intersection density* and *proportion of four-way intersections* in their meta-analysis. They found *three-way intersection density* more strongly related to walking than *proportion of four-way intersections*. Forsyth et al. (2008) also used *three-way* and *four-way intersection density* and found both measures associated with walking for transport. Chatman et al. (2009) related the number of four-way intersections to active transport and found that the active transport frequency increased by 3.2% with each additional four-way intersection. When this association was controlled for self-selection, it fell to 2.6%.

Intersection density was also positively associated with cycling for transport. Especially men, younger respondents, respondents with a high socio-economic status and residents living in the eastern part of the city reported more cycling when they were living in high connectivity neighbourhoods than respondents living in low connectivity neighbourhoods. The indicator *four-way intersection density* even showed this association for almost all sub-groups (except residents living on the west side of the river) when the neighbourhood was defined as a 1,500m street network buffer. No studies were found that investigated the association between objective measures of *three-way* or *four-way intersection density* and cycling for transport. Titze et al. (2010) found a positive association between the self-reported presence of four-way intersections and cycling for transport. Respondents reporting a high presence of four-way intersections in their neighbourhoods reported 1.8 times more cycling for transport than respondents reporting a low presence of four-way intersections (Titze et al., 2010).

In the present empirical study, we found no association between street connectivity and BMI. Ball et al. (2012), Sarkar, Gallacher and Webster (2013) and Burgoine, Alvanides and Lake (2011) conducted studies in the United Kingdom and also found no association between connectivity and BMI. Sarkar, Gallacher and Webster (2013) even provided longitudinal evidence. Based on study results from the US, European research teams have hypothesised that BMI would be negatively associated to connectivity. They conclude that their findings may be explained by the different context in Europe (Ball et al., 2012, Burgoine, Alvanides and Lake, 2011). The analysis of recent longitudinal data in the US, however, also found no association between connectivity (using block size and block length as indicators) and BMI (Michael et al., 2013, Michael et al., 2014). Thus, there is some indication that objectively measured connectivity and BMI may not be related to each other, or the association may be more complex, and mediating factors may have to be taken into account.

In the present study, connectivity was negatively associated with mean neighbourhood satisfaction, neighbourhood satisfaction with social environmental quality and neighbourhood satisfaction with social cohesion. There was a positive association between connectivity and neighbourhood satisfaction with infrastructure. Studies on the association between objectively measured intersection density and neighbourhood satisfaction are rare. Another study conducted in Ghent found no association between *three-way intersection density* and neighbourhood satisfaction (Van Dyck et al., 2011). In fact, one Australian study also found a negative association between a destination/connectivity score and perceived social cohesion (Van Dyck et al., 2013). More research is certainly needed to get a clearer picture on the association between connectivity and neighbourhood satisfaction.

The question of how connectivity should be measured remains. A high density of three-way intersections enables direct travel between different destinations (e.g. households, places of employments, schools, shops, services). A high density of three-way intersections means more options for travel routes and therefore promotes walking (Leslie et al., 2007). *Four-way intersection density* is a measure of grid street patterns adjusted for different block sizes (Forsyth et al., 2006). A high *four-way intersection density* means more route options, better permeability to destinations, shorter routes and overall better connectivity than high *three-way intersection density*. In the present study, the pattern of the association between connectivity and health-related outcomes was clearer when connectivity was measured as *four-way intersection density* than when measured as *three-way intersection* density. As described above, there have only been a few studies that used *four-way intersection density* as a measure of connectivity. A general conclusion about which measure performs better in association with health-related outcomes cannot be drawn. In Graz, the connectivity is already rather high. The mean *three-way intersection density* in Graz was 73 (SD 25) per km^2 for the 1,000m circular buffer, while it was 52 (SD 14) per km^2 across different places in the US, for example (Hou et al., 2010). In high-connectivity places such as Graz, *four-way intersection density* may be the more relevant measure. The differentiation between high-walkable and low-walkable areas, and between more health-promoting and less health-promoting environments may be easier to investigate with an indicator that demands a higher level of connectivity. Further studies in other European countries should explore the association between health-related outcomes and *four-way intersection density.*

The present study used street network data to measure connectivity. People can take shortcuts and cut-throughs, especially through parks and parking lots (Forsyth et al., 2006). One Australian study showed that the connectivity of low-walkable neighbourhoods improved significantly when the pedestrian network was taken into account. Connectivity measures improved up to 120%, but high-walkable neighbourhoods still had better connectivity overall (Chin et al., 2008). In the present study, the pedestrian network was not accounted for because only the street network data was used. For the present study area of Graz, it has to be assumed that the connectivity of already high-connected neighbourhoods would improve. In particular, the centre of Graz, with its extensive street network, also has an extensive network of pedestrian paths that is not captured in the street network data in the present study. Consequently, when pedestrian networks were accounted for, the differentiation between high-walkable and low-walkable areas may improve, and associations between connectivity and health-related outcomes may be stronger.

This has further research implications. First, further research should compare the connectivity measured using street network data and connectivity measured by data including the pedestrian network in different neighbourhoods in Graz. This approach would test the assumption that the connectivity of already highly connected areas would improve. Second, the impact of the two different measurement methods of connectivity on the association with health-related outcomes should be investigated. This investigation would shed light on the aforementioned conclusion that associations between connectivity and health-related outcomes may become stronger if the pedestrian network data were accounted for.

The quality of the available street network data also caused problems during the GIS analysis. As described above (see section 4.3.2), a large number of identical streets were recorded twice in the data set. The lines were overlapping, so the issue could be solved by dissolving all streets to one line. It could be that there was one or another street line that was not overlapping, but rather it was the same street and was therefore recorded in the final data as two streets instead of one. This would have caused an overestimation of the intersection density. However, no such case was apparent while working with the data during the GIS analysis.

The present study tried to follow the protocol of Forsyth et al. (2006), but due to the problems related to the data, a different approach for the GIS analysis had to be found. This undertaking was very time consuming. Brownson et al. (2009) have already pointed out that researchers using GIS to measure built environment are often confronted with a mismatch between conceptualised variables and messy geographic data. They also mentioned that access to GIS technicians is limited. For the present study, the GIS analyses were run by the author herself, who received some training at the Institute of Geography at the University of Graz. An experienced GIS technician may have found a quicker and probably different solution for the problem. In the end, all streets were dissolved to one line. In this case, all the information related to each individual street line (e.g. name of street, street type) was lost. For the present analysis, the loss of information did not matter because only the number of intersections was relevant. However, if other measures based on the street network data need to be calculated (e.g. number of streets with a speed limit), other solutions will have to be found to deal with the problem of the double recording of streets.

Another quality issue related to the street centre line data was that the data did not always capture the reality (as show, in satellite photos provided by Google maps). In some cases, for instance, the street border line was recorded instead of the street centre line. Figure 6 shows one intersection in the street centre line data and the same intersection as shown in Google maps. Because the roadside was recorded instead of the street centre, there were four intersections in the data, while Google maps shows that there are only two. The same applied to the feeder lines of large streets, which yielded a larger number of three-way intersections in the data than was pictured in Google maps. There were about 6,700 three-way intersections in the data of the present study. Around each three-way intersection point a 10m buffer was produced, and buffers that overlapped (about 500) were checked visually and edited manually. However, it is likely that not all errors in the data were eliminated. Another cross-check with the satellite photos of Google maps would have been necessary. Therefore, some measurement error remains. There is an over-recording of three-way intersections of an estimated 3-5% (201 to 335 from 6,700 points) in the data of the present study. This problem is more important for the *three-way intersection density* than for the *four-way intersection density*. The chance to produce a point with the valence four or more by erroneous data is much lower than to produce a point with the valence three.

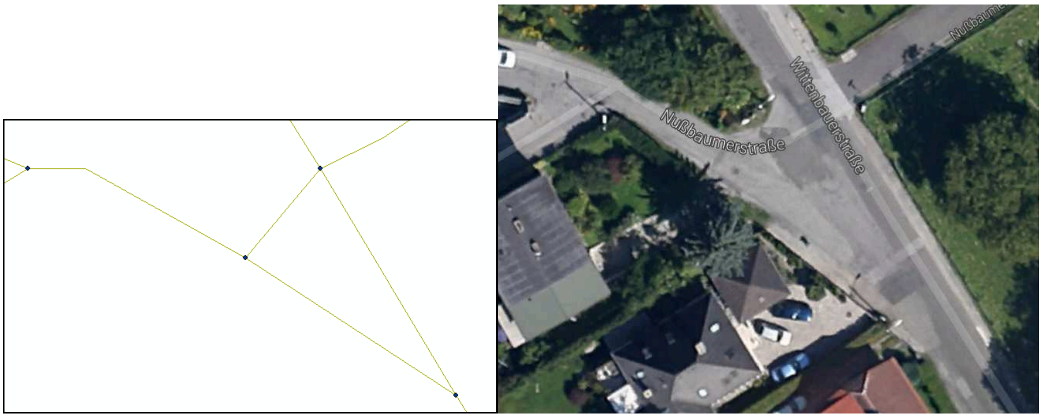


Figure 6: Border of the street instead of street centre

In other cases, the street centre line data also captured small streets to houses or small residential areas or short cuts, which are not captured in Google maps as streets. These small streets can only be discovered in the satellite photos in Google maps. Therefore, there is probably also some over-recording of intersections in the data used in the present study.

These measurement errors in the street centre line data lead to neither overestimation nor underestimation of the association between walkability and health-related outcomes, because the error is scattered across the whole study area and is not more frequent in areas with high or low walkability. However, these measurement errors may be one of the reasons why *four-way intersection density* was more often associated with health-related outcomes than *three-way intersection density*. In the present study, *four-way intersection density* is the more valid measure of connectivity.

Finally, the question of whether or not connectivity measures should be used for surveillance and planning and, if so, which one should be used is still open. From the results described to date, it can be concluded that connectivity is positively associated with modes of active transport. In the case of the city of Graz, there was also an association between connectivity and neighbourhood satisfaction. Consequently, it can be concluded that connectivity should be considered for surveillance and planning as a correlate of health-related outcomes. In the model including multiple outcomes, *four-way intersection density* was the most important correlate of all walkability measures. Consequently, *four-way intersection density* should be the preferred measure for surveillance and planning in the city of Graz. However, further research should be conducted, and research from additional European studies has to be taken into account.

6.2.4 Issues related to the walkability indices

Composite measures such as walkability indices combine population density, land use mix and connectivity indicators into one index and try to capture the overall walkability of an area. Composite measures are computed so as to take the inter-relatedness of individual environmental characteristics into account and to reduce the effects of spatial collinearity (Brownson et al., 2009). Furthermore, the results from a single index are easier to communicate (Brownson et al., 2009).

The literature review of the present study has shown that the *IPEN walkability index* was positively associated with walking for transport, which has been further supported by more recent studies (Arvidsson et al., 2012, Frank et al., 2010, McCormack et al., 2012). In addition, European studies have found a positive association between the walkability indices and walking for transport in both Belgium (Van Dyck et al., 2010, Van Dyck et al., 2010a) and Sweden (Arvidsson et al., 2012).

The present study found a positive association between the walkability indices and walking for transport, but only in sub-groups, and the association was not linear. Respondents living in high-walkable areas reported more walking for transport than respondents living in medium-walkable areas. This association was found among older respondents and respondents with a high socio-economic status. Among respondents residing in the eastern part of the city there was a linear positive association. Thus, the association between walkability indices were not as clear in the present study as in other studies. If the measurement of walking for transport were improved, it is assumed that this association would be clearer.

The walkability indices were clearly positively associated with biking for transport in the present study, but also in studies conducted in Belgium (Van Dyck et al., 2010, Van Dyck et al., 2010a). Looking at the whole sample in Graz, we also found a positive association between walkability and active transport. This association was not found in all sub-groups. In summary, it can be concluded that walkability was positively associated with active modes of transport in Graz.

The present study found no association between walkability and BMI. The literature review of the present study and of Feng et al. (2010) showed mixed results on the association between walkability and BMI. More recent and longitudinal studies have found no association between walkability and BMI (Berry et al., 2010a, Berry et al., 2010b, Michael et al., 2014). There is some indication that there is no association between walkability and BMI, but no firm conclusions can be drawn yet, and further research should be conducted – especially in Europe.

In the present study, we found strong negative associations between the composite measures of walkability and mean neighbourhood satisfaction, neighbourhood satisfaction with social environmental quality and neighbourhood satisfaction with social cohesion. Neighbourhood satisfaction with infrastructure was positively associated with walkability. Evidence on the association between the walkability indices and neighbourhood satisfaction is scarce, but as discussed above (see section 6.1), the results of the present study are supported by most of the more recent available literature.

The present study used two walkability indices. The *IPEN walkability index* is the most prevalent in the literature, and studies using this index are meant to be comparable. However, full comparability is not established because first, the measures used to build the index are not entirely the same (e.g. differences in the operationalization of the *entropy index*), and second, the computation of the index differs. Some studies included FAR in the index, while others did not. Especially studies from outside the US and Australia did not include FAR in the *IPEN walkability index*, such as studies from Canada (Berry et al., 2010a, Berry et al., 2010b, Pouliou and Elliott, 2010) or Belgium (Van Dyck et al., 2010, Van Dyck et al., 2010a, Van Dyck et al., 2011). The Swedish Neighbourhood and Physical Activity study included the Herfindahl-Hirschman Index as a measure of land use mix and weighted intersection density only with a weight of 1.5 instead of 2, as in the *IPEN walkability index* (Arvidsson et al., 2012, Sundquist et al., 2011). Although these differences in the computation of the index do not improve comparability, they show that different composite measures may be necessary in different contexts. The results from the present study underline this need for different indices. In the present study, the *Graz walkability index* performed much better as a correlate of health-related outcomes than the *IPEN walkability index*. The *Graz walkability index* included different measures of land use mix and connectivity than the *IPEN walkability index,* and connectivity was not given more weight than the other factors. To the author's knowledge, the present study was the first to use the *IPEN walkability index* and an index adapted to the specific context. Even though comparability across different locations is desirable for establishing a sound evidence base, adaptation to the context und to the available GIS data may be necessary to find valid and reliable walkability measures.

Both walkability indices were associated with active mode of transports and neighbourhood satisfaction, while the *Graz walkability index* performed better. For surveillance and planning purposes in Graz, the *Graz walkability index* should be given preference.

6.3 Definition of neighbourhood

Associations between walkability and health-related outcomes are sensitive to the scale of spatial area (Oliver, Schuurman and Hall, 2007). Therefore it is important to choose the spatial scale carefully and to test different scales (Diez Roux, 2007, Macintyre, Ellaway and Cummins, 2002). The circular buffer may provide a representative assessment of the area, but may not adequately represent the area influencing health-related outcomes (Oliver, Schuurman and Hall, 2007). Oliver, Schuurman and Hall (2007), who used a circular and a street network buffer, concluded that land use characteristics are more strongly associated with walking using street network buffer than using circular buffers. Other researchers have found associations for both buffer types and concluded that both were useful for understanding and interpreting the associations between the built environment and health (Coffee et al., 2013, Forsyth et al., 2007, Learnihan et al., 2011, Lee and Moudon, 2006, Moudon et al., 2006). In the present study, walkability measures were also associated to health-related outcomes within both buffer types. Associations between walkability and health-related outcomes were more often statistically significant in the 1,000m circular and in the 1,500m street network buffer than in the 1,000m street network buffer.

Thus, buffer size may be the more relevant issue. Some researchers have suggested that distances shorter than 1,000m should be considered, since the perceived walkable neighbourhood seems to be much smaller (Ball et al., 2012, Coffee et al., 2013, Lee and Moudon, 2006, Moudon et al., 2006, Smith et al., 2010). Smith et al. (2010) showed that even though perceived neighbourhood is a lot smaller, about 96% of the respondents reported that they were walking to destinations within a 1,000m and 1.6km circular and steet network buffer around their home. Thus, the area relevant to walkability may be larger than the perceived neighbourhood. In addition, the European environmental questionnaire ALPHA used a distance of 10 to 15 minutes walk (i.e. approximately 1 - 1.6km) as a neighbourhood scale (Spittaels et al., 2009). Especially in Europe, where the active transportation behaviour and the built environment are entirely different from the US and Australia, people may be willing to walk up to 15 minutes to destinations. In the binary analysis of the present study, we also used 800m circular and street network buffers (see 5.2.1). Since these spatial scales performed worse than the 1,000m and 1,500m buffer, the study focused on the 1,000m and 1,500m buffers.

Some researchers have investigated the difference in associations between walkability measures and health-related outcomes by different neighbourhood scales (Coffee et al., 2013, Learnihan et al., 2011, Villanueva et al., 2014). Although Coffee et al. (2013) and Villanueva et al. (2014) also found associations on a smaller neighbouhood scale, there is some indication that associations between walkability and health-related outcomes more often reach statistical significance and are stronger in larger areas than in smaller areas. In the present study, we also found that larger buffers performed better than smaller buffers. Associations between walkability measures and health-related outcome were more often statistically significant and were stronger in the 1,000m circular buffer and in the 1,500m steet network buffer than in the 1,000m street network buffer. The area of the latter was roughly half the size of the other two. The median area of the 1,000m street network buffer was 1.5 km^2, while the area of the 1,000m circular buffer was 3.1 km^2, and the median area of the 1,500m street network buffer was 3.5 km^2. A larger area may better represent the walkability characteristics of the neighbourhood (Oliver, Schuurman and Hall, 2007), especially when street network data is used. The quality and appropriateness of the street data are open to debate (see 6.2.3). If the street network data is not accurate, the street network buffer will not be correct. Furthermore, the street network data covers streets, but not footpaths and short cuts. Hence, the street network buffer may not cover all relevant walkability routes. In locations with many pedestrian paths and shortcuts, the circular buffer may be better than the network buffer (Forsyth et al., 2006).

6.4 Potential confounders

Sex

In the present study, we found differences by sex in the bivariate and the bivariate controlled analyses. There were no remarkable differences between men and women for the association between density and health-related outcomes, but all other walkability measures were associated with biking and active transport more for men than for women and with neighbourhood satisfaction more for women than for men. The review of Wendel-Vos et al. (2007) made a similar observation, showing associations between built environmental factors and walking more often for men than for women. One would expect that the walkability of the residential neighbourhood is more important for women's than for men's health, since women generally spend more time at home taking care of children, elderly, disabled persons and the household. However, the empirical results suggest the opposite. Due to women's multiple roles, other determinants such as social support and societal messages (Vrazel, Saunders and Wilcox, 2008) may be more important. However, sex differences in the association between walkability and health-related outcomes need further exploration.

The literature analysis of the present study (see Table 5) suggested that especially the association between walkability and weight-related outcomes differ by sex. Weight-related measures were associated with walkability among men, but not among women (see Table 5). To date, no review has investigated or discussed this difference. Furthermore, the inverse relationship between density measures and weight-related outcomes discussed above (see section 6.2.1) is mainly found among women (Frank et al., 2008, Smith et al., 2008, Wen and Kowaleski-Jones, 2012). This sex-specific pattern is difficult to explain (Wen and Kowaleski-Jones, 2012). Socio-economic factors may be confounding variables. High-density areas often have populations with a lower socio-economic status than low-density areas. The composition of the population and the socio-economic status of the individuals may play a role. Further exploration of this inverse and counterintuitive relationship would be desirable (Wen and Kowaleski-Jones, 2012).

Age

Reviews on the association between walkability and walking for transport or active transport among older adults found inconsistent evidence. Van Couwenberg et al. (2011) reported mixed results on the association between walking for transport and residential density, land use mix and street connectivity. In one study, land use mix was even inversely related to walking for transport (Van Cauwenberg et al., 2011). There was, however, a positive association between walking for transport and overall walkability. Kerr, Rosenberg and Frank (2012) reported positive associations between walking for transport and overall walkability, residential density and land use mix. According to their review, connectivity seems to be less important to older people because they may not feel comfortable with street crossings (Kerr, Rosenberg and Frank, 2012).

In the present study, we did not find pronounced differences between the individual walkability measures and their relationship with health-related outcomes, but the sample was also rather homogenous regarding age (15 to 60 years of age) and did not cover older adults. As described in section 5.3.2, in the exploratory binary analysis controlled for sex, age and socio-economic status, we found differences between younger and older respondents. Walkability measures were more related to walking for transport among older respondents than among younger ones. The opposite was true for all other health-related outcomes. These results suggest that the association between walkability and health-related outcomes is more important for younger population groups than for older ones. In the final analysis (controlled additionally for place of residence), this pattern remained to some extent. The results suggested that walkability is associated with biking for transport and active transport more among younger respondents than among older ones. In contrast, walking for transport was more associated with walkability among older respondents than among younger ones. To the author’s knowledge, to date no investigators have stratified their results by age groups within adults. Therefore, no comparison of the results of the present study with the results of other studies can be made. The observed pattern is difficult to explain. There may be a trend towards safety concerns among the older population group in the sample that attenuates the association between walkability and biking for transport. Walking may be more popular. For older respondents, walkability may also be more important to determine walking for transport than for younger respondents. Since there were some problems related to measuring walking for transport in the present study (see section 6.1), no conclusions can be drawn.

In the present study, the negative association between walkability measures and neighbourhood satisfaction was slightly stronger (lower p-values) for younger than for older respondents, except for the satisfaction with infrastructure. Neighbourhood satisfaction with infrastructure was slightly more strongly positively associated with walkability among older than among younger adults. One possible explanation could be that the walkability of the neighbourhood differs between younger and older respondents. The comparison showed that there was a trend towards older adults living in less walkable neighbourhoods than younger adults (see section 5.3.2). However, this difference was not statistically significant. Another possible explanation could be that older adults are generally less critical and easier to satisfy, and therefore the association between walkability and neighbourhood satisfaction is less pronounced among this group.

The buffer size in the present study could also add to the explanation of the age-related findings. The buffers used were rather large compared to studies investigating the association between walkability and health-related outcomes among the elderly (Kerr, Rosenberg and Frank, 2012). However, among the studies focusing on older people, the best buffer size has also not been established yet (Kerr, Rosenberg and Frank, 2012, Van Cauwenberg et al., 2011). Nevertheless, since the population group in the present study did not include older people, the buffer size probably cannot explain the differences described in the present study. The differences seen in the present study between younger and older respondents are difficult to explain. More research looking at age is needed to investigate which environmental features are relevant to the health of different age groups.

Socio-economic status

The present study analysed the association between walkability measures and health-related outcomes stratified by socio-economic status. In most cases where the association between walkability measures and health-related outcomes differed by socio-economic status, walkability was associated with health-related outcomes among high socio-economic respondents but not among low socio-economic respondents. Especially walking for transport, biking for transport, active transport and neighbourhood satisfaction with infrastructure were more often associated with walkability measures among respondents with a high socio-economic status. Most often, the differences by socio-economic status were observed for the two connectivity measures. Connectivity, and especially *three-way intersection density,* seems to be more important for respondents with a high socio-economic status than for respondents with a low socio-economic status.

Almost all studies include some kind of measure of socio-economic status as a covariate in their analyses. But there are only very few studies that provide insight into the difference of the association between walkability and health-related outcomes by socio-economic status. These few studies show no entirely clear pattern. Forsyth et al. (2009) found that density was associated with walking for transport among low-educated and unemployed respondents, but not among high-educated and employed respondents. Owen et al. (2007), in contrast, found that walkability was associated with walking for transport among high-educated respondents, but not among low-educated respondents. Frank et al. (2008) found that the *walkabiliy index* was associated with walking for transport among respondents with and without a university degree. However, the association was stronger among respondents with a degree than among respondents without a degree. The study of Ball et al. (2007) indicated that there is no mediating effect of education on the association between street connectivity and walking for transport. These studies are from the US and Australia, and the walkability of the residential neighbourhoods, the health behaviour and the social structure of the population differs between the US and Europe. Therefore, their results may not be comparable with the results of the present study. Nevertheless, the majority of the available evidence described above (Frank et al., 2007, Owen et al., 2007) seems to support the results from Graz that walkability as a positive correlate of modes of active transport is more important to high socio-economic groups than to low socio-economic groups.

This may be due to non-concordant perceptions of the walkability of the residential neighbourhood. Gebel, Bauman and Owen (2009) found that those respondents with lower income and lower education in particular perceived their objectively measured high walkable neighbourhood as low walkable. Arvidsson et al. (2012) confirmed this pattern for Europe. In Sweden, more individuals without a university degree misperceived the residential density of their neighbourhood as low. The misperception of the walkability may explain the lack of associations between objectively measured walkability and health-related outcomes for low socio-economic respondents in Graz. There may be a need to improve the perceptions low socio-economic individuals have of their walkable neighbourhood. But before social marketing strategies can be recommended, further insights into the accordance or non-accordance of perceived and objectivley measured walkabillity among different population groups in Graz are necessary.

More recent studies have investigated the difference in the association between walkability and health-related outcomes by socio-economic status at the neighbourhood level instead of at the individual level. Here as well, the results are mixed. The BEBAS and PLACE studies found no effect of neighbouhood socio-economic status on the association between walkability and walking for transport and cycling for transport (Owen et al., 2007, Van Dyck et al., 2010). In the US, the NQLS found that walkability was associated with walking for transport in all neighbourhoods, but the association was stronger in high-income neighbourhoods (Sallis et al., 2009). One result in the same direction comes from the URBAN study in New Zealand. Witten et al. (2012) found that the strength of association between walkability and walking for transport increased when they controlled for neighbourhood deprivation (Witten et al., 2012). Another study using BMI as an outcome also found that population density and land use mix were especially related to BMI in advantaged neighbourhoods (Lovasi et al., 2009). The HABITAT study in Australia, in contrast, found that the association between walkability and walking for transport was stronger in the more disadvantaged neighbourhoods (Turrell et al., 2013). Thus, no clear picture emerges based on the studies from the US, Australia and New Zealand.

As already argued above, the results from these countries have to be interpreted with caution, since Europe differs in its social and built environment contexts from these countries. The only European study (BEPAS) found no effect of neighbourhood socio-economic status on the association between walkability and walking for transport.

The question remains of how far the neighbourhood socio-economic status may also influence the associaiton between walkability and health-related outcomes in Graz. Since the impact of interventions such as improving the walkability could even increase social inequality, the issues discussed here related to socio-economic differences on the individual and on the neighbourhood level in the association between walkability and health-related outcomes should be further investigated before policy implications can be recommended and interventions implemented.

Place of residence

The results of the present empirical study showed striking differences in the association between walkability and health-related outcomes by place of residence. Among respondents residing in the eastern part of the city, all walkability measures (except the entropy index) were positively associated with walking for transport, biking for transport, active transport and neighbourhood satisfaction with infrastructure, while these associations were lacking among respondents residing in the western part of the city. Comparing the characteristics of the respondents showed that they differed statistically significantly from each other. Respondents residing in the eastern part of the city were better educated, had a higher socio-economic status and had better health-related outcomes than their counterparts in the western part of the city. The built environment, in contrast, differed only for the *entropy index* and the *three-way intersection density*, but not for the other walkability measures. Krenn (2012) developed a bikeability index for Graz, and the maps created based on the bikeability index also showed no obvious differences between the western and eastern parts of the city (Krenn, 2012). Thus, in terms of walkability, the two parts of the city were comparable, but their inhabitants and the association between walkability and health-related outcomes differed.

There are four possible explanations for the difference in the association between walkability and health-related outcomes. First, respondents residing on the west side of the river, who were also the less educated group and the group with a lower socio-economic status, may have answered differently during the survey than respondents residing on the east side of the river. Second, low socio-economic population groups more often residing in the western part of the city may also consider walking as a mode of transport of low status and therefore prefer to take the car or public transport, even though they live in a high walkable neighbourhood. Third, the result may be due to non-concordant perceptions of the neighbourhood. The lower educated respondents and respondents with a lower socio-economic status residing in the western part of the city may misperceive their neighbourhood as low walkable even though it is high walkable (see further discussion in section 6.1), and therefore no association between walkability and modes of active transport was found. Fourth, traditionally the western part of the city has been considered to be less walkable and bikeable than the eastern part of the city. This may also contribute to a misperception of the walkability of the neighbourhood.

Self-selection

The association found between walkability and health-related outcomes in the present study may be confounded by self-selection. People who choose to live in a high-walkable neighoubourhood may be different from people who choose to live in a low-walkable neighbourhood. Their preference for and attitude towards walking and physical activity may differ. Frank et al. (2007) have shown that people prefering and selecting walkable neighbourhoods also walk more than people who prefer car-oriented neighbourhoods. Those who prefered walking walked more than those who prefered other modes of transport independent of walkability, even though the prevalence of walking was low in both groups. Those who lived in a high-walkable neighbourhood walked more than those who lived in a low-walkable neighbourhood, independent of preference (Frank et al., 2007). Thus, neighbourhood preferences, selection and walking behaviour were related to each other, as were walkability and walking behaviour in the SMARTRAQ study. Nevertheless, the association between walkability and walking remained after taking neighbourhood selection and preference into account (Frank et al., 2007). These results are supported by results from the NQLS (Sallis et al., 2009), from Canada (McCormack et al., 2012) and from the URBAN study in New Zealand (Witten et al., 2012). Systematic reviews have also confirmed that walkability remains associated with walking after controlling for self-selection (Cao, Mokhtarian and Handy, 2009, Ewing and Cervero, 2010). Because of this evidence, it is assumed that the results of the present study are not significantly confounded by self-selection.

6.5 Surveillance

This study aimed to develop GIS-based indicators of walkability that are relevant to public health for surveillance and planning purposes in Graz. The present study first analysed the literature to identify relevant indicators and then analysed the association between walkability and health-related outcome to determine the empirical validity of the indicators. Finally, whether or not walkability indicators should be used for public health surveillance should be discussed. Based on Bardehle (2007), Etches et al. (2006) and Pencheon (2008) the following criteria should be considered: conceptual framework, importance and relevance, validity, reliability and objectivity, specificity, sensitivity, feasibility, meaning and understandability, timeliness, comparability, implications. Section 6.2 argued that the following indicators should be used for surveillance: *household unit density, proportion of mixed land use, four-way intersection density and the Graz walkability index*. These indicators were recommended because they showed consistent associations with active modes of transport and neighbourhood satisfaction. In this section, these indicators are assessed against the criteria mentioned for choosing indicators for public health surveillance (see Table 50).

Table 50: Assessment of walkability measures as public health surveillance indicators

Assessment criterion	**Household unit density**	**Proportion of mixed land use**	**Four-way intersection density**	**Graz walkability index**
Conceptual framework	+	+	+	+
Importance and relevance	+	+	+	+
Validity	++	+	+	++
Reliability and objectivity	+	+	+	+
Specificity	+	+	+	+
Sensitivity	+	+	+	+
Feasibility	++	+	~	+
Meaning and understandability	+	+	+	~
Timeliness	~	~	~	~
Comparability	++	+	+	+
Implications	~	~	~	~

- = not fulfilled, ~ = fulfilled with constraints, + = fulfilled, ++ = better fulfilled than for the other indicators, na = not applicable

Indicators should be based on a conceptual framework so that they capture all important aspects of the phenomenon that is to be observed. In the present case, a theory-based definition of walkability was used and applied to select indicators. Therefore, this criterion is fulfilled for all walkablity indicators.

Indicators should be of high importance and relevance and should be related to the most important aims of the system (Pencheon, 2008). Since the city of Graz has put a major emphasis on increasing modes of active transport (especially biking), walkability as a potential determinant of non-motorized transport should be of high importance to the local decision makers. From a public health perspective, walkability as a correlate of health-related outcomes, especially of modes of active transport, is also of high importance. Changes in walkability may increase physical activity up to 80 minutes per week. In Belgium, respondents living in high-walkable areas walked 80 minutes per week more for transport, cycled 40 minutes per week more for transport, and walked 20 minutes more than respondents living in low-walkable areas (Van Dyck et al., 2010). This effect can be achieved across the entire population and not only for a small group of high motivated individuals, and it can be achieved permanently (Saelens, Sallis and Frank, 2003). Therefore, walkability is especially important and relevant from a population health perspective.

The consistent association with health-related outcomes is one indication of the validity of the indicator. Validity can be described as the extent to which the conclusions drawn from the indicator are based on empirical evidence (Anon, 2007). The present study has provided empirical evidence that the walkability indicators mentioned are associated with health-related outcomes in Graz. Therefore, they can be considered as valid correlates that are relevant for the health of the population of Graz. *Household unit density* and the *Graz walkability index* were even more consistently associated with walking for transport, biking for transport and active modes of transport. Therefore, they scored higher in the assessment than the other indicators.

Reliability is the extent to which the indicator delivers the same results when measurement is repeated within the same measurement circumstances (Anon, 2007). This criterion is strongly related to the objectivity of the indicator. The walkability measures used in the present study are based on objective data and on an analysis protocol from Forsyth et al. (2006). Therefore, it can be assumed that the repetition of the measurement using the walkability indicators within the same circumstances will deliver the same result. The results would be independent from the researcher undertaking the measurement.

Specificity is commonly used in health care for the ability of an indicator to identify within a group of people the healthy person as healthy (Bardehle, 2007, NN, 2007). When this concept is applied to walkability, this means that the walkability indicator is able to identify the high-walkable area within a total area.

The sensitivity is the ability of an indicator to measure changes of the observed phenomenon (Bardehle, 2007). This means identifying the diseased persons. Applying this concept to walkability means that the indicators should be able to identify the low-walkable area within a total area. Based on the results of the present study and the created maps (see Figure 7 to Figure 14), it seems plausible to assume that the walkability indicators differentiated well between high- and low-walkable areas.

The next criterion refers to the feasibility of populating the indicator with meaningful data. The present study used census data, zoning data and street centre line data to construct the walkability indicators. Since all three data sources are readily available, it is feasible to construct the indicators rather easily. Especially the census data is a data source of rather high quality, as it is collected for a wide range of administrative (and not for accounting) purposes. In addition, it is a full inventory count, and citizens are obliged to participate and to provide information (Statistik Austria, 2005). The zoning is undertaken by law in each community and provides the basis for local land use planning (Steiermärkisches Raumordnungsgesetz, 2010). Graz is considered to provide rather high quality and comprehensive zoning data. For other communities, it can also be assumed that the zoning information is rather meaningful, even though the degree of accuracy will vary from one community to the other. More problematic is the feasiblity of using street centre line data for surveillance. As described in section 6.2.3, the quality of the street centre line data was low, and it was rather work intensive to find a good solution for analysing the data. The solution found for the present study is rather simple and can also be used for surveillance purposes to construct the indicator *four-way intersection density*. Even though major efforts needed to ensure high accuracy, some concern remains regarding measurement errors. For surveillance, an expert on street centre line data should be included to increase feasibility.

Good indicators should also be meaningful and understandable to the audience. They should be easy to communicate, deconstruct and understand. All walkability indicators are simple measures, which is essential for surveillance. The audience of surveillance data consists first and foremost of decision makers. Decision makers are usually busy people who are not trained in public health and who like to grasp complex issues based on simple indicators. The walkabiltity indicators are very suitable for communicating to decision makers. The concepts behind the indicators are based on common knowledge, are easy to understand and, combined with the maps, are easy to visualize and therefore easy to communicate. Mapping walkability indicators can support this communication process effectively (Procyk et al., 2013). Only the walkability index, as with any composite measure, is more difficult to understand and may place some constraints on the fulfillment of the criterion understandability.

Time is another important criterion in surveillance. In some areas of surveillance (e.g. infectious diseases), it is of utmost importance that data is available and indicators are analysed quickly and on a very regular basis. The aspect of regularity applies to all areas of surveillance. Time intervals of analysis of indicators differ depending on the observed phenomenon. To detect changes, indicators that are related to chronic diseases should have longer observation periods than infectious diseases. This also applies to walkability, as it does to most (potential) health determinants. Over longer time periods, it should be possible to detect changes in walkability, at least in areas with new developments. However, there are constraints to the criterion of timeliness.

Indicators in surveillance should be comparable across location and population groups. Since the data used for the walkability indicators is routine data, it is available for different places and population groups in Austria. Within Austria, especially the indicator *household unit density* is highly comparable because the census data is collected by Statistics Austria, and the data is therefore available in the same quality across the entire state. As mentioned above, the zoning data and the street centre line data are somewhat less comparable, since the data is not from one source and will be of different quality in places other than Graz. Overall, comparability is constrainted by the fact that GIS-based walkabilty measures have not yet been established as public health surveillance indicators.

Finally, the implications of the indicators and the actions taken based on the results have to be considered. There should be evidence on how to act on the issue identified, or there should be the possibility for further investigation (Pencheon, 2008). The walkability indicators should be responsive to modifications. It is relatively difficult to modify the walkability of a city. As in the centre of Graz, it seems to be difficult to change density, land use mix or connectivity. In the US, minor changes in density (i.e. from 6 to 15 units per acre) have already been shown to double the odds of walking (Devlin, Frank and vanLoon, 2009). Therefore, even small changes may improve walkability and, consequently, health-related outcomes. More importantly, in the more suburban neighbourhoods and in new developments, walkability can be modified and should be considered as a health-relevant aspect of planning. Nevertheless, because of the limited ability to intervene, the implications criterion was assessed as fulfilled with constraints for all walkability indicators.

Table 50 summarizes the assessment of the walkability measures as public health surveillance indicator. In summary, most criteria are fulfilled at least to some extent, except for the timeliness and implications criteria. It also has to be kept in mind that ‘indicators only indicate’ (Pencheon, 2008). Indicators reduce the complex and rich reality to a few numbers and cannot capture the whole truth. They may provide a good snapshot, but further investigation is usually necessary to figure out the underlying issues and the appropriate intervention. Keeping in mind that these walkability indicators should only indicate in which direction to go, it can be concluded that the indicators should be considered for planning and surveillance in the city of Graz.

Other cities have already undertaken efforts towards implementing walkability measures for planning and monitoring purposes. San Diego (www.sandag.org) and the Metro Vancouver region (Frank et al., 2010, Procyk et al., 2013), for example, have created GIS-based maps of the built environment to inform decision making. Mapping walkability indicators can be a powerful tool for communicating data to decision makers, but also for enabling comparisons between indicators and regions and for identifying intervention areas (Procyk et al., 2013). Procyk et al. (2013) have recommended using built environment indicators and maps to monitor and reassess the implementation of the Metro Vancouver transportation plan. Using GIS for public health surveillance is already good practice (e.g. Public Health Observatories in the UK). However, GIS is currently mainly used for mapping in surveillance and less for data analysis, as it would be for the walkability indicators. Nevertheless, GIS has great potential to be a useful public health surveillance tool in relation to physical activity surveillance (Brownson et al., 2009). There is a need to adapt public health surveillance systems to assess policy and environmental factors as well (Macera and Pratt, 2000). Determinants of health should be routinely part of public health surveillance systems (Bardehle, 2007). Consequently, the city of Graz could be one of the European pioneers in piloting walkability measures as planning and surveillance indicators. However, for the implementation, it is of utmost importance to have consensus about the aims of an organization and of the related indicators (Pencheon, 2008). Therefore, as a next step, a consensus exercise should be undertaken with stakeholders from the public health, urban planning and transportation departments of the city of Graz, including scientific experts. Only by testing the walkability indicators in practice can their usefulness for surveillance and planning be established.

Independent of the implementation of walkability indicators, it has to be ensured that health-related outcomes are stratified by sex, age, socio-economic status and place of residence in public health surveillance in the city of Graz. The analysis of the multiple associations between walkability and health-related outcomes has shown that individual characteristics are strongly associated with health-related outcomes. Normally, it is good practice to stratify data based on individual characteristics in public health surveillance, and this method of analysing data has to be maintained.

6.6 Policy implications

The present study has shown that there are associations between walkability measures and health-related outcomes in the city of Graz. As discussed above, policy makers should consider walkability measures for surveillance and planning. The way forward would be to use the results of the present study for a consensus exercise to establish indicators for surveillance and planning. Furthermore, as discussed above a wide range of further research questions arose from the present study. Due to the importance of the built environment for the public’s health, decision makers should support more research in this area by cooperating with research institutions and by financing and co-financing further investigations.

The results of the present study provide the planners and decision makers of the city of Graz with maps of the current walkability situation in Graz and can be used to identify intervention areas (see Figure 7 to Figure 14). Even though the walkability measures reduce the complexity of the built environment to a few single indicators, the situation remains complex. The maps show that the inner city districts Innere Stadt and St. Leonhard have a rather high walkabiliy (except the Schlossberg area). The districts Lend, Geidorf, Gries and Jakomini do well in some areas, but others also show need for improvement. In the outer districts, the walkability is rather low. Overall, the districts in the South and Southwest of Graz (i.e. St. Peter, Liebenau, Puntigam, Straßgang, Wetzelsdorf and Eggenberg) have a slightly higher walkability than the other outer districts of Gösting, Andritz, Mariatrost, Ries and Waltendorf, mostly because of higher density and better land use mix. Those districts are characterized by large but rather compact residential areas. The districts Gösting, Andritz, Mariatrost, Ries and Waltendorf are characterized by large green areas, where residential areas are developed along the main traffic connections. However, for the identification of intervention areas, planners and decision makers have to look at smaller units than the district. There are large differences in walkability within a district. For instance, the main weakness in the largest parts of St. Peter is the low land use mix, except in the statistical sectors 350 and 351. Density is even low in some areas of the inner city districts, such as Gries or Jakomini. To make recommendations for improvements in individual statistical sectors, the local context has to be known. For some places (e.g. Puchwerke or the Zentralfriedhof) it will be undesirable or even impossible to improve walkability. Planners with the necessary local knowledge will be needed to fully interpret the results and recommend individual measures. The walkability maps should support their work and help them to identify intervention areas.

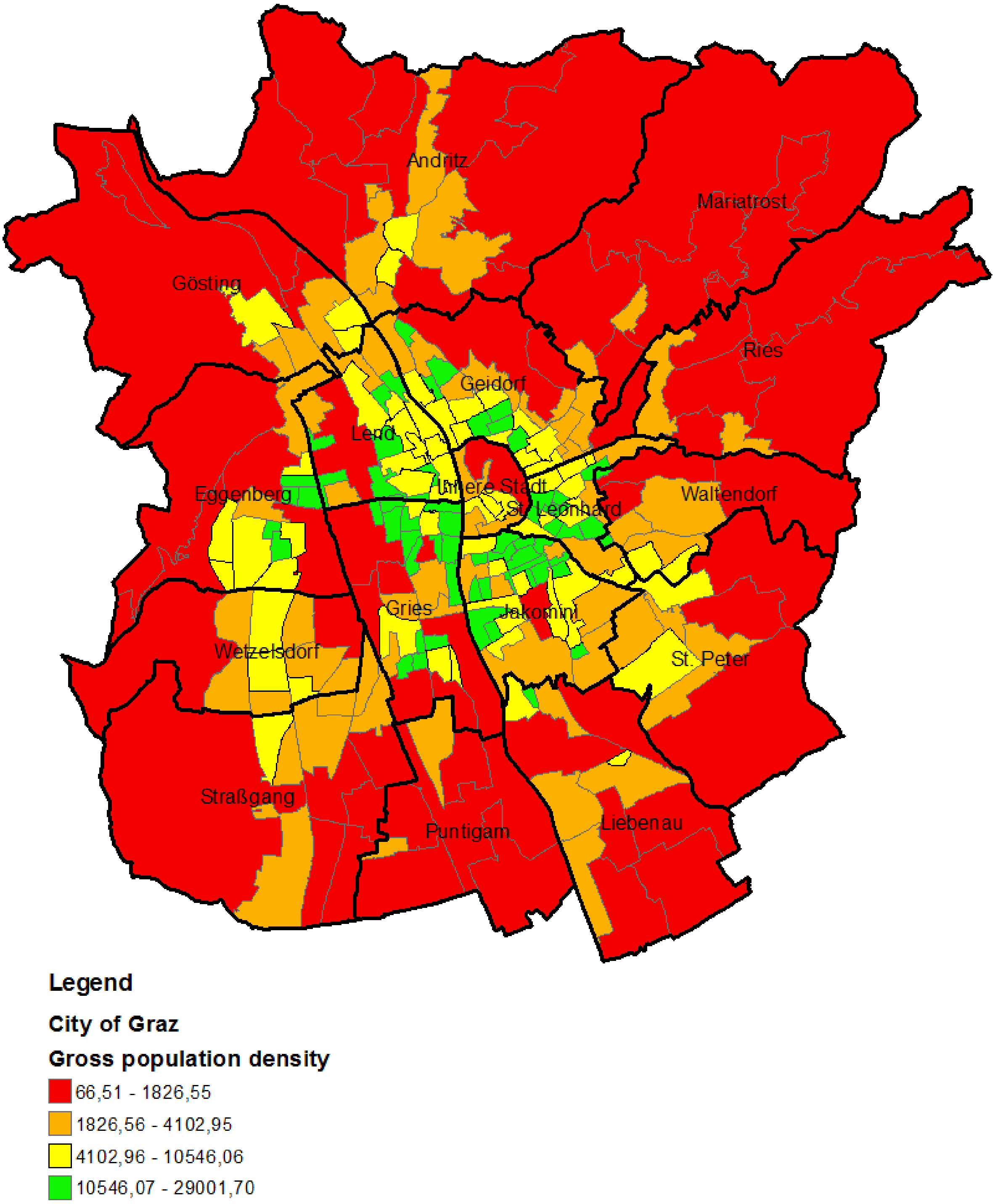


Figure 7: Gross population density of the city of Graz based on statistical sectors

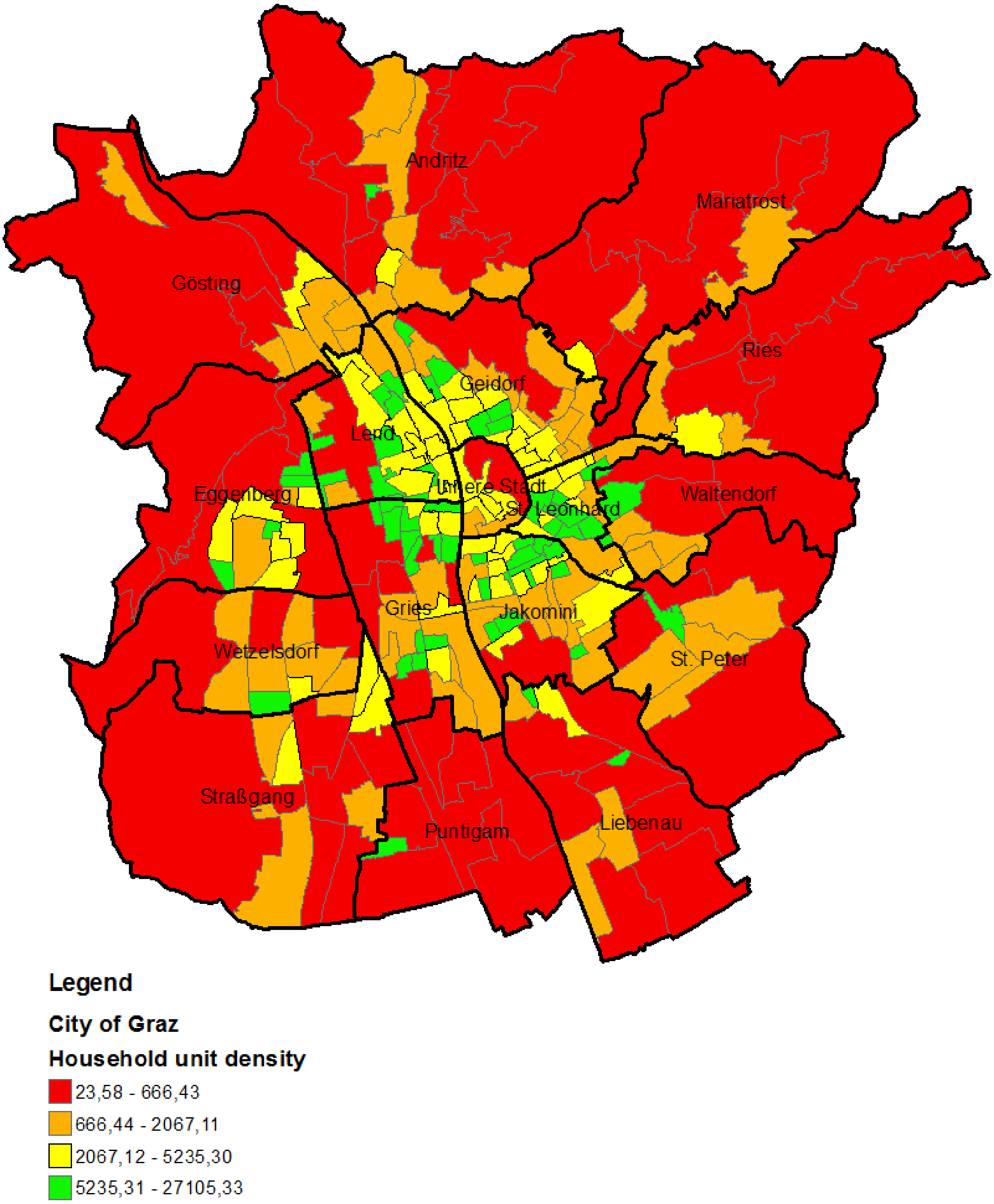


Figure 8: Household unit density of the city of Graz based on statistical sectors

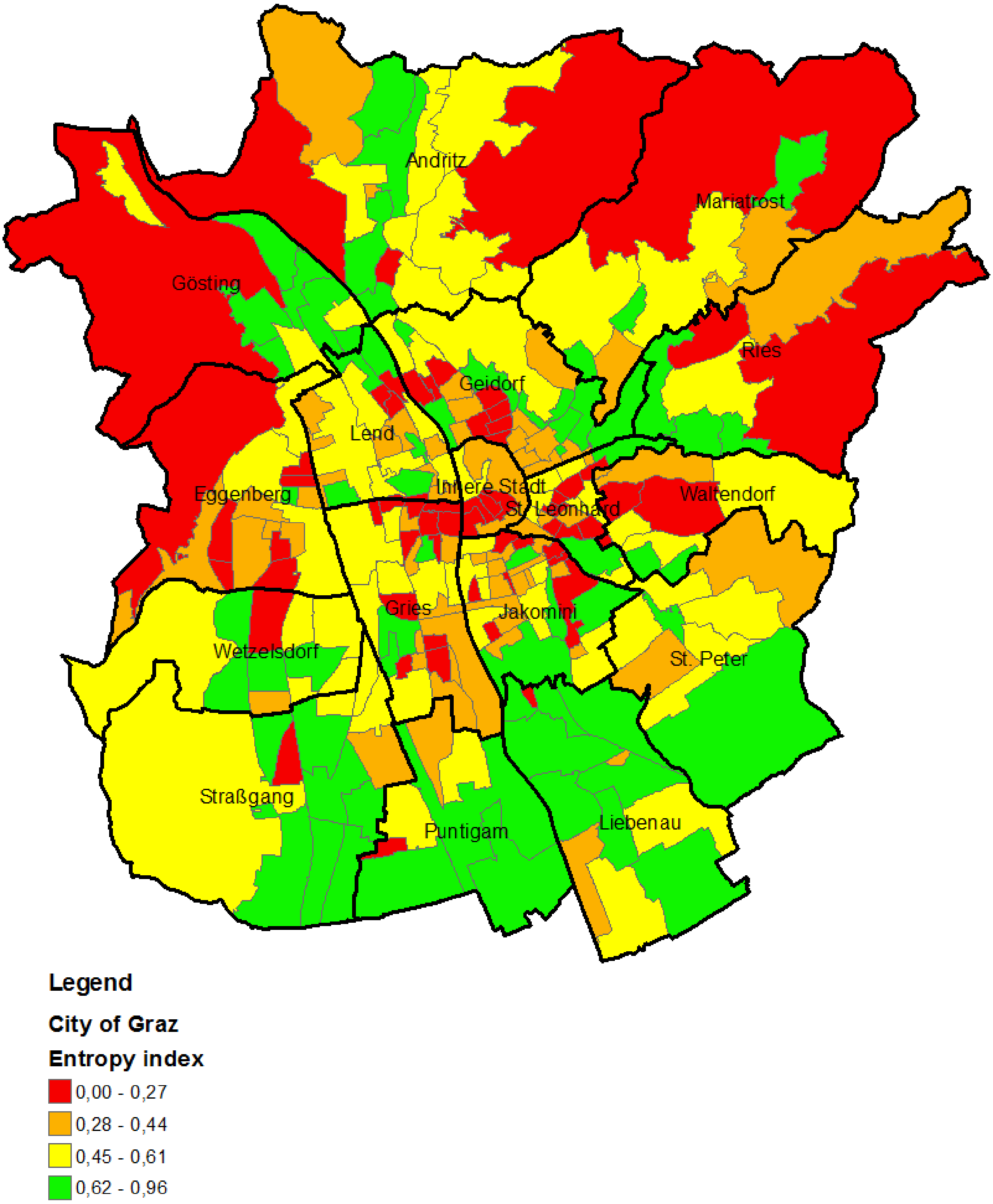


Figure 9: Entropy index of the city of Graz based on statistical sectors

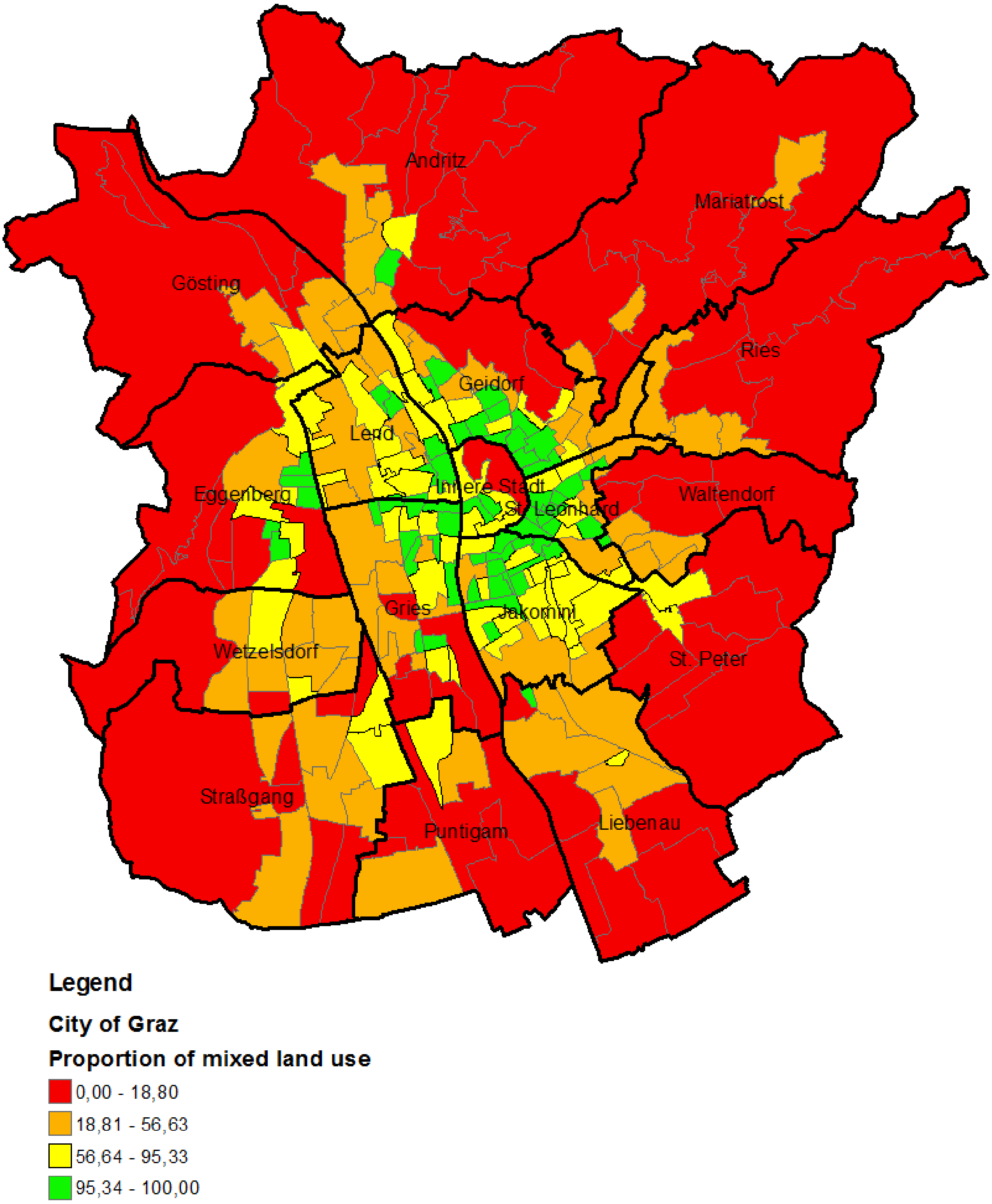


Figure 10: Proportion of mixed land use of the city of Graz based on statistical sectors

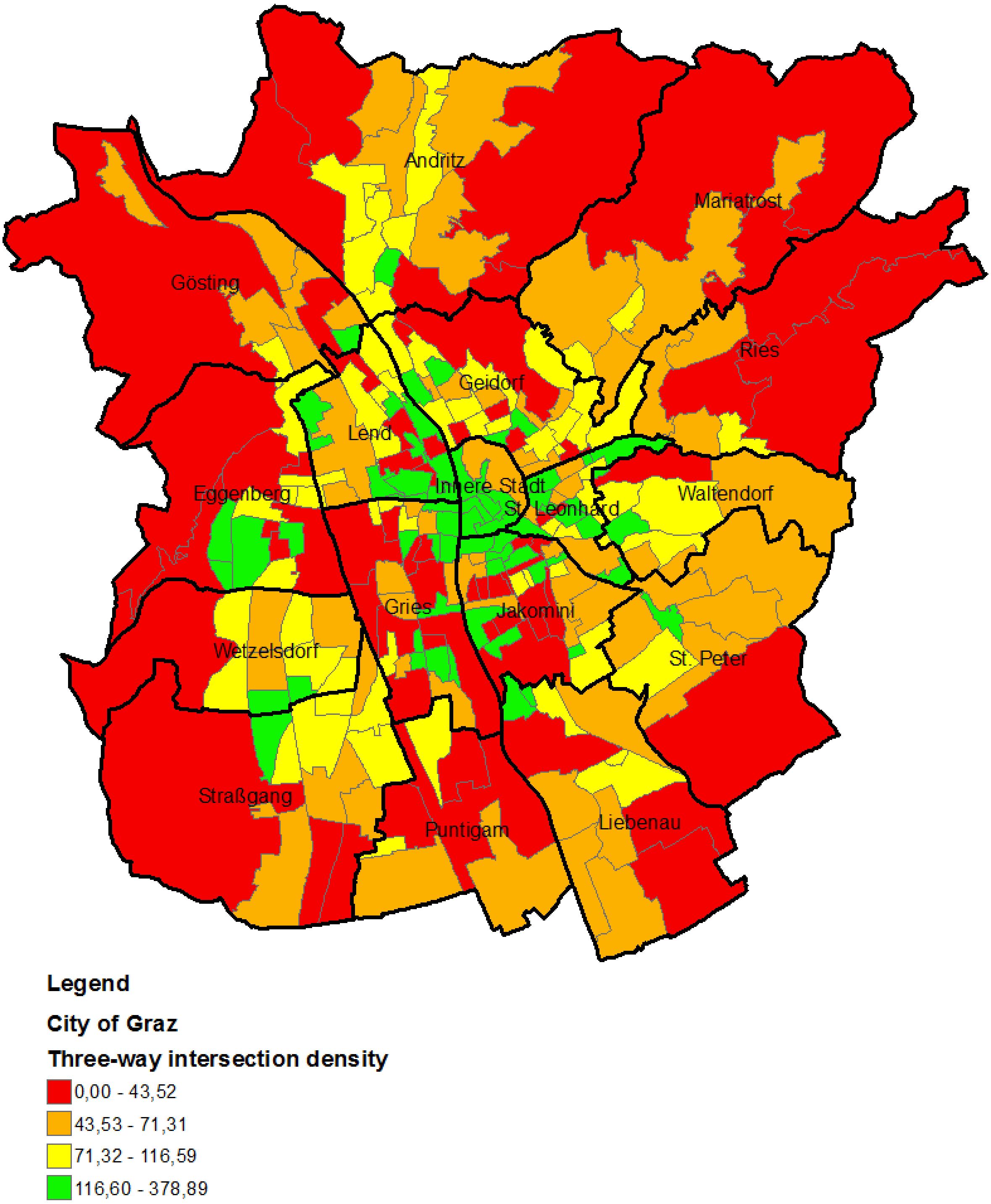


Figure 11: Three-way intersection density of the city of Graz based on statistical sectors

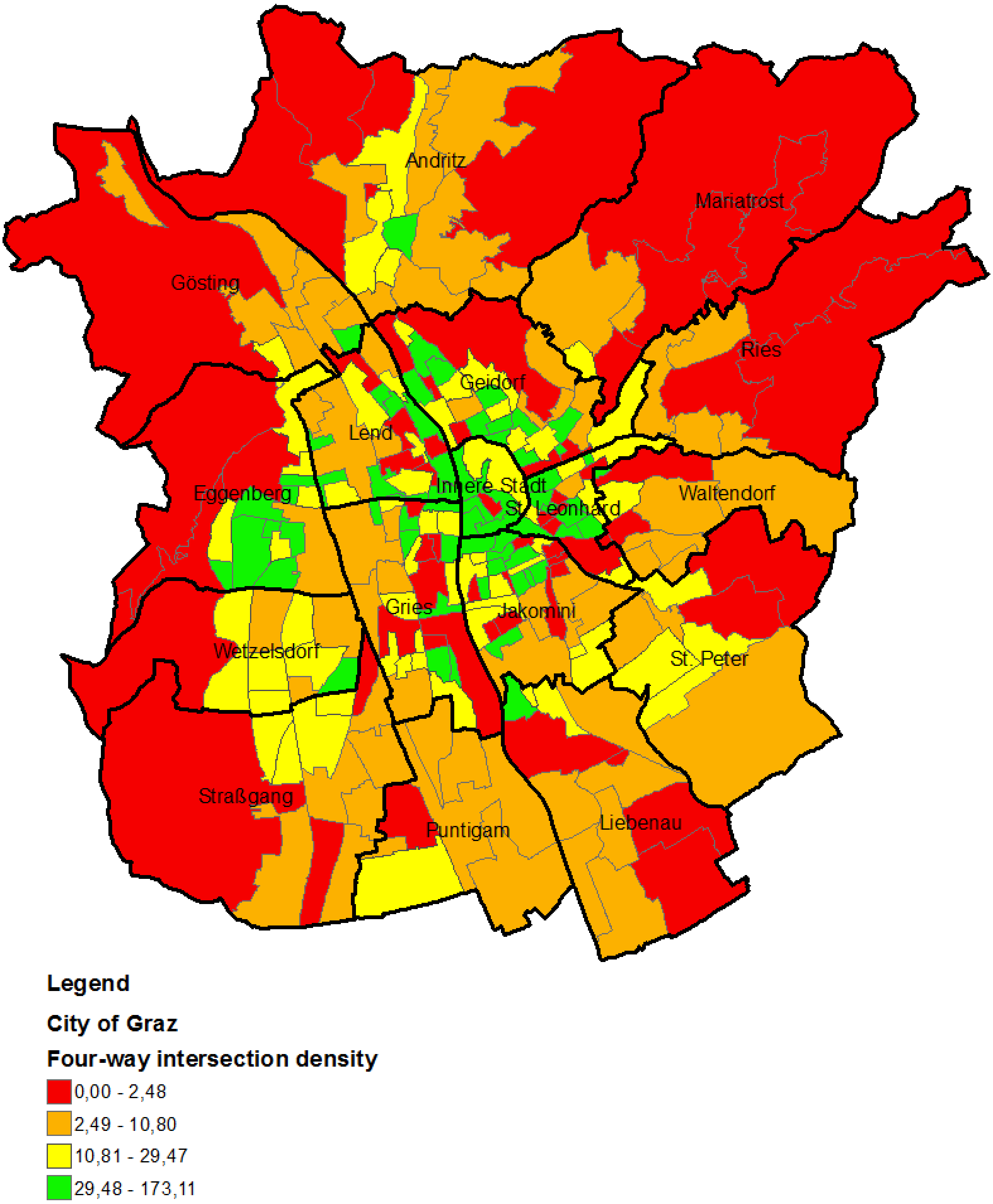


Figure 12: Four-way intersection density of the city of Graz based on statistical sectors

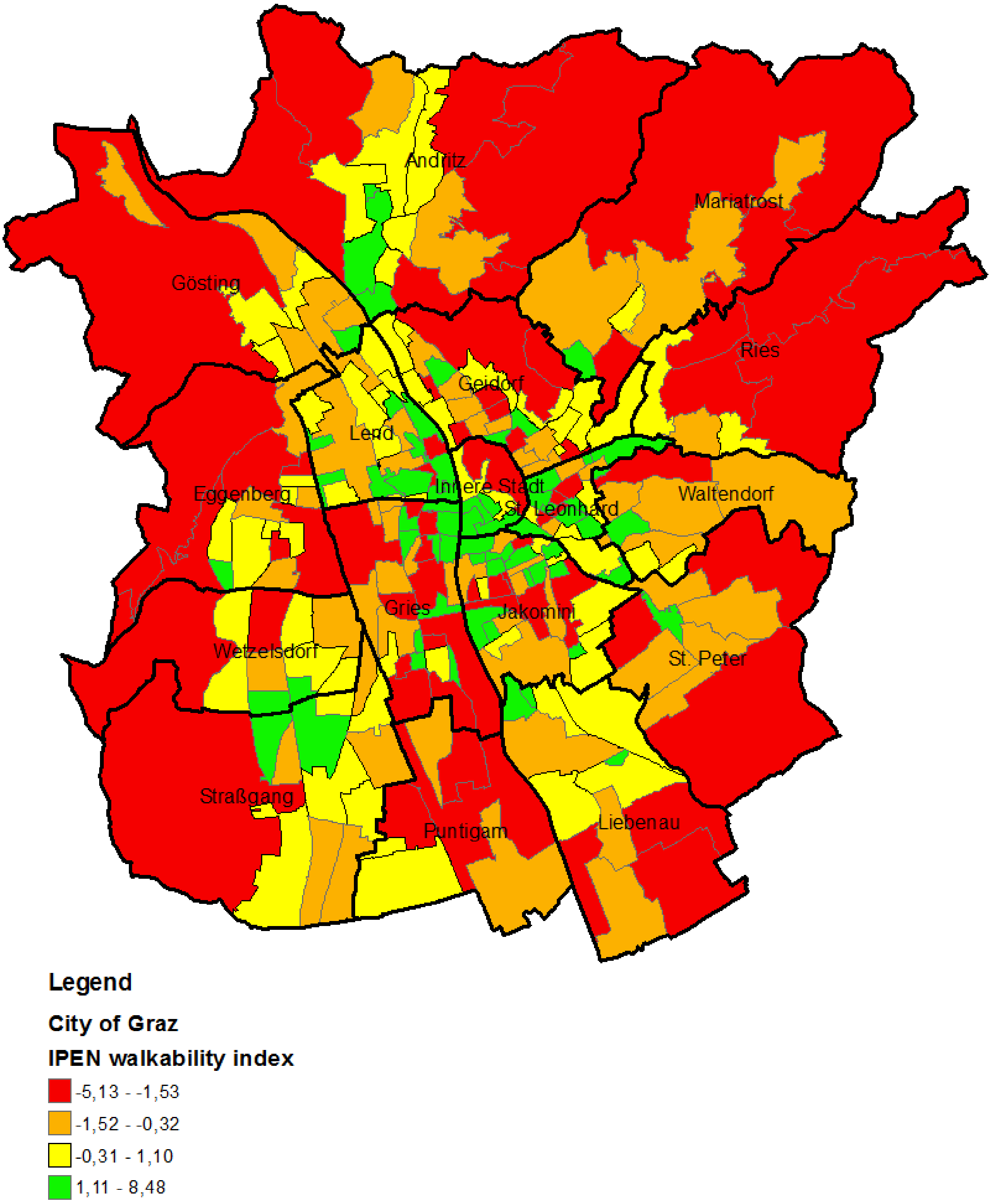


Figure 13: IPEN walkability index of the city of Graz based on statistical sectors

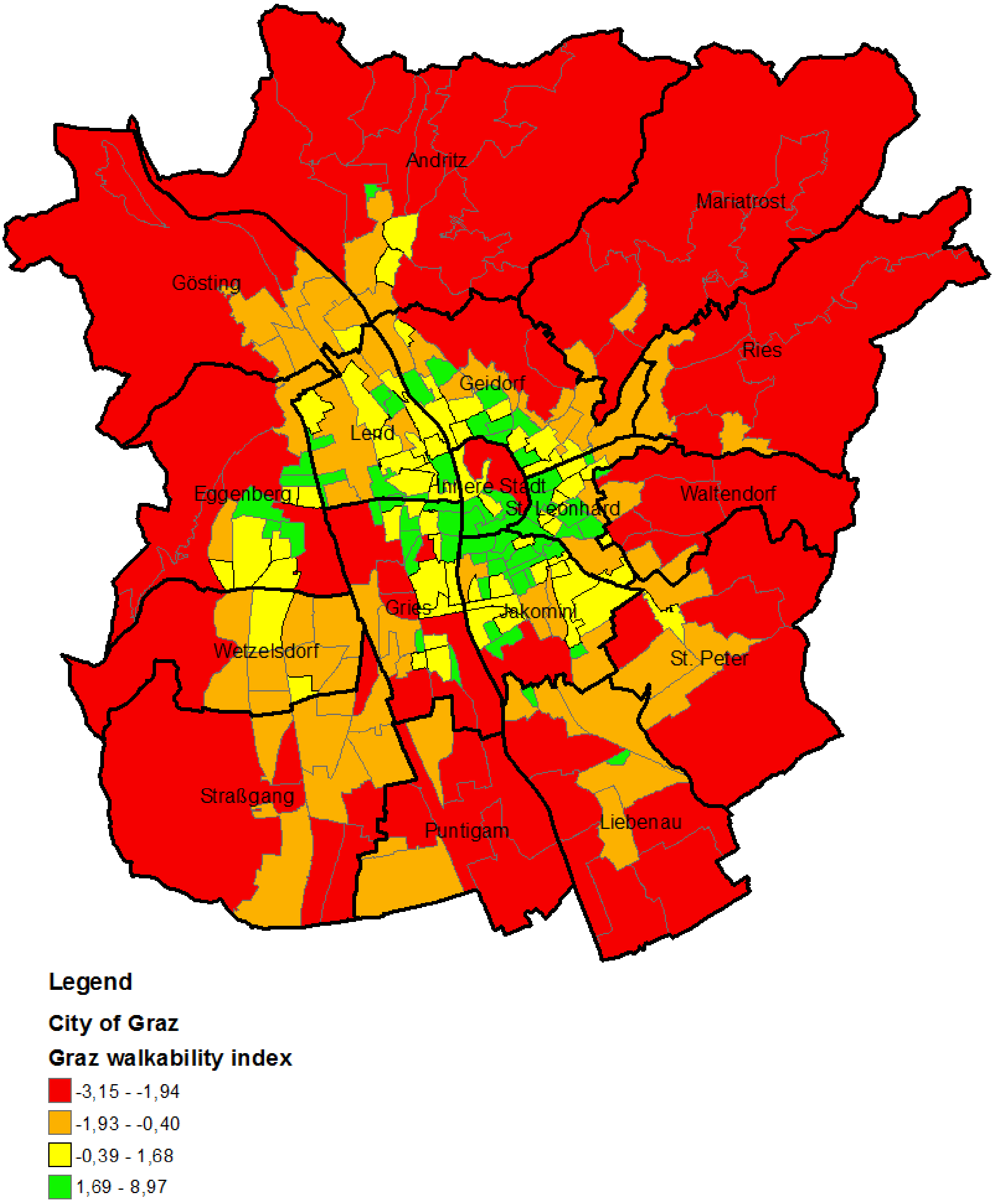


Figure 14: Graz walkability index based on statistical sectors

Another issue that policy makers must address is the association between high walkability and low neighbourhood satisfaction. In the models analysing multiple associations of all outcomes, neighbourhood satisfaction remained most often statistically significantly associated with walkability. Residents of high-walkable areas (i.e. mainly in inner city districts) were not satisfied with aspects of neighbourhood satisfaction, such as the reputation, appearance, safety and environmental quality of the neighbourhood. Since 2006, the city of Graz has been measuring the life quality (LQI) of the residents of Graz to identify needs and resources. In the 2013 report, the stress related to the residential migration is described, and community development measures for establishing neighourhood ties are recommended (City of Graz, 2013). Thus, there is already awareness of the need to improve neighbourhood satisfaction, especially in inner city districts. Furthermore, the already established LQI monitoring and planning system would be a good entry point for testing the walkability measures for their usefulness in practice and for further integration of these indicators in surveillance and planning.

6.7 Study strengths and weaknesses

Due to the cross-sectional design of the study, it was not possible to establish causality. Although the questionnaire showed a good test-retest reliability (Titze et al., 2007), there may have been issues related to measuring walking for transport (see section 6.1). Therefore, no final conclusion on the association between walkability and walking for transport can be drawn.

Additionally, the self-report of outcome data has to be taken into account when interpreting the results. Objectively measured outcome data would increase the precision of the results and the understanding of the association between walkability and health-related outcomes.

One further limitation of the present study is the low quality of the street centre line data used to measure connectivity, as described in section 6.2.3. However, it is assumed that this issue did not have a significant impact on the association between walkability and health-related outcomes.

The present empirical study is the first of its kind in an Austrian city. The use of the same walkability measures as in other studies and in the IPEN enables international comparability. Furthermore, the study provides alternative measures for walkability in relation to land use mix and connectivity, as well as a newly developed walkability index. These measures, *proportion of land use mix* and *four-way intersection density,* as well as the *Graz walkability index,* performed quite well in detecting associations between walkability and health-related outcomes. In the European context, they may be more applicable than the other walkability measures developed in the US or in Australia.

Additionally, the results of the present study contribute to the current limited understanding of the associations between walkability and health-related outcomes in Europe. In particular, the study contributes to the knowledge on the association between walkability and biking for transport and neighbourhood satisfaction, which have rarely been investigated.

The present study is also a good basis for developing further research, since a broad range of further investigation areas arose.

One additional strength of the study is the sound theoretical and empirical evidence foundation, which was ensured by the systematic literature review, the use of a questionnaire with a good test-retest reliability (Titze et al., 2007) and the use of objective walkability data and measures.

Another important newsworthy characteristic of the present study is the analysis of the association between walkability and health-related outcomes for population sub-groups. Few studies have taken this approach, even though the present study has detected important differences. The present study is one step towards the integration of built environment as one health determinant in public health surveillance and in planning.

7 Conclusions

This study contributes to the identification of the best GIS-based walkability measures in relation to health and to the further development of the theory on the built environment.

The study showed that all walkability measures were related to health-related outcomes, especially to cycling for transport, active modes of transport and neighbourhood satisfaction. However, cycling for transport was positively associated with walkability, while neighbourhood satisfaction was negatively associated with walkability. No associations were found between walkability and self-rated health and BMI.

Especially the walkability measures *household unit density, proportion of mixed land use* and *four-way intersection density*, as well as the walkability index based on these measures (i.e. the *Graz walkability index)*, performed well in detecting an association between walkability and health-related outcomes. The *entropy index* as a measure of land use mix was the least applicable indicator due to limitations in the available zoning data.

Associations between walkability and health-related outcomes were more often found among men than among women, among younger respondents than among older respondents, among respondents with a high socio-economic status than among respondents with a low socio-economic status and among respondents residing in the eastern part of the city than among respondents residing in the western part. These differences may be explained by misperceptions of the built environment in the neighbourhood, especially by low socio-economic groups. Consequently, measures to improve the adequate perception of walkability should be considered. In addition, the negative association between walkability and neighbourhood satisfaction needs to be addressed using community development methods.

The present study has shown that walkability is a correlate of different health-related outcomes. Therefore, the walkability measures proposed in the study should be considered for surveillance and planning. A consensus exercise with stakeholders from public health, city and transport planning should be undertaken to generate agreement on which walkability indicators are useful and valuable for surveillance and planning in Graz.

Further research should support the integration of walkability indicators in the surveillance and planning in Graz. Investigations in Graz should look at the association between walkability and walking for transport, at differences in the association between walkability and health-related outcomes by socio-economic status, and at further testing and validating the walkability indicators.

In addition, more research is needed – especially throughout Europe – on the association between walkability and biking for transport and neighbourhood satisfaction and on walkability indicators that are better applicable to the European context (e.g. *proportion of mixed land use*, *four-way intersection density*).

8 Literature

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Appendix 1: GIS Dictionary

The following section provides the reader with definitions and descriptions of terms used for the analyses of the geodata. Since ESRI provides a professional GIS Dictionary, the definitions and descriptions are copied directly word by word from their dictionary (http://support.esri.com/en/knowledgebase/GISDictionary/search). The descriptions of terms that were not described in the GIS Dictionary (printed in italics) were copied from the ESRI ArcGIS Help 10.2 (http://resources.arcgis.com/de/help/).

- Attribute table: A database or tabular file containing information about a set of geographic features, usually arranged so that each row represents a feature and each column represents one feature attribute. In a GIS, attribute tables are often joined or related to spatial data layers, and the attribute values they contain can be used to find, query, and symbolize features or raster cells.
- Buffer: A polygon enclosing a point, line, or polygon at a specified distance.
- Clip: A command that extracts features from one feature class that reside entirely within a boundary defined by features in another feature class.
- Coordinate system: A reference framework consisting of a set of points, lines, and/or surfaces, and a set of rules, used to define the positions of points in space in either two or three dimensions.
- *Dangel point*: The endpoint of a dangling arc.
- Dbf: A database file format.
- Dissolve: A geoprocessing command that removes boundaries between adjacent polygons that have the same value for a specified attribute.
- Euclidian: The straight-line distance between two points on a plane. (…) ‘as the crow flies’.

- Feature: A representation of a real-world object on a map.
- Geocoding: A GIS operation for converting street addresses into spatial data that can be displayed as features on a map, usually by referencing address information from a street segment data layer.
- Geodata: geographic data; Information describing the location and attributes of things, including their shapes and representation. Geographic data is the composite of spatial data and attribute data.
- Geodatabase: A database or file structure used primarily to store, query, and manipulate spatial data. Geodatabases store geometry, a spatial reference system, attributes, and behavioral rules for data.
- *Modelling*: A set of rules and procedures for representing a phenomenon.
- Intersect: A geometric integration of spatial datasets that preserves features or portions of features that fall within areas common to all input datasets.
- Impedance: A measure of the amount of resistance, or cost, required to traverse a path in a network, or to move from one element in the network to another. Resistance may be a measure of travel distance, time, speed of travel multiplied by distance, and so on.
- Layer: The visual representation of a geographic dataset in any digital map environment.
- Line feature: A map feature that has length but not area at a given scale, such as a river on a world map or a street on a city map.
- *Merge:* Combines multiple input datasets of the same data type into a single, new output dataset. This tool can combine point, line, or polygon feature classes or tables.
- Multipart: A digital representation of a place or thing that has more than one part but is defined as one feature because it references one set of attributes.
- *Multipart to singlepart*: Creates a feature class containing singlepart features generated by separating multipart input features.

- Overlay: A spatial operation in which two or more maps or layers registered to a common coordinate system are superimposed, (…) for the purpose of showing the relationships between features that occupy the same geographic space.
- Polygon: On a map, a closed shape defined by a connected sequence of x,y coordinate pairs, where the first and last coordinate pair are the same and all other pairs are unique.
- Projection: A method by which the curved surface of the earth is portrayed on a flat surface.
- Spatial join one to many: A type of table join operation in which fields from one layer's attribute table are appended to another layer's attribute table based on the relative locations of the features in the two layers.
- *Split line at vertices*: Creates a feature class containing lines that are generated by splitting input lines or polygon boundaries at their vertices.
- *Symmetrical difference*: Features or portions of features in the input and update features that do not overlap will be written to the output feature class.
- Topology: In geodatabases, the arrangement that constrains how point, line, and polygon features share geometry. For example, street center lines and census blocks share geometry, and adjacent soil polygons share geometry. Topology defines and enforces data integrity rules (for example, there should be no gaps between polygons).
- Transformation: The process of converting the coordinates of a map or an image from one system to another, typically by shifting, rotating, scaling, skewing, or projecting them.
- Zoning: The application of local government regulations that permit certain land uses within geographic areas under the government’s jurisdiction. Zoning regulations typically set a broad category of land use permissible in an area, such as residential, commercial, agricultural, or industrial.