Mikko Kärmeniemi

THE BUILT ENVIRONMENT AS A DETERMINANT OF PHYSICAL ACTIVITY

LONGITUDINAL ASSOCIATIONS BETWEEN NEIGHBORHOOD CHARACTERISTICS, URBAN PLANNING PROCESSES, AND PHYSICAL ACTIVITY
MIKKO KÄRMENIEMI

THE BUILT ENVIRONMENT AS A DETERMINANT OF PHYSICAL ACTIVITY

Longitudinal associations between neighborhood characteristics, urban planning processes, and physical activity

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Abstract

The health benefits of physical activity (PA) are indisputable, but physical inactivity remains a global public health concern. There is a need to design cities that support active transportation because the built environment (BE) is a possible major contributor to physical inactivity. The present study aimed to examine the BE as a determinant of PA with a specific focus on longitudinal associations, residential relocation, and producing policy-relevant knowledge of land use and transportation policies, and urban form and transportation modal share development.

First, previous longitudinal studies were reviewed using the narrative synthesis analysis method. Second, population-based prospective Northern Finland Birth Cohort 1966 data were used to assess the longitudinal associations between residential relocation and changes in regular walking and cycling behavior. Finally, a longitudinal mixed methods approach focused on the interconnection between qualitative document analysis of local land use and transportation policies and quantitative analysis of urban form development and its association with transportation modal share development.

Increases in urban form density, mixed land use, and access networks (DMA) were associated with increased walking and cycling and decreased car use. Residential relocation trajectories were mostly stable. Relocation focused more often to less dense and diverse neighborhoods, but relocating to the most urban neighborhoods increased the odds of starting both regular cycling and walking, as compared to the opposite relocation trajectory. In the city of Oulu, urban form did not develop entirely according to related policies, and goals to increase active transportation modal share were not achieved, possibly due to an inadequate functional mix outside the city center, increased urban sprawl, and building more capacity for cars.

Changing how community structures are developed seems a promising strategy for increasing population PA by inducing demand for active modes of transportation. Designing dense, compact, and diverse neighborhoods and greater investments in active transportation infrastructure require strong political leadership and appear as important factors in adopting an active lifestyle that could reduce the global disease burden caused by physical inactivity.

Keywords: built environment, causality, cycling, longitudinal research, physical activity, urban planning, walking
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Tiivistelmä


Yhdyskuntarakenteen tiiviyyden, toimintojen sekottumisen ja katuverkoston risteydyksen lisääntyminen olivat yhteydessä lisääntynyt kävelyyn ja pyöräilyn yhteydessä. Suurin osa tutkimuksessa kävelevän ageenien liittyneet osa oli samaa aikaa kävelevän ajavaa. Tutkimuksen tulos perustuu yleisemmin kävelevän ajavaan osaan, jossa on kävelevän ajavaa osan yhteydessä. Tutkimuksen tulos perustuu yleisemmin kävelevän ajavaan osaan, jossa on kävelevän ajavaa osan yhteydessä. Tutkimuksen tulos perustuu yleisemmin kävelevän ajavaan osaan, jossa on kävelevän ajavaa osan yhteydessä. Tutkimuksen tulos perustuu yleisemmin kävelevän ajavaan osaan, jossa on kävelevän ajavaa osan yhteydessä. Tutkimuksen tulos perustuu yleisemmin kävelevän ajavaan osaan, jossa on kävelevän ajavaa osan yhteydessä. Tutkimuksen tulos perustuu yleisemmin kävelevän ajavaan osaan, jossa on kävelevän ajavaa osan yhteydessä. Tutkimuksen tulos perustuu yleisemmin kävelevän ajavaan osaan, jossa on kävelevän ajavaa osan yhteydessä. Tutkimuksen tulos perustuu yleisemmin kävelevän ajavaan osaan, jossa on kävelevän ajavaa osan yhteydessä. Tutkimuksen tulos perustuu yleisemmin kävelevän ajavaan osaan, jossa on kävelevän ajavaa osan yhteydessä. Tutkimuksen tulos perustuu yleisemmin kävelevän ajavaan osaan, jossa on kävelevän ajavaa osan yhteydessä. Tutkimuksen tulos perustuu yleisemmin kävelevän ajavaan osaan, jossa on kävelevän ajavaa osan yhteydessä. Tutkimuksen tulos perustuu yleisemmin kävelevän ajavaan osaan, jossa on kävelevän ajavaa osan yhteydessä. Tutkimuksen tulos perustuu yleisemmin kävelevän ajavaan osaan, jossa on kävelevän ajavaa osan yhteydessä. Tutkimuksen tulos perustuu yleisemmin kävelevän ajavaan osaan, jossa on kävelevän ajavaa osan yhteydessä. Tutkimuksen tulos perustuu yleisemmin kävelevän ajavaan osaan, jossa on kävelevän ajavaa osan yhteydessä. Tutkimuksen tulos perustuu yleisemmin kävelevän ajavaan osaan, jossa on kävelevän ajavaa osan yhteydessä. Tutkimuksen tulos perustuu yleisemmin kävelevän ajavaan osaan, jossa on kävelevän ajavaa osan yhteydessä.

Asiasanat: fyysinen aktiivisuus, kaupunkisuunnittelu, kausaalisuus, kävely, pitkittäistutkimus, pyöräily, rakennettu ympäristö
To my family
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Oulu, April 2021

Mikko Kärmeniemi
**Abbreviations**

<table>
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<th>Definition</th>
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<tbody>
<tr>
<td>BE</td>
<td>Built environment</td>
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<tr>
<td>CI</td>
<td>Confidence interval</td>
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<td>CVD</td>
<td>Cardiovascular disease</td>
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<td>DMA</td>
<td>Density, mixed land use, and access networks</td>
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<td>GLMM</td>
<td>Generalized linear mixed model</td>
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<tr>
<td>GIS</td>
<td>Geographic information system</td>
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<td>LTPA</td>
<td>Leisure time physical activity</td>
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<td>LPA</td>
<td>Light-intensity physical activity</td>
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<td>MET</td>
<td>Metabolic equivalent</td>
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<td>MVPA</td>
<td>Moderate to vigorous intensity physical activity</td>
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<tr>
<td>NCD</td>
<td>Non-communicable disease</td>
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<td>OR</td>
<td>Odds ratio</td>
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<tr>
<td>PA</td>
<td>Physical activity</td>
</tr>
<tr>
<td>SB</td>
<td>Sedentary behavior</td>
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<td>SD</td>
<td>Standard deviation</td>
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<tr>
<td>TPA</td>
<td>Transportation-related physical activity</td>
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Original publications

This thesis is based on the following publications, which are referred throughout the text by their Roman numerals:


Contribution: In study I, MK participated in planning and designing the study. He was responsible for formulating the research questions, selecting methods, and conducting database searches. He also screened the articles’ eligibility based on title and abstract, and participated in the full text and risk of bias evaluations. MK further extracted the data from the included studies, conducted narrative synthesis of the results, wrote the first draft of the manuscript, and finalized the manuscript based on co-authors’ comments. In study II, MK participated in planning and designing the study and prepared the research questions. He was responsible for selecting statistical methods, analyzing previously collected data, interpreting the results, writing the first draft of the manuscript, and finalizing the manuscript according to co-authors’ comments. In study III, MK was responsible for planning and designing the study. He completed part of the data collection by deriving land use and transportation policy documents from Oulu’s webpages and archives. He also selected the analysis methods, analyzed previously collected data, interpreted the results, wrote the first draft of the manuscript, and finalized the manuscript based on co-authors’ comments.
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1 Introduction

Disease etiology is multifactorial, but non-communicable diseases (NCDs) are predominantly determined by lifestyle and poor health behavior (Hovell, Wallhgren, & Gehrman, 2002). Physical activity (PA) is beneficial to several aspects of health, including cardiorespiratory and muscular fitness, body mass and composition, bone health, functional health, and cognitive function (Lee et al., 2012). On the contrary, physical inactivity, a global public health concern, decreases life expectancy and is one of the leading risk factors behind the emergence and incidence of major NCDs, such as coronary heart disease, type 2 diabetes, breast and colon cancers, and dementia, which account for 71% of all deaths annually (Lee et al., 2012; Sallis, Bull, Guthold et al., 2016; World Health Organization, 2019). Moreover, sedentary behavior (SB), defined as any waking behavior with an energy expenditure ≤ 1.5 metabolic equivalents (MET, rate of energy expenditure relative to resting state) while in a sitting, reclining, or lying posture (Tremblay et al., 2017), has been found to independently associate with adverse health outcomes (Thorp, Owen, Neuhaus, & Dunstan, 2011).

Exposure to environmental factors mediated by PA behavior is one of the central mechanisms in disease dynamics that determines the health of individuals (Pinter-Wollman, Jelic, & Wells, 2018; Sallis, Owen, & Fisher, 2008). Globally, anthropogenic drivers such as the built environment (BE), which is modified through urban planning, land use and transportation policies, have been suggested as major contributors to NCDs caused by low PA levels (Pinter-Wollman et al., 2018; Sallis, Bull, Burdett et al., 2016). Hence, the association between the BE and PA has attracted growing scientific attention over the last two decades. There is increasing evidence that exposure to urban form characteristics, such as population density, street connectivity, land use mix, and non-residential destinations impact citizens’ PA (Bird et al., 2018; McCormack & Shiell, 2011; Saelens & Handy, 2008).

Individual- or small group–focused PA interventions have been criticized as ineffective because they have produced moderate and temporary effects and reached only small numbers of people (Sallis et al., 2006). Consequently, ecological models were attested for use as comprehensive frameworks for effective multilevel interventions to increase population PA, as they take account of physical environment and policies besides individual-level psychosocial factors (Hovell et al., 2002; Sallis et al., 2006; Sallis et al., 2008).

However, two major limitations remain in the existing research. First, there is a lack of large-scale prospective longitudinal studies. A majority of previous studies...
have relied on cross-sectional data, which hinders the assessment of causal inference (Ding & Gebel, 2012; McCormack & Shiell, 2011; van de Coevering, Maat, & van Wee, 2015). One general limitation of the previous longitudinal studies is the failure to model residential relocation trajectories in assessing residential preferences and self-selection. They have also relied solely on self-reported physical activity data and have not assessed cycling or regular physical activity (Bentley et al., 2018; Knuiman et al., 2014).

Second, there is a gap between research and practice. Thus, the enhanced use of science to guide urban planning is necessary but knowledge transfer is hindered because academic research rarely meets the needs of policymakers and practitioners (Giles-Corti et al., 2015; Sallis, Bull, Burdett et al., 2016). Lack of collaborations between researchers, practitioners, and policy makers do not ensure that health research is used routinely and effectively in urban and transportation planning (Sallis, Bull, Burdett et al., 2016). Evidence-based policy making and successful research translation demand robust, context-specific, local, policy-relevant evidence of the implementation of local policies and are dependent on cooperation with fields beyond PA and health (Giles-Corti et al., 2015; Hooper, Foster, & Giles-Corti, 2019).

The present study addresses these gaps in the existing knowledge by utilizing a longitudinal design to identify the environmental determinants of PA and assess the association between residential relocation and changes in walking and cycling behavior. A trajectory-based approach enabled quantifying exposure to various residential environments during the follow-up (Coulter, Ham, & Findlay, 2016) and indicated preferences and possibilities for residential location choices. Moreover, the present study used a mixed methods approach to assess the interconnection of local community and transportation planning policies with urban form and transportation modal share development to enhance earlier findings’ utility.
2 Review of the literature

2.1 Urban planning and public health

The field of public health evolved in conjunction with city planning during the late 19th century as a consequence of attempts to manage the detrimental exposure to pollution and communicable diseases related to the era’s rapid industrialization and urbanization (Corburn, 2004). During this time, when sanitary reforms such as sewerage, garbage collection, and rodent control emerged as means to improve the health of urban populations, the two fields were closely related. However, along with a better understanding of pathogens, public health’s focus shifted toward biomedical factors that eventually became the dominant paradigm in epidemiology (Duhl & Sanches, 1999).

Concurrently, zoning emerged as a tool in urban planning to separate residential areas from industrial land uses to prevent exposure to “undesirable externalities of the economy, such as industrial pollution” (Corburn, 2004, p. 524). By the late 20th century, public health and urban planning had become more or less separate fields and lost their common means of enhancing health of the citizens. However, contemporary global health challenges related to NCDs originating from the increasing prevalence of physical inactivity, obesity, and exposure to traffic emissions require reassessing approaches to disease prevention, as well as a reunion of public health and urban planning fields (Giles-Corti et al., 2016).

The 1933 CIAM (Congrès Internationaux d’Architecture Moderne) meeting in Athens paved the way for modernism and wider acceptance of functionalist planning principles in urban planning (Gold, 1998). According to these principles, the various city functions such as dwellings, work, recreation, and traffic should be separated. During the following decades, functionalism became the dominant paradigm in city planning and contributed considerably to the post-World War II urban sprawl and car dependency as cities grew. Increasing incomes and declining transportation costs operated as a catalyst for the rise of the automobile, which together with the functional zoning policies gave rise to car-centric city planning manifested as unconnected low-density urban form, and expanding city footprints (Nechyba & Walsh, 2004).

Functionalism was criticized as early as the 1960s by Jacobs (1961), who argued that it would destroy the city as a living community. Separate zones and the super-highways that connect them would put an end to dense neighborhoods and
multi-activity streets, which Jacobs (1961) considered as the core of urbanism. Thus, urban design thinkers should address the human scale in urban planning instead of moving cars as fast as possible. In a similar vein, Gorz (1973) stated:

Above all, never make transportation an issue by itself. Always connect it to the problem of the city, of the social division of labour, and to the way this compartmentalizes the many dimensions of life. One place for work, another for “living”, a third for shopping, a fourth for learning, a fifth for entertainment. The way our space is arranged carries on the disintegration of people that begins with the division of labour in the factory. It cuts a person into slices, it cuts our time, our life, into separate slices so that in each one you are a passive consumer at the mercy of the merchants, so that it never occurs to you that work, culture, communication, pleasure, satisfaction of needs, and personal life can and should be one and the same thing: a unified life, sustained by the social fabric of the community. (para. 24)

Most developed countries still implement the antiquated zoning laws, though their primary public health incentives have transformed considerably (Peiser, 2001). Changing the dominant way of thinking is not easy. For example, Sadik-Khan and Solomonov (2017) recently described the resistance to the pursuit of more human-centered urban and transportation planning in New York as a street fight and stated that “when you push the status quo, it pushes back, hard” (p. 27).

However, the downsides of car-centric planning are becoming more and more evident. Today, physical inactivity and exposure to traffic emissions are among the leading risk factors of NCDs, such as cancers, diabetes, cardiovascular disease (CVD), and chronic respiratory diseases, which account for 71% of all deaths annually (World Health Organization, 2019). Congestion, loss of open space amenities, and the unequal supply of public goods and services contribute to residential segregation (Nechyba & Walsh, 2004). Cities struggle to manage ever increasing levels of urbanization (United Nations, 2015b), which is placing growing demands on urban planning and transportation infrastructure. Moreover, motor vehicle–related air pollution contributes to growing levels of greenhouse gas emissions that accelerate the climate crisis (Intergovernmental Panel on Climate Change, 2018). Thus, the goal for more active cities is highly interconnected to many of the political priorities of the sustainable development agenda (United Nations, 2015a).

Due to the undesired effects of car-centric planning, policies that promote compact urban form, mixed land use, high-quality infrastructure for walking,
cycling, and public transportation, and environmental sustainability have gained popularity.

New urbanism emerged as a counterforce for the car-oriented, low-density, separated-use sprawl development advocating human-scale urban design by creating compact, mixed-use, and mixed-income neighborhoods (Trudeau, 2013). New urbanism concerns physical form, stating that changes in the BE are essential for economic, social, and ecological change (Knaap & Talen, 2005). According to the charter of the Congress for the New Urbanism, the movement stands for the restoration of existing urban centers and the reconfiguration of sprawling suburbs into communities of real neighborhoods and diverse districts (Congress for the New Urbanism, 1996).

Similarly, smart growth focuses on development that emphasizes economy, the community, and the environment by reducing the externalities of growth (Grant, 2009). At a regional level, smart growth assesses land use and transportation systems to balance housing and workplaces and utilizes incentives to encourage the market to intensify urban development (Grant, 2009). Still, in practice implementing the policies advocated by smart growth and new urbanism has been difficult. As an example, in Canada, it was acknowledged that market constraints and private sector solutions may affect development practice, and more attention is needed on communication between different organizations and establishing a common political will (Grant, 2009).

2.2 Physical activity and population health

PA has been defined as any bodily movement produced by skeletal muscles that causes energy expenditure, but should not be interpreted merely as exercise, which is more goal-oriented behavior aiming to improve or maintain physical fitness (Caspersen, Powell, & Christenson, 1985). Beyond exercise, PA can occur in other domains, such as the household, transport, work, and other leisure-time activities (World Health Organization, 2010). It has been suggested that the occupational, household, and transport domains comprise the majority of total PA in low- and middle-income countries, whereas leisure-time activities have higher significance in high-income countries (MacNiven, Bauman, & Abouzeid, 2012).
2.2.1 Physical activity behavior

Physical activity recommendations and health benefits

The health benefits of PA and exercise are well established, and practically anyone can gain these benefits in a dose-response manner by becoming more physically active (Warburton & Bredin, 2017). In the last 50 years, a plethora of epidemiological studies have emphasized especially the benefits of moderate to vigorous intensity physical activity (MVPA) in reducing morbidity and mortality due to NCDs (Archer & Blair, 2011; Warburton & Bredin, 2017; World Health Organization, 2010). PA’s benefits comprehensively extend to mental wellbeing, better quality of life, improved sleep, reduced stress, stronger relationships, and social connectedness (Das & Horton, 2012).

Recently, more evidence has become available on the benefits of light-intensity physical activity (LPA) in relation to health outcomes such as obesity, markers of lipid and glucose metabolism, cardiometabolic health and mortality (Farrahi et al., 2021; Saint-Maurice, Troiano, Berrigan, Kraus, & Matthews, 2018; Wen et al., 2011). Current evidence has suggested that considerable relative health benefits might occur at fairly low PA volumes, which contradicts threshold-centered PA recommendations (Warburton & Bredin, 2017). Replacing sedentary time with PA of any intensity has been found to be associated with a substantially reduced risk for premature mortality (Ekelund et al., 2019). Moreover, LPA seems beneficial for health outcomes even after adjusting for moderate to vigorous intensity activities, which has important implications for activating the most inactive individuals (Amagasa et al., 2018).

Accordingly, the latest PA recommendations in the U.S. and subsequently also in Finland accounted for replacing sedentary time with light-intensity activities (UKK Institute, 2019; US Department of Health and Human Services, 2018). In 2020, the World Health Organization recommended that adults do at least 150–300 minutes of moderate-intensity aerobic PA, or at least 75–150 minutes of vigorous-intensity aerobic PA, or an equivalent combination of these throughout the week, whereas muscle-strengthening activities involving all major muscle groups should be done on two or more days a week (World Health Organization, 2020). For children and adolescents, the recommendations were higher, involving at least an average of 60 minutes per day of mostly aerobic MVPA and vigorous-intensity aerobic activities, as well as muscle- and bone-strengthening activities on at least three days a week (World Health Organization, 2020).
The World Health Organization 2020 guidelines also stated that some PA is better for health than none and accounted for limiting and breaking up long bouts of sedentary time and replacing them with activities of any intensity (World Health Organization, 2020). For the first time, these recommendations also paid special attention to subpopulations (e.g. pregnant and postpartum women and people with chronic conditions or disability), the benefits of PA for mental and cognitive health, and sleep, as well as how PA bouts of any length provide health benefits (World Health Organization, 2020).

**Active transportation**

As land use and transportation policies are globally recognized as key factors that contribute to physical inactivity, one of the primary solutions is to design cities that support active modes of transportation (Sallis, Bull, Burdett et al., 2016), which include walking, cycling, and other non-motorized means of transport and are usually part of a trip chain for public transportation users (Young et al., 2020).

Previous evidence has suggested that a considerable amount (30%) of daily PA occurs during transportation, and thus, an increase in active transportation modal shares could have a major impact on the proportion of people achieving PA recommendations (Chaix et al., 2014). Active transportation has been found to be associated with substantial health benefits that exceed the detrimental effects of traffic-related incidents and emission exposure (Mueller et al., 2015). For example, bicycle commuting has been associated with a reduced risk of all-cause mortality, CVD, and cancer, as compared to commuting by private motor vehicles (Celis-Morales et al., 2017; Patterson et al., 2020). Intervention studies related to cycling have detailed a dose-response association between the amount of cycling and lower risk of all-cause mortality, CVD, colon cancer, and incidence of overweight and obesity (Oja et al., 2011).

Commuting by walking revealed to lower the risk of CVD incidence and cancer (Celis-Morales et al., 2017). Walking interventions have also been shown to have clinically significant effects on CVD risk factors such as body mass index, body fat, systolic and diastolic blood pressure, fasting glucose, and maximal oxygen uptake (Oja et al., 2018). Further, existing evidence has indicated that increased walking pace could better reduce the risk for all-cause and CVD mortality (Stamatakis et al., 2018), and that a cadence of 100 steps per minute or more could be used as a threshold to indicate moderate-intensity PA (Tudor-Locke et al., 2018).
Physical inactivity

Despite compelling evidence for PA’s health benefits and recommendations for it, physical inactivity remains a global public health concern, given that globally 31% of adults aged 18 years and over and 80% of 13–15-year-old adolescents do not meet the recommendations, and that the prevalence of inactivity is generally higher in high-income countries (Hallal et al., 2012). In Finland, only around 40% of 18–64-year-old adults reached both the aerobic and muscle-strengthening PA guidelines (Wennman & Borodulin, 2020). More recent evidence has also indicated that the global prevalence of insufficient PA is high (27.5%) and has remained stable over the previous 15 years, thus failing to meet the World Health Organization targets to prevent NCDs through PA (Guthold, Stevens, Riley, & Bull, 2018). Consequently, physical inactivity has been described as a global pandemic and the fourth leading cause of death (Kohl et al., 2012), accountable for a substantial worldwide economic burden with estimated costs of more than international $ 67.5 billion through health care costs and productivity losses (Ding et al., 2016).

Physical inactivity decreases life expectancy and is one of the major risk factors behind NCDs, such as coronary heart disease, type 2 diabetes, breast and colon cancers and dementia (Lee et al., 2012; Sallis, Bull, Guthold et al., 2016), which are responsible for 71% of all deaths annually (World Health Organization, 2019). An evolutionary perspective reflects why this is not surprising. For most of human history, survival has demanded continuous physical exertion, and the human physiology has evolved to meet the demands of hunting, gathering, and being on the move (Archer & Blair, 2011). Hence, one might argue that it is embedded in our DNA that we need regular PA to be healthy. However, most routine daily physical activities have been ruled out by technological advances and car-dependent community structures in modern urbanized societies, which have contributed to the prevalence of sedentary lifestyles.

Sedentary behavior

By definition, SB implies any waking behavior characterized by an energy expenditure ≤ 1.5 METs while in a sitting, reclining, or lying posture (Tremblay et al., 2017). It has been suggested that that SB is potentially a distinct risk factor of adverse health outcomes independent of PA (Thorp et al., 2011). Globally, 41.5% of adults spent 4 or more hours sitting each day, and in Europe, the proportion
exceeds 60% (Hallal et al., 2012). Prolonged bouts of SB have been associated with detrimental effects on cardiometabolic health and mortality (Broeklebank, Falconer, Page, Perry, & Cooper, 2015; Rezende et al., 2016), but the existing evidence is insufficient to give guidance on specific limits or maximum amounts of sedentary time to minimize these health risks. However, it seems that high levels of moderate-intensity physical might eliminate the increased risk of mortality due to excessive sitting time (Ekelund et al., 2016).

The 24-hour activity cycle

So far, the interconnection of physiological mechanisms by which sleep, SB, LPA, and MVPA are related to health has not been well understood (Rosenberger et al., 2019). Studies have commonly assessed the association of time spent on one activity behavior and health outcomes in isolation. However, as the time spent on one activity can only be increased by decreasing the time spent on other activity behaviors, and taking into account the interrelationships among the activities, novel approaches such as the 24-hour activity cycle model utilizing compositional data analysis are needed (Rosenberger et al., 2019).

Scholars have indicated that MVPA might be the most important factor to reducing mortality (McGregor, Palarea-Albaladejo, Dall, del Pozo Cruz, & Chastin, 2019) and other negative effects of physical inactivity (Chastin, Palarea-Albaladejo, Dontje, & Skelton, 2015; Janssen et al., 2020) after considering its synergies with time spent on other activity behaviors. However, more time spent on LPA at the expense of SB has also been associated with improved diabetes risk markers (Chastin et al., 2015) and cardiometabolic health (Farrahi et al., 2021), as well as reduced mortality risk (Janssen et al., 2020; McGregor et al., 2019).

Existing evidence supports combining recommendations of all activity behaviors into a single public health guideline, which is hindered by the low volume and quality of the evidence, though (Janssen et al., 2020). Canada’s movement guidelines were the first to emphasize the interconnection of all movement behaviors across the whole 24-hour day and provide evidence-based recommendations that comprise a combination of sleep, SB, LPA, and MVPA (Ross et al., 2020). According to these guidelines, “Replacing SB with additional PA and trading LPA for more MVPA, while preserving sufficient sleep, can provide greater health benefits” (Ross et al., 2020, p. 70).
2.2.2 Measuring physical activity

PA measurements attempt to capture the dimensions (frequency, duration, intensity, and type) and domains (occupational, domestic, transportation, and leisure time) of a given activity with the goal of providing a reliable and valid quantification of that activity (Bauman, Phongsavan, Schoeppe, & Owen, 2006), which is the key to successfully studying trends and associations with disease (Warren et al., 2010). PA is typically assessed by determining energy expenditure in kilocalories or by using MET, or by specifying time spent in different PA intensity categories in a certain time frame (Strath et al., 2013). There are a variety of subjective and device-based methods to measure PA, though ultimately, method selection is based on feasibility and suitability with the research aims and the PA dimensions and domains that need to be assessed (Warren et al., 2010). In relation to reliable and valid PA measurement, there are additional challenges among children and adolescents, older adults, and culturally diverse populations (Bauman et al., 2006).

Subjective methods

Self-reported methods are most widely used and rely on individual participants documenting their behavior with questionnaires, diaries, logs, or interviews to identify PA dimensions and domains (Strath et al., 2013; Warren et al., 2010). These methods are the easiest and fastest way to collect PA data from a large number of people and have been used, for example, to monitor global PA trends through population-based surveys (Guthold et al., 2018; Warren et al., 2010). Self-reported methods are the least expensive but also the least accurate (Warren et al., 2010) since they differ in their detail, are vulnerable to recall bias, and their validity is better for more vigorous-intensity activities (Bauman et al., 2006; Helmerhorst, Brage, Warren, Besson, & Ekelund, 2012; Strath et al., 2013). However, structured questionnaires can capture PA by domain and type, which is not possible with device-based methods (Warren et al., 2010). For example, the International Physical Activity Questionnaire’s validity and reliability have been tested and replicated in many settings (Craig et al., 2003).

Device-based methods

Device-based methods comprise wearable monitors that directly assess energy expenditure, physiology, motion, or a combination thereof (Strath et al., 2013). The
most used sensors to assess body motion are accelerometers and pedometers. Accelerometers can be attached to the waist, wrists, thighs, or ankles (Yang & Hsu, 2010) and measure acceleration during habitual activities, which can be used to estimate energy expenditure, total PA volume (Strath et al., 2013; Welk, 2002), and activity patterns (Warren et al., 2010). The placement of an accelerometer is important, as the most used position on the waist does not capture, for example, cycling (Warren et al., 2010). Pedometers measure the number of steps taken and can estimate distance walked (Strath et al., 2013; Tudor-Locke & Myers, 2001). Therefore, they are most useful in interventions that target increased walking and provide better accuracy at faster walking speeds, but not while running (Warren et al., 2010). Given that heart rate increases linearly according to aerobic activity intensity, it has widely been used as a physiological measure of PA (Strath et al., 2013). However, it is not a reliable method for measuring time spent in LPA (Warren et al., 2010) because heart rate is affected by other factors that cause sympathetic reactivity, such as caffeine consumption, emotional state, and temperature (Strath et al., 2013).

2.2.3 Ecological models and determinants of physical activity

Preventing morbidity and mortality due to lifestyle and poor health behavior is a public health goal that can be achieved through behavior changes and emphasizing modifiable factors in an individual’s environment (Hovell et al., 2002). Because of their moderate and temporary effects and reach to small numbers of people (Sallis et al., 2006), intervention programs focusing on individual-level behavior change have been insufficient to support increased population PA (Guthold et al., 2018). The mechanisms by which population behavior patterns could be most effectively changed remain one of the greatest uncertainties for public health research and policy (Ogilvie et al., 2020). A systems approach and multilevel interventions addressing not only individuals and social environments but also physical environments and policies are suggested methods (Kohl et al., 2012; Sallis et al., 2006).

Ecological models (Fig. 1) are comprehensive frameworks for effective multilevel interventions to increase population PA (Hovell et al., 2002; Sallis et al., 2006; Sallis et al., 2008), as they take into account multiple and interacting health behavior determinants and target change mechanisms at each level of influence (Sallis et al., 2008). Hence, ecological models encompass people’s interaction with their environment and acknowledge context-specific factors related to different PA
domains (Giles-Corti, Timperio, Bull, & Pikora, 2005; Sallis et al., 2006). The 2018‒2030 Global Action Plan on Physical Activity also highlights the interconnected actions required between societal norms, environmental factors, individual-focused programs, and policy systems to engage the global population in regular physical activities (World Health Organization, 2018).

Fig. 1. Adapted ecological model of the determinants of physical activity. From “Correlates of physical activity: why are some people physically active and others not?” by A. E. Bauman et al., 2012, Lancet, 380, p. 259. Copyright 2012 by Elsevier Ltd. Reprinted with permission.

**Intrapersonal determinants of physical activity**

The number of studies assessing correlates and determinants of PA has proliferated, but predominantly, these studies have addressed individual-level factors. Previous literature has suggested that age, sex, health status, self-efficacy, intention to exercise, previous PA and motivation are possible determinants of PA (Aleksovska et al., 2020; Bauman et al., 2012), whereas low education level, obesity, and cardiometabolic diseases have been associated with lower odds of active living (Yen & Li, 2019). Among women, besides self-efficacy, self-rated health, and intentions, perceived behavioral control has been found to be positively and consistently associated with PA, but having children in the household was associated with decreased MVPA (Prince et al., 2016). Moreover, previous studies
have shown that beliefs about capabilities, motivation, and goals are related to PA maintenance (Amireault, Godin, & Vezina-Im, 2013).

Given that PA begins to decline early in life, that PA habits tend to stabilize with age, and inactivity is a more tenacious habit than activity, childhood is an important phase of life for PA (Lounassalo et al., 2019). Strong evidence has been established on the positive effects of self-efficacy in relation to PA in children and adolescents (Cortis et al., 2017). Among adolescents, higher perceived behavioral control, support for PA (Craggs, Corder, Van Sluijs, & Griffin, 2011), and ethnicity (Uijtdewilligen et al., 2011) have been associated with enhanced PA.

Recently, more evidence has also revealed the importance of the interconnection of biological and genetic determinants with self-efficacy and social-behavioral models in regulating daily PA behavior through mechanisms that encompass personality, emotion regulation, reward processing, and cardiorespiratory and muscle capacity (Lightfoot et al., 2018).

**Interpersonal and social environment determinants of physical activity**

Social environment comprises social interactions and interpersonal relationships, which are related to PA through social support and norms that constrain or enable healthy behaviors (Berkman, 2000). Social environment determinants can be categorized according to social support and networks, socioeconomic position, racial discrimination, social cohesion, and neighborhood factors, which have all been reported to affect PA behavior through different mechanisms (McNeill, Kreuter, & Subramanian, 2006).

Effective social support interventions for PA have been conducted within communities and worksites, and school-based strategies comprising physical education, classroom activities, after-school sports, and active transport have been utilized successfully as well (Heath et al., 2012; Kahn et al., 2002). Socioeconomic status seems to predict increased leisure time and decreased occupational PA for adults, whereas no association between PA and parental socioeconomic situation was found for children and adolescents (O’Donoghue et al., 2018). However, family social support has been found to consistently associate with positive effects on adolescent PA (Bauman et al., 2012). It has been stated that the effectiveness of different kinds of PA interventions could be improved by incorporating social support (Greaves et al., 2011), which is important also for the maintenance of PA behavior (Giles-Corti & Donovan, 2002).
Besides individual-level and social environmental factors, exposure to different types of physical environments, as mediated by PA behavior, is an important pathway in determining individuals’ health (Pinter-Wollman et al., 2018; Sallis et al., 2008). Therefore, research on environmental PA correlates and determinants has also burgeoned during the past two decades (Bauman et al., 2012).

2.3 The built environment and physical activity

The BE is an anthropogenic driver that has been suggested to be one of the primary contributors to global disease burden caused by physical inactivity (Pinter-Wollman et al., 2018; Sallis, Bull, Burdett et al., 2016). The BE, as defined by Handy, Boarnet, Ewing and Killingsworth (2002), “comprises urban design, land use, and the transportation system, and encompasses patterns of human activity within the physical environment” (p. 65). As such, BE refers not only to the land use patterns and built features of the environment, but also to the transportation system that facilitates moving from one place to another.

In this regard, urban and transportation planning seem a feasible strategy to enhance especially utilitarian PA, that is, activities with a primary purpose other than the activity itself, such as transportation-related walking and cycling. Since walking and cycling are common means of transportation and enable engagement in regular PA on a daily basis, they could enhance the adoption of an active lifestyle with long-lasting effects at a population level. The underlying question is, how do we design and build neighborhoods, community structures, and cities that make people walk, cycle, and use public transportation more?

In Finland, the municipal land use planning is organized and steered by local master plans and more detailed local plans. The local land use master plan defines the general principles of land use in the municipality, whereas the local detailed plan defines how land-areas within a municipality are used and built (Ministry of the Environment 1999). Hence, the Finnish municipalities have a strong planning autonomy in relation to the state, and the general goal of the land use and planning act is to ensure preconditions for creating ecologically, economically, socially, and culturally sustainable living environments (Ministry of the Environment 1999).
2.3.1 Neighborhood walkability and urban density, mix and access networks

Leslie et al. (2007) defined neighborhood walkability as “the extent to which characteristics of BE 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” (p. 113). Therefore, neighborhood walkability can be assessed in terms of proximity to different types of destinations and street connectivity, which previous studies have recognized as the two underlying factors related to walking for transportation (Saelens, Sallis, & Frank, 2003). Proximity refers to the distance between destinations and is determined by density (compactness of land use) and land use mix (blending of different types of land uses such as residential and commercial), and connectivity involves the directness of travel and the ease of moving between origins and destinations within the street and sidewalk network (Saelens et al., 2003). A walkability index combining objectively measured net residential density, retail floor area ratio, intersection density, and land use mix was found to be associated with increased walking (Frank et al., 2010). The applicability of the walkability index has also been shown in several settings (Leslie et al., 2007; Sundquist et al., 2011; Van Dyck et al., 2010) and it has been more strongly associated with most PA outcomes than single-environment variables (Sallis et al., 2020).

Increases in the environmental characteristics included in the walkability index, that is, street connectivity, residential density, and land use heterogeneity, have been longitudinally associated with increases in walking for transport (Bentley et al., 2018). Additionally, temporal changes in neighborhood walkability following residential relocation have been connected to changes in walking and cycling for transportation (McCormack, McLaren, Salvo, & Blackstaffe, 2017). It has also been suggested that the characteristics of bikeability are somewhat different compared to walkability, and cycling might be more responsive to bike infrastructure and network quality (Muhs & Clifton, 2016). Bikeability measures often contain urban form characteristics such as access to destinations, land use mix, and street connectivity, with additional components related to topography, bicycle infrastructure quality, and natural elements like bodies of water and green areas (Krenn, Oja, & Titze, 2015; Winters, Brauer, Setton, & Teschke, 2013; Winters, Teschke, Brauer, & Fuller, 2016).

There is extensive evidence that dense, compact, and diverse neighborhoods with proper walking and cycling infrastructure enhance active transportation
(Giles-Corti et al., 2016). As it is arguable that the need for PA is written in our DNA, one could similarly argue that the odds for adopting a physically active lifestyle are embedded in the cities’ DMA, that is, density, mixed land use and access networks. These morphological conditions encompass the same factors that comprise the concept of walkability, which can be regarded as a set of capacities of any given neighborhood concerning the densities (concentrations) of buildings and people, the mix of different functions, and the access networks that are used to navigate between them (Dovey & Pafka, 2020).

Dovey & Pafka (2020) argued that the synergies between density, mix and access (the urban DMA) are the key drivers, that could be used for understanding how cities work and guiding the design of more walkable cities. The urban DMA includes the characteristics needed for urban street-life intensity (Dovey, 2016). Walkability as an aspect of the urban DMA can be regarded as a set of interrelated and interdependent characteristics of any given neighborhood included in urban morphologies (Dovey & Pafka, 2020). It is noteworthy that each of these factors is a set of interdependent relations and difficult to define or measure (Dovey & Pafka, 2020).

Density defines the quantity of population, built form, and open space concentrated in a given area while reducing distances between people and accessible destinations (Dovey & Pafka, 2014). Initially derived from physics, density in the urban context assesses quantities such as people, floor space, buildings, or dwellings per unit area. Net density can be determined within a development site, while gross density is calculated according to the wider scale of public space. Building density is mediated by building height but also depends on the footprint of the building; similarly, population density is dependent on household and dwelling sizes (Dovey & Pafka, 2014).

Functional mix, or land use mix refers to the co-functioning of various city functions and reduces the need to travel since people and amenities are brought closer together (Dovey & Pafka, 2017). Dovey and Pafka (2017) argued that functional mix and the interconnection of these functions are the key factors that make cities work and what makes them urban in the first place, and suggested using three primary functional categories (live, work, and visit) due to the instability of multicategory systems.

Access networks are defined by street network connectivity and enable or constrain urban activity by mediating traffic flows (Pafka & Dovey, 2017). In this regard, permeability is an important concept referring to the ease of movement through a particular area and the variety of route choices between origins and
destinations. Intersection density is a widely used measure for permeability, but area-weighted average perimeter, where the block perimeter is multiplied by its area and then averaged, could bring additional benefits (Pafka & Dovey, 2017).

2.3.2 Measuring the built environment

A variety of environmental measures have been used to study the association between the BE and PA, falling into three major categories: 1) perceived measures, 2) systematic observational measures (audits), and 3) objective quantitative measures of urban form and street network assessed with geographic information systems (GIS) (Brownson, Hoehner, Day, Forsyth, & Sallis, 2009). Perceived environmental measures vary across individuals and are assessed by interviewers or self-administered questionnaires, whereas audit tools capture architectural or landscape features through direct observation (Brownson et al., 2009). GIS-based measures have a spatial reference and assess environmental characteristics derived from existing geocoded databases (Brownson et al., 2009).

Previous research literature suggests that different BE factors are associated with different PA domains (Giles-Corti et al., 2005), and other studies have identified inconsistencies with objective and perceived BE measures (Gebel, Bauman, & Owen, 2009; Gebel, Bauman, Sugiyama, & Owen, 2011). However, recent evidence indicates that GIS and self-reported BE measures could yield similar associations across different PA outcomes, indicating more comprehensive benefits of activity supportive urban planning (Sallis et al., 2020).

There are some contradictions related to measuring BE. First of all, defining a home neighborhood is not straightforward, and three main classifications have been utilized to study the associations between the BE and health: administrative units, circular buffers, and road network buffers (Mavoa et al., 2019). As the result might differ depending on the definition, careful consideration is necessary when evaluating the suitability of these boundaries and their geographical scale (Mavoa et al., 2019). Still, no ideal definition of a neighborhood has been established. Considering the PA recommendations, it has been argued that a roughly 10–15-minute walk could be utilized as the boundary to study neighborhood effects on PA (Giles-Corti et al., 2005). Various buffer sizes have been examined, but most consistent associations emerged with 800-m and 1,000-m road network buffers (Mavoa et al., 2019). Moreover, internationally generalizable evidence demonstrates that even if the BE measure values differ significantly across different
road network buffering methods, their association with PA outcomes tend to remain similar (Frank et al., 2017).

Second, the BE correlates of PA are generally assessed within the neighborhood, but studies have revealed that a large proportion of PA is undertaken outside of the home neighborhood (Hillsdon, Coombes, Griew, & Jones, 2015). Hence, activity space approaches have gained popularity to more dynamically capture exposure to different environments according to the locations where an individual has spent time (Hasanzadeh, Broberg, & Kytta, 2017; Smith, Foley, & Panter, 2019). This is important because the characterization of neighborhoods close to home might fail to capture all environmental influences on PA (Hillsdon et al., 2015). Current evidence suggests that transportation mode is a central dimension of activity spaces that can be defined according to size, activity intensity, trip volume, exteriority, polycentricity, elongation, and destination specialization (Hasanzadeh et al., 2019). Moreover, there is individual variation in activity spaces due to socio-demographic characteristics such as age, gender, employment, household characteristics, and residential neighborhood (Hasanzadeh et al., 2019).

2.3.3 Built environment factors as predictors of physical activity

Transportation research literature has consistently associated neighborhood environmental factors with active transportation (Sallis, Frank, Saelens, & Kraft, 2004). According to early studies in the PA field, BE factors such as destination accessibility, sidewalks, the connectivity of trails, aesthetic attributes, and perceptions of traffic have consistently correlated with PA behavior (Humpel, Owen, & Leslie, 2002; Wendel-Vos, Droomers, Kremers, Brug, & van Lenthe, 2007), particularly walking (Owen, Humpel, Leslie, Bauman, & Sallis, 2004). Studies utilizing more advanced research designs, such as quasi-experiments and cross-sectional studies adjusted for neighborhood self-selection, have illuminated that land use mix, street network connectivity, population density, and overall neighborhood design are possible determinants of PA and transportation-related walking among adults (McCormack & Shiell, 2011). The role and domain specificity of functional, aesthetic, destination, and safety characteristics have also been emphasized in qualitative studies assessing the BE’s impacts on PA (Salvo, Lashewicz, Doyle-Baker, & McCormack, 2018).

For children and adolescents, transport infrastructure such as sidewalks, controlled intersections, and access to public transportation have been supportive correlates of PA (Davison & Lawson, 2006), in addition to objectively measured
walkability, traffic speed/volume, access to recreational facilities, land use mix, and residential density among youth (Ding, Sallis, Kerr, Lee, & Rosenberg, 2011). Moreover, the availability of backyard space and outdoor equipment seem supportive of overall PA among preschool children, whereas PA programs, equipment within schools, and neighborhood safety features have been suggested as more important factors for school children and adolescents (Carlin et al., 2017). For older adults, perceived environmental factors such as crime, traffic safety, and access to facilities were recognized as important predictors of PA initiation and maintenance (van Stralen, De Vries, Muddie, Bolman, & Lechner, 2009). Moreover, neighborhood factors such as residential density, walkability, street connectivity, overall access to destinations/services, land use mix, and pedestrian-friendly features have been positively associated with older adults’ transportation-related walking, whereas littering, vandalism, and decay were constraining factors (Cerin et al., 2017).

There is further evidence of the natural environment’s impact on PA. Previous studies have suggested that the quality and accessibility of urban green space is connected to its use for PA (Lee & Maheswaran, 2011), while access to parks has provided mixed results (Bancroft et al., 2015). Changes in urban greenspace seem a more promising strategy to support PA when combined with PA programs (Hunter et al., 2015).

Overall, the most consistent associations between the BE and active transportation have been related to density, street connectivity, land use mix, and non-residential destinations (Bird et al., 2018; McCormack & Shiell, 2011; Saelens & Handy, 2008). Both perceived and objectively assessed BE factors related to population density, street connectivity, and land use diversity have been positively associated with walking and cycling for transportation globally (Christiansen et al., 2016; Kerr et al., 2016). In addition to these characteristics, perceived environmental measures related to aesthetics, safety, and distance to destinations seem supportive of transportation-related walking and cycling (Kerr et al., 2016). Moreover, youth active travel has been found to positively associate with social interactions, assisting facilities, neighborhood urban form characteristics, shorter route length, and road safety (Panter, Heinen, Mackett, & Ogilvie, 2016).

In terms of recreational and leisure time physical activity (LTPA), environmental aesthetic features and access to recreational facilities are supportive factors (Sugiyama, Leslie, Giles-Corti, & Owen, 2009; Van Dyck et al., 2013), but findings on the associations between traffic safety, crime, and PA have been inconsistent (Bracy et al., 2014; Foster & Giles-Corti, 2008). However, there is
some evidence implying that the factors associated with transportation-related physical activity (TPA) might be beneficial as well regarding LTPA behavior (Sallis et al., 2020). Recent evidence also indicates that the behavioral responses to diverse BE are relatively stable across different countries, which tells that these impacts could be generalizable across the globe (Sallis et al., 2020).

Accordingly, policy approaches encompassing creating and improving access to places for PA, community- and street-scale urban design, land use, active transport policy and practices, and community-wide policies have been suggested as targets for intervention strategies (Heath et al., 2012). Moreover, interventions focusing on destination accessibility, employment distribution, parking policies, pedestrian- and cycling-friendly street networks, residential density, public transportation accessibility, mixed land use, and the desirability of active travel modes have been recommend to implement to increase walking, cycling, and public transportation modal shares, and reduce private motor vehicle use (Giles-Corti et al., 2016). In turn, these intervention strategies could enable the development of more sustainable compact cities and limit diabetes, CVD, and respiratory diseases (Stevenson et al., 2016). However, even though community- and street-scale urban design and land use policies have been found to support PA at the population level, the level of this evidence remains low (Puggina et al., 2018).

Literature on built environments and physical activity is growing rapidly but there are some major gaps. The evidence of the association between the BE and PA primarily emanates from cross-sectional studies, meaning studies with better research designs that account for temporal order are needed to assess the issues of residential self-selection and causation (Ding & Gebel, 2012; Ding et al., 2018; McCormack & Shiell, 2011). To strengthen the evidence for more successful policy implementation, natural experiments follow one design that can assess the impact of changes in land use or infrastructure, while prospective longitudinal designs are advised to examine the impact of residential relocation (van de Coevering et al., 2015). A recent study indicated a paucity of research and less consistent results in residential relocation context (Ding et al., 2018).

In terms of residential relocation studies, it is important to consider factors related to age, family status, quality of life, and the timing of life events because previous studies have suggested that they are highly interconnected (Geist & McManus, 2008). The key life events and subsequent residential relocation choices have also been shown to associate with car ownership and travel behavior (Scheiner & Holz-Rau, 2013). Moreover, it is important to acknowledge that also people who
do not change residential location may be exposed to different environmental characteristics over time due to gradual changes in the BE factors.

It is not fully understood to what degree the different BE measures apply to different populations and settings, and it is possible that barriers and facilitators vary by age, socioeconomic factors, and culture (Brownson et al., 2009; Smith et al., 2017). Additionally, there remains a limitation in understanding associations between the BE and cycling behavior (Smith et al., 2017).

Finally, a gap between research and practice requires the better use of science to guide urban planning processes (Giles-Corti et al., 2015; Sallis, Bull, Burdett et al., 2016). Existing research literature suggests that context-specific, local, policy-relevant evidence on the implementation of local policies is necessary for evidence-based policy making and successful research translation, which is dependent on cooperation with fields beyond PA and health, such as urban and transportation planning, finance, parks and recreation, and environmental protection (Giles-Corti et al., 2015; Hooper et al., 2019).
3  Aims of the study

The overall aim of this study was to examine the BE as a determinant of PA. The specific objectives were:

1. To identify the longitudinal BE determinants of PA and evaluate how changes in the BE are associated with changes in PA (I).
2. To model residential relocation trajectories and assess the longitudinal association between neighborhood DMA and self-reported regular walking and cycling from 31 to 46 years of age (II).
3. To generate local policy-relevant information by integrating land use and transportation policies with urban form and transportation modal share development in the Finnish city of Oulu from 1998 to 2016 (III).
4 Materials and methods

4.1 Study design

This study utilized a longitudinal research design. First, previous longitudinal studies and natural experiments were reviewed (I). Second, a population-based prospective birth cohort study was conducted (II). Finally, a mixed-methods study was conducted that combined both a qualitative longitudinal document analysis and a quantitative analysis of urban form development and its association with transportation modal share development (III).

4.2 Materials

4.2.1 Literature review (I)

Six electronic databases (Medline, PubMed, Scopus, Web of Science, Transportation Research Information Services, and Active Living Research) were searched from each database’s inception until December 11, 2015 for prospective cohort studies that assess residential relocation and natural experiments focusing on changes in the BE such as infrastructural improvements. The search terms for PA included physical activity, active transportation, walking, bicycling, motor activity, and exercise, while for the BE, neighborhood, physical environment, built environment, walkability, environment design, environment, and cities were used. In terms of study design, the terms included longitudinal studies, cohort studies, follow-up studies, natural experiments, causality, residential relocation, and neighborhood self-selection. The Medline search strategy is presented in Appendix 1. The studies were considered eligible if they assessed changes in both the BE and PA between baseline and follow-up, were written in English, and were published in peer-reviewed journals. Moreover, participants of the eligible studies had to represent a general population of all ages.

The literature search produced 4,335 articles, and 35 publications were identified through reference lists from relevant publications. After screening their titles and abstracts, 4,101 studies were excluded because they were out of scope. Searches and title and abstract screenings were conducted by the first author. For inclusion, full texts (n = 111) were screened by at least three review authors. Disagreements were resolved through discussion. Finally, 51 articles were deemed
eligible, of which 20 were prospective cohort studies and 31 were natural experiments. Data from the included studies were extracted according to the following items: methods, participants, exposures, and main results.

4.2.2 Northern Finland Birth Cohort 1966 — NFBC1966 (II)

The Northern Finland Birth Cohort Studies is an epidemiological and longitudinal research program aiming to promote population health by providing prospective data to study genetic, biological, social, behavioral, and environmental disease risk factors (University of Oulu, 1966). The NFBC1966 comprises all people born in 1966 (N = 12,058) from Finland’s the two northernmost provinces (Oulu and Lapland). The cohort has been prospectively observed by means of interviews, postal questionnaires, and clinical measurements in follow-ups at the age of 1, 14, 31, and 46 years. The original data were supplemented by various hospital records and national register data. Data were used from the 5,974 participants who attended the follow-ups at 31 and 46 years, conducted in 1997 and 2012, respectively.

4.2.3 The Finnish National Travel Survey (III)

Transportation modal share data were derived from the four most recent Finnish National Travel Surveys (years 1998, 2004, 2010, and 2016), which are repeated independent cross-sectional studies that have been conducted every six years since 1974 and provide an overview of Finns’ mobility and demographic, regional, and temporal variations of trips (Finnish Transport Agency, 2012, 2018b; Ministry of Transport and Communications, 1999, 2006). In all surveys, a travel diary was utilized to record the participants’ detailed travel information (all trips, time, primary travel mode, destination, and purpose of the trip) within 24 hours, including background information such as sociodemographic factors. The 2016 survey was a multimode survey, and the participants were able to respond by phone, online, or mail, but in the previous surveys, only telephone interviews were used to collect the data. The participants’ places of residence were available according to postal code areas in all the surveys. All Finns above 6 years old were eligible for the surveys, except for citizens living in Åland and those in institutional care. Each survey was conducted within one year and included random samples defined by the Finnish Population Register Center. Participants sampled from Oulu were included in this study (1998: n = 271, 2004: n = 342, 2010: n = 417, 2016: n = 1,568).
4.2.4 Urban form and street network data (II and III)

Urban form data were derived from the Finnish Community Structure Grid Database from the years 2000, 2002, 2003, 2005, and 2007–2016 (Statistics Finland, 2020). The database provides nationally and temporally comparable information for longitudinally analyzing the urban form. It is based on 250 m * 250 m grids and includes variables related to population structure, educational structure, households, buildings, dwellings, workplaces, stores, employment, and income (Statistics Finland, 2020). For the majority of the variables, information since 1990 is available, but population numbers specifically have been followed since 1980.

Street network data from 2005, 2010, 2012, and 2015 was derived from the Finnish National Road and Street Database (Digiroad), which contains the geometric and attribute data of the national road and street network and has been available since 2004 (Finnish Transport Agency, 2018a). The data consists of center line geometry for the transport network, traffic-related attribute data, and other transport system objects, and covers vehicle-accessible roads, railways, and separate pedestrian and cycling routes. The attribute data contains information on traffic elements, as well as the restrictions, limits, and other features of the road and street network (Finnish Transport Agency, 2018a).

4.2.5 Land use and transportation policy documents (III)

Community and transportation planning policy documents that were approved by the Oulu city council or city government were derived from Oulu’s the web pages and archives for the period 1998–2016. Overall, 4 city strategies (1999, 2001, 2005 and 2013), 2 transportation strategies (2003 and 2013), 12 land use strategies (2001, 2003, 2004, 2005, 2007, 2009, 2011, 2012, 2013 and 2016), and 3 environmental strategies (years 2001, 2005, and 2014) were included. The city strategy, which is a declaration of the political intent of the city council, is the basis of Oulu’s strategic control system. The environmental program guides the implementation of community structure goals related to sustainability according to the city strategy. The land use masterplan is a long-term legal strategy document that guides the city’s development over the next 10 years according to land use, urban structure, and the integration of functions, whereas the land use program guides the implementation of these goals. Transportation strategies present the objectives and processes for developing the region’s transportation system.
4.3 Methods

4.3.1 Exposure and outcome variables

Exposure variables

In study I, changes in both perceived and objective (measured with GIS) factors related to the residential environment were used as the main exposures. Change was assessed by means of moving between different kinds of residential environments or the development of neighborhood- or town-level infrastructure.

For studies II and III, urban form DMA was used as the main exposure and assessed with ArcGIS 10.3 (II) and QGIS 3.10.0 (III). In study II, the residential coordinates of all participants in the NFBC1966 from 31 to 46 years old were obtained from the Digital and Population Data Services Agency. A 1-km circular buffer surrounding the residential locations was used to assess neighborhood DMA for each year from 31 to 46 years by combining population density, number of destinations (retail, recreation, office, and community institutions), and intersection density. The closest available year for which data were available was used to link residential coordinates and geographical data with a maximum difference of 2 years.

In study III, participants’ residential locations were available according to postal code areas, so the exposure variables related to urban form were also measured according to the Oulu’s postal code areas for each year from 1998 to 2016. In terms of density, floor area ratio (total floor area/site area), residents per hectare, and jobs per hectare were calculated. An entropy score assessed land use mix (Song, Merlin, & Rodriguez, 2013), and access networks were calculated according to the number of intersections per hectare.

In studies II and III, the variables related to density, land use mix, and access networks were standardized using z-scores by subtracting the variable mean and dividing the centered value by the variable standard deviation (SD). They were then combined into a DMA score for statistical analyses.

Outcome variables

In study I, change in the self-reported or device-based measurements of overall PA, TPA, and LTPA were used as the main outcomes. Studies with diverse outcome
measures, such as walking, cycling, jogging, exercise, MVPA, and travel mode, were included.

In study II, the main outcomes were self-reported regular walking and cycling, as assessed with an identical question at 31 and 46 years: “How often are you engaged in the following kinds of physical activities? Choose the alternative that best represents the average situation during the previous year.” Response alternatives for walking and cycling were assigned to a 6-point Likert scale (1 = not at all, 2 = once a month or less, 3 = two to three times a month, 4 = once a week, 5 = two to three times a week, and 6 = four times a week or more). Both outcomes were coded as binary variables, with four times a week or more indicating regularity based on contemporary recommendations for adult PA (at least 150 minutes of moderate-intensity aerobic PA throughout the week; World Health Organization, 2010).

In study III, travel information within 24 hours was assessed with a travel diary. A trip was defined as moving from one place to any given location outside the home yard. The trip to the destination and the trip back from the destination were considered two separate trips. The main outcome was each trip’s transportation mode, as stratified into five categories: 1 = walking, 2 = cycling, 3 = public transportation, 4 = car, and 5 = other.

Confounding variables

In studies II and III, sociodemographic and socioeconomic variables including sex, age, education, employment, marital status, and having children under 18 years old were selected as potential confounders. Previously, these factors have been associated with PA and residential location, and it has thus been suggested that they can account for residential self-selection (Næss, 2014; van de Coevering et al., 2015).

4.3.2 Statistical analyses

R versions 3.5.0 (II) and 3.6.2 (III) were used for statistical analyses (R Core Team, 2018). In study II, sequence analysis was conducted with TraMineR to model residential relocation trajectories and subsequently cluster participants into distinct groups according to those trajectories (Gabadinho, Ritschard, Mueller, & Studer, 2011). TraMineR is an R package for mining and visualizing sequences of categorical data that describes life courses, and the analysis was comprised of
defining sequences, measuring dissimilarities between them, and categorizing sequential patterns into clusters. This method was shown to produce similar life course typologies to latent class analysis (Han, Liefbroer, & Elzinga, 2017; Mikolai & Lyons-Amos, 2017).

First, the DMA score was categorized into quintiles that were then assigned to each follow-up year from 1997 to 2012 for each subject. The Hamming distance (Hamming, 1950) was next used to measure distances between sequences and conduct sequence dissimilarity matrices, which were grouped with fastcluster using the Ward agglomerative hierarchical clustering method (Muellner, 2013). Finally, to test whether the number of study participants who started regular walking or cycling during the follow-up differed across clusters, Fisher’s exact test with odds ratio (OR) was employed.

Random effects can be used to encompass variation among individuals when multiple responses are measured per individual, and generalized linear mixed models (GLMM) are regarded as the best tool to analyze non-normal data including random effects (Bolker et al., 2009). Hence, GLMMs (II and III) were used to examine the statistical significance of the longitudinal association between urban form and PA. Exposure (DMA score) was used as both a continuous variable (II and III) and an ordinal variable categorized into three classes (III). The outcome variables walking and cycling (II) and transportation modes (III) were coded as binary variables, and the association of urban form development to each outcome was assessed in separate models. The models were adjusted for sociodemographic factors. In study II, these included sex (male, female), education (higher education, vocational/secondary/basic education), children under 18 years living in the home (yes, no), and marital status (married/de facto relationship, single/divorced/widowed), which were assessed with identical questions at 31 and 46 years of age. In study III, the models were adjusted for age (continuous), sex (male, female), and employment (employed, outside workforce), which were also assessed with identical questions in all surveys.

The GLMMs in studies II and III were run with the lme4 package using binomial distribution with a logit link function (Bates, Maechler, Bolker, & Walker, 2015). Model fitting was based on maximum likelihood, fixed effects predictors were estimated with Laplace approximation, and the Wald test was used to test their significance. In study II, subject served as the random intercept due to the longitudinal data structure. In study III, the data included observations of different cross sections across time and multiple measures per subject (all trips in 24 hours); accordingly, the models’ random effect structure was defined to include year as a
fixed effect, and random variation was allowed in the intercept among the subjects in each study year. Effect sizes were presented with OR and 95% confidence intervals (CI).

Moreover, in study III, post-stratification weights were used in the modal share analysis, as the sample sizes were relatively small and might not be representative of the population. The weights were calculated based on population, age, and sex distributions in Oulu according to each study year using the rake function in the survey package, which uses iterative post-stratification to match marginal distributions of a survey sample to known population margins (Lumley, 2004).

4.3.3 Qualitative methods

The review (I) followed the PRISMA statement guidelines (Moher, Liberati, Tetzlaff, Altman, & PRISMA Group, 2009). Due to study heterogeneity and the diversity of exposure and outcome measures, narrative synthesis was selected for the method of analysis. The resulting BE categories were formed inductively from the studies, which included combining all measures into a single table and then thematically combining similar measures into categories stratified by PA domain (overall, transport, and leisure time). The individual studies’ risk of bias were assessed with the QualSyst tool, which was selected because of its flexibility in assessing different study designs (Kmet, Lee, & Cook, 2004). The risk of bias was evaluated with a summary score according to the following criteria: objective, study design, method of participant selection, use of control group if applicable, participant characteristics, intervention allocation and blinding if applicable, definition of exposure and outcome measures, sample size, analytic methods, estimate of variance, control for confounding, follow-up time, loss to follow-up, and reporting results and conclusions.

In study III, document analysis was used to interpret the land use and transportation policies (Bowen, 2009), an iterative process involving elements of qualitative content and thematic analysis to organize the information into emerging themes (Bowen, 2009; Fereday & Muir-Cochrane, 2006). Thus, identifying the major community planning themes was an inductive process derived empirically from the documents. The analysis involved reading and re-reading the documents, coding text into categories to reveal data patterns and pertinent themes, and analyzing the urban form policy development according to these themes. First, all coded information was combined into a timeline from the baseline to follow-up endpoint according to policy document areas (city strategy, land use, transportation,
and environment). Then, all information was thematically combined into categories and analyzed accordingly. Finally, the findings of the document analysis were used to triangulate the results of the quantitative urban form analysis by searching for convergence and correspondence.
5 Results

5.1 Longitudinal associations between the built environment and physical activity (I)

There were 51 studies eligible for the review, of which 20 were prospective cohort studies and 31 were natural experiments. The population sizes in the included studies ranged from 32 to 1,300,000 participants, and most of the studies focused on adults. On average the participants were followed up for 3.7 years. All studies were conducted in high-income countries. PA was measured with activity monitors in five studies, systematic observations were used in nine studies, and 34 studies assessed PA with self-reports. Three studies used both questionnaires and activity monitors. GIS was used to assess BE features in 30 studies.

The review results showed that changes in some of the objectively assessed BE characteristics were associated with changes in PA (Fig. 2). A higher objective destination and public transport access, and land use mix were associated with increased overall PA and TPA. Regarding TPA, the strongest evidence was found for the number of destinations. Similar results were obtained from natural experiments concerning the creation of new infrastructure for walking, cycling, and public transportation. Majority of the associations concerned overall PA and TPA, and the most consistent findings were related to the creation of new walking and cycling trails.

In terms of perceived BE, aesthetics and safety were associated with changes in PA in a few studies (Fig. 3). More specifically, pleasantness and positive neighborhood features were associated with all PA domains, and neighborhood safety seemed to support overall PA and LTPA. Additionally, perceived destination and public transit accessibility were associated with TPA in one study.
### Fig. 2. Associations between objective BE measures and PA.

Characters in the cells: O = objectively measured physical activity, S = self-reported physical activity, Quality score = Quality score, N = Sample size.

<table>
<thead>
<tr>
<th>Objective BE measures</th>
<th>PA domains (number of studies)</th>
<th>Number of associations obtained from different studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>New infrastructure for walking, cycling, and public transport (routes for walking and cycling, rail infrastructure, bike parking, street improvements)</td>
<td>Overall PA (n=11)</td>
<td>![Table content]</td>
</tr>
<tr>
<td></td>
<td>Transport PA (n=3)</td>
<td>![Table content]</td>
</tr>
<tr>
<td></td>
<td>Leisure time PA (n=8)</td>
<td>![Table content]</td>
</tr>
<tr>
<td>Accessibility (number of destinations, land use, public transport availability, sport facility availability, distance to parks)</td>
<td>Overall PA (n=4)</td>
<td>![Table content]</td>
</tr>
<tr>
<td></td>
<td>Transport PA (n=6)</td>
<td>![Table content]</td>
</tr>
<tr>
<td></td>
<td>Leisure time PA (n=4)</td>
<td>![Table content]</td>
</tr>
<tr>
<td>Park and playground improvements (connective, new equipment)</td>
<td>Overall PA (n=5)</td>
<td>![Table content]</td>
</tr>
<tr>
<td></td>
<td>Transport PA</td>
<td>![Table content]</td>
</tr>
<tr>
<td></td>
<td>Leisure time PA (n=4)</td>
<td>![Table content]</td>
</tr>
<tr>
<td>Street network characteristics (street connectivity, road characteristics)</td>
<td>Overall PA (n=4)</td>
<td>![Table content]</td>
</tr>
<tr>
<td></td>
<td>Transport PA (n=3)</td>
<td>![Table content]</td>
</tr>
<tr>
<td></td>
<td>Leisure time PA (n=4)</td>
<td>![Table content]</td>
</tr>
<tr>
<td>Density (population density, employment, and service/ job density)</td>
<td>Overall PA (n=3)</td>
<td>![Table content]</td>
</tr>
<tr>
<td></td>
<td>Transport PA (n=4)</td>
<td>![Table content]</td>
</tr>
<tr>
<td></td>
<td>Leisure time PA (n=4)</td>
<td>![Table content]</td>
</tr>
<tr>
<td>Aggregate walkability measures (walkability index, walk score, travel times)</td>
<td>Overall PA (n=4)</td>
<td>![Table content]</td>
</tr>
<tr>
<td></td>
<td>Transport PA</td>
<td>![Table content]</td>
</tr>
<tr>
<td></td>
<td>Leisure time PA (n=4)</td>
<td>![Table content]</td>
</tr>
<tr>
<td>Other (social location, crime, landscape diversity)</td>
<td>Overall PA (n=1)</td>
<td>![Table content]</td>
</tr>
<tr>
<td></td>
<td>Transport PA</td>
<td>![Table content]</td>
</tr>
<tr>
<td></td>
<td>Leisure time PA (n=1)</td>
<td>![Table content]</td>
</tr>
</tbody>
</table>
Fig. 3. Associations between perceived BE measures and PA. Characters in the cells: O = objectively measured physical activity, S = self-reported physical activity, Quality score ∈ [1, 5], N = Sample size.
5.2 The associations of residential relocation trajectories and neighborhood DMA with regular walking and cycling (II)

At the 31-year follow-up study, 5,947 subjects of the NFBC1966 participated in the clinical examination and completed the survey questionnaires. At the 46-year follow-up study, data were obtained from 4,006 (67.4%) participants. The participants’ characteristics are presented in Table 1. There were 1,941 individuals lost to the follow-up who were more likely male, not living in a relationship, reported lower self-rated health, and did not have children.

Table 1. The NFBC1966 participant characteristics at 31 (n = 5,947) and 46 (n = 4,006) years old.

<table>
<thead>
<tr>
<th>Variable</th>
<th>31 years, n (%)</th>
<th>46 years, n (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sex</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>3,096 (52.1)</td>
<td>2,261 (56.4)</td>
</tr>
<tr>
<td>Male</td>
<td>2,851 (47.9)</td>
<td>1,745 (43.6)</td>
</tr>
<tr>
<td><strong>Body mass index</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>24.7 (4.2)</td>
<td>26.8 (4.8)</td>
</tr>
<tr>
<td><strong>Household income</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>35,424 (29,509)</td>
<td>60,000 (34,497)</td>
</tr>
<tr>
<td><strong>Education</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Higher education</td>
<td>685 (11.7)</td>
<td>984 (26.6)</td>
</tr>
<tr>
<td>Vocational/secondary/basic education</td>
<td>5,176 (88.3)</td>
<td>2,747 (73.4)</td>
</tr>
<tr>
<td><strong>Marital status</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Married/de facto relationship</td>
<td>4,269 (72.5)</td>
<td>3,019 (78.9)</td>
</tr>
<tr>
<td>Single/divorced/widowed</td>
<td>1,617 (27.5)</td>
<td>806 (21.1)</td>
</tr>
<tr>
<td><strong>Children &lt; 18 years at home</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3,555 (62.8)</td>
<td>2,572 (73.7)</td>
</tr>
<tr>
<td><strong>Employment</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Employed</td>
<td>3,710 (63.2)</td>
<td>3,374 (88.4)</td>
</tr>
<tr>
<td>Not in workforce</td>
<td>2,160 (36.8)</td>
<td>444 (11.6)</td>
</tr>
<tr>
<td><strong>Self-rated health</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Good</td>
<td>3,901 (66.4)</td>
<td>2,564 (67.3)</td>
</tr>
<tr>
<td>Poor</td>
<td>1,978 (33.6)</td>
<td>1,245 (32.2)</td>
</tr>
<tr>
<td><strong>Neighborhood DMA</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.36 (2.98)</td>
<td>-0.09 (2.54)</td>
</tr>
<tr>
<td><strong>Regular walking</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>711 (12.6)</td>
<td>739 (18.8)</td>
</tr>
<tr>
<td><strong>Regular cycling</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>882 (15.7)</td>
<td>437 (11.1)</td>
</tr>
</tbody>
</table>

Mean (SD)

The DMA score values ranged from -2.62 to 19.87. The clustered residential relocation trajectories based on sequence analysis are presented in Fig. 4.
Fig. 4. Sequence analysis representing clustered residential relocation trajectories based on neighborhood DMA quintiles from 31 to 46 years of age (n = 5,947).
Clusters where neighborhood DMA remained stable featured over four out of five participants, whereas 5% of the participants relocated into a neighborhood with increased DMA and 12% to a neighborhood with decreased DMA during the follow-up. Clusters with higher DMA scores included more participants who were female, spouseless, had higher education, and did not have children. On the contrary, self-rated health was lowest in clusters with the lowest DMA scores.

Relocating to a neighborhood with higher DMA was associated with starting to walk and bike regularly (Table 2). The trajectory from the lower to the highest neighborhood DMA quintile in cluster 6 was associated with increased odds of starting regular walking (OR 3.15; 95% CI: 1.50, 7.14; p = 0.001) and cycling (OR 2.63; 95% CI: 1.23, 5.79; p = 0.009), as compared to participants with trajectories from higher to lower neighborhood DMA levels in clusters 8 and 9. Moreover, remaining in the lowest DMA quintile was associated with decreased odds of starting to regularly walk (OR 0.53; 95% CI: 0.33, 0.84; p = 0.004) and cycle (OR 0.30; 95% CI: 0.16, 0.59; p < 0.001), as compared to relocating from the lower to highest DMA neighborhoods. In contrast, the participants who remained in the highest DMA quintile throughout the follow-up period were more likely to start regularly walking than those who stayed in very low DMA neighborhoods (OR 1.52; 95% CI: 1.06, 2.18; p = 0.020) or relocated from the higher to lowest DMA quintile (OR 2.53; 95% CI: 1.28, 5.44; p = p < 0.01).

As shown in Table 3, a one-unit increase in the neighborhood DMA score was associated with a 3% increase in regular walking (OR 1.03; 95% CI: 1.00, 1.05; p = 0.023) and a 17% increase in regular cycling (OR 1.17; 95% CI: 1.12, 1.23; p < 0.001). The association between neighborhood DMA and regular cycling decreased but remained statistically significant (OR 1.13; 95% CI: 1.07, 1.19; p < 0.001) after adjusting for sex, education, children under 18 years of age living at home, and marital status. Intersection density was the neighborhood DMA component with the greatest effect size for both walking (OR 1.12; 95% CI: 1.04, 1.19; p = 0.001) and cycling (OR 1.87; 95% CI: 1.63, 2.13; p < 0.001).
Table 2. Associations of starting regular walking and cycling (in bold) between different clusters (OR, 95% CI).

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Cluster 1</th>
<th>Cluster 2</th>
<th>Cluster 3</th>
<th>Cluster 4</th>
<th>Cluster 5</th>
<th>Cluster 6</th>
<th>Cluster 7</th>
<th>Cluster 8</th>
<th>Cluster 9</th>
<th>Cluster 10</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cluster 1</strong></td>
<td>1.17</td>
<td>1.31</td>
<td>0.94</td>
<td>1.52</td>
<td>0.80</td>
<td>1.29</td>
<td>0.92</td>
<td>2.53</td>
<td>0.80</td>
<td>1.29</td>
</tr>
<tr>
<td></td>
<td>(0.81, 1.69)</td>
<td>(0.92, 1.84)</td>
<td>(0.71, 1.35)</td>
<td>(1.06, 2.18)</td>
<td>(0.51, 1.29)</td>
<td>(0.71, 2.49)</td>
<td>(0.56, 1.53)</td>
<td>(1.28, 5.44)</td>
<td>(0.13, 1.65)</td>
<td></td>
</tr>
<tr>
<td><strong>Cluster 2</strong></td>
<td>0.87</td>
<td>1.12</td>
<td>0.84</td>
<td>1.30</td>
<td>0.68</td>
<td>1.11</td>
<td>0.78</td>
<td>2.15</td>
<td>0.80</td>
<td>1.29</td>
</tr>
<tr>
<td></td>
<td>(0.54, 1.40)</td>
<td>(0.79, 1.57)</td>
<td>(0.60, 1.15)</td>
<td>(0.91, 1.86)</td>
<td>(0.43, 1.10)</td>
<td>(0.61, 2.12)</td>
<td>(0.48, 1.31)</td>
<td>(1.10, 4.64)</td>
<td>(0.11, 1.40)</td>
<td></td>
</tr>
<tr>
<td><strong>Cluster 3</strong></td>
<td>1.16</td>
<td>1.32</td>
<td>0.75</td>
<td>1.16</td>
<td>0.61</td>
<td>0.99</td>
<td>0.70</td>
<td>1.93</td>
<td>0.80</td>
<td>1.29</td>
</tr>
<tr>
<td></td>
<td>(0.72, 1.85)</td>
<td>(0.86, 2.05)</td>
<td>(0.56, 1.01)</td>
<td>(0.83, 1.63)</td>
<td>(0.39, 0.97)</td>
<td>(0.55, 1.88)</td>
<td>(0.44, 1.15)</td>
<td>(0.99, 4.11)</td>
<td>(0.10, 1.25)</td>
<td></td>
</tr>
<tr>
<td><strong>Cluster 4</strong></td>
<td>1.36</td>
<td>1.56</td>
<td>1.18</td>
<td>1.56</td>
<td>0.82</td>
<td>1.32</td>
<td>0.94</td>
<td>2.58</td>
<td>0.80</td>
<td>1.29</td>
</tr>
<tr>
<td></td>
<td>(0.84, 2.18)</td>
<td>(1.00, 2.42)</td>
<td>(0.76, 1.81)</td>
<td>(1.14, 2.14)</td>
<td>(0.54, 1.27)</td>
<td>(0.75, 2.48)</td>
<td>(0.60, 1.52)</td>
<td>(1.35, 5.44)</td>
<td>(0.14, 1.66)</td>
<td></td>
</tr>
<tr>
<td><strong>Cluster 5</strong></td>
<td>2.36</td>
<td>2.71</td>
<td>2.04</td>
<td>1.74</td>
<td>0.53</td>
<td>0.85</td>
<td>0.60</td>
<td>1.66</td>
<td>0.78</td>
<td>1.31</td>
</tr>
<tr>
<td></td>
<td>(1.35, 4.20)</td>
<td>(1.60, 4.70)</td>
<td>(1.21, 5.52)</td>
<td>(1.02, 2.99)</td>
<td>(0.33, 0.84)</td>
<td>(0.47, 1.62)</td>
<td>(0.37, 0.10)</td>
<td>(0.85, 3.55)</td>
<td>(0.09, 1.08)</td>
<td></td>
</tr>
<tr>
<td><strong>Cluster 6</strong></td>
<td>0.71</td>
<td>0.82</td>
<td>0.61</td>
<td>0.52</td>
<td>0.30</td>
<td>1.61</td>
<td>1.15</td>
<td>3.15</td>
<td>0.54</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.39, 1.34)</td>
<td>(0.46, 1.50)</td>
<td>(0.35, 1.12)</td>
<td>(0.29, 0.96)</td>
<td>(0.16, 0.59)</td>
<td>(0.82, 3.29)</td>
<td>(0.64, 2.06)</td>
<td>(1.50, 7.14)</td>
<td>(0.16, 2.13)</td>
<td></td>
</tr>
<tr>
<td><strong>Cluster 7</strong></td>
<td>0.89</td>
<td>1.01</td>
<td>0.76</td>
<td>0.65</td>
<td>0.38</td>
<td>1.24</td>
<td>0.71</td>
<td>1.94</td>
<td>0.54</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.42, 1.99)</td>
<td>(0.46, 1.50)</td>
<td>(0.35, 1.12)</td>
<td>(0.29, 0.96)</td>
<td>(0.16, 0.59)</td>
<td>(0.82, 3.29)</td>
<td>(0.64, 2.06)</td>
<td>(1.50, 7.14)</td>
<td>(0.16, 2.13)</td>
<td></td>
</tr>
<tr>
<td><strong>Cluster 8</strong></td>
<td>1.00</td>
<td>1.15</td>
<td>0.87</td>
<td>0.74</td>
<td>0.43</td>
<td>1.41</td>
<td>1.14</td>
<td>2.75</td>
<td>0.47</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.50, 2.12)</td>
<td>(0.59, 2.39)</td>
<td>(0.45, 1.79)</td>
<td>(0.38, 1.53)</td>
<td>(0.20, 0.93)</td>
<td>(0.64, 3.21)</td>
<td>(0.44, 2.86)</td>
<td>(1.27, 6.34)</td>
<td>(0.14, 1.88)</td>
<td></td>
</tr>
<tr>
<td><strong>Clusters 8 and 9</strong></td>
<td>1.87</td>
<td>2.15</td>
<td>1.61</td>
<td>1.38</td>
<td>0.79</td>
<td>2.63</td>
<td>2.11</td>
<td>NA</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.97, 3.83)</td>
<td>(1.14, 4.30)</td>
<td>(0.87, 2.72)</td>
<td>(0.73, 2.75)</td>
<td>(0.39, 1.68)</td>
<td>(1.23, 5.79)</td>
<td>(0.84, 5.18)</td>
<td>(0.04, 0.76)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Clusters in rows serve as reference categories for starting regular walking, and clusters in columns serve as reference categories for starting regular cycling.

1 p < 0.05, 2 p < 0.01, 3 p < 0.001
Table 3. Association between changes in neighborhood DMA and its components and changes in regular walking and cycling (OR, 95% CI).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Regular walking</th>
<th></th>
<th>Regular cycling</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crude model</td>
<td>Adjusted model</td>
<td>Crude model</td>
<td>Adjusted model</td>
</tr>
<tr>
<td>Neighborhood DMA</td>
<td>1.03 (1.00, 1.05)</td>
<td>1.01 (0.98, 1.04)</td>
<td>1.17 (1.12, 1.23)</td>
<td>1.13 (1.07, 1.19)</td>
</tr>
<tr>
<td>Population density</td>
<td>1.06 (0.99, 1.13)</td>
<td>1.00 (0.93, 1.08)</td>
<td>1.36 (1.21, 1.53)</td>
<td>1.24 (1.09, 1.42)</td>
</tr>
<tr>
<td>Number of destinations</td>
<td>1.03 (0.97, 1.10)</td>
<td>0.98 (0.91, 1.06)</td>
<td>1.25 (1.12, 1.40)</td>
<td>1.14 (0.99, 1.30)</td>
</tr>
<tr>
<td>Intersection density</td>
<td>1.12 (1.04, 1.19)</td>
<td>1.07 (0.99, 1.16)</td>
<td>1.87 (1.63, 2.13)</td>
<td>1.74 (1.49, 2.02)</td>
</tr>
</tbody>
</table>

1 p < 0.05, 2 p < 0.01, 3 p < 0.001
4 Four or more times per week
5 GLMM with no adjustments
6 GLMM adjusted for sex (female/male), education (higher education/vocational or secondary or basic education), children under 18 years of age living at home (yes/no), and marital status (married or de facto relationship/single or divorced or widowed)
7 Summed z-scores of population density, number of destinations and intersection density
8 Z-score of population density within 1-km buffer around residential location
9 Z-score of number of destinations within 1-km buffer around residential location
10 Z-score of number of intersections with three or more legs within 1-km buffer around residential location

5.3 Land use and transportation policies and the development of urban form and transportation modal shares in Oulu from 1998 to 2016 (III)

5.3.1 Focus areas of urban and transportation planning policies

Four interconnected themes emerged from the document analysis related to Oulu’s land use and transportation policies: 1) infill development and densification of the urban form; 2) mixing functions in local and regional centers to improve service accessibility; 3) city center development; and 4) increasing active transportation modal shares.

Community structure, housing, and transportation policies highlighted the necessity of densification. During the follow-up, city growth and new housing production were mainly established as greenfield developments in the urban fringe, but the latest infill plans directed the development close to existing high-quality walking, cycling, and public transportation infrastructure. The policy documents also emphasized good access to services in the city center and local suburban centers, and the goal was to locate services in a structured manner that would induce
little traffic. The city center was planned to be developed by increasing service level and the density of dwellings and workplaces, mixing functions, and emphasizing walking, cycling, and public transportation. Overall, the policy documents highlighted increasing levels of walking, cycling and public transportation use since 1998.

5.3.2 The association between urban form development and changes in transportation modal shares

The inner urban area comprised the most dense and diverse postal code areas (Fig. 5). The postal code areas’ characteristics are presented in Appendix 2. Two postal code areas in the urban fringe and one in the inner city were characterized as places for work, but most were mainly single-use developments for dwellings. The DMA score development focused on the city center and the adjacent postal code areas in the inner urban area (Fig. 6).

There was a continuous increase in floor area ratio in the inner urban area. Similarly, the growth of dwellings and residents per hectare was concentrated in the inner urban area in addition to one postal code area in the outer urban area. Workplaces and jobs per hectare also increased mostly in the city center and one of the adjacent postal code areas. In terms of functional mix, the category live was the main one in most postal code areas. It more often mixed with workplaces than places to visit. Balanced land use was only found in the city center, which was also illustrated by the entropy score. Growth in intersection density centered on the inner urban area as well.

As a whole, active transportation modal share decreased from 47% to 45% in Oulu during the period 1998–2016. Most of the increase in car trips occurred on the urban fringe, whereas in the inner urban area, walking and cycling modal shares increased. The study participants’ characteristics are presented in Table 4.
Fig. 5. Postal code areas in Oulu stratified by DMA class.
Fig. 6. Urban form development Oulu from 1998 to 2016. Panel A: Boxplot of the DMA scores in postal code areas. Panel B: Development of the DMA scores according to postal code areas stratified by DMA class.
Table 4. Characteristics of the participants sampled from Oulu in the 1998 (n = 271), 2004 (n = 342), 2010 (n = 417) and 2016 (n = 1,568) National Travel Surveys.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n (%)</td>
<td>n (%)</td>
<td>n (%)</td>
<td>n (%)</td>
</tr>
<tr>
<td><strong>Age</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6–17</td>
<td>58 (21.4)</td>
<td>68 (19.9)</td>
<td>60 (14.4)</td>
<td>326 (20.8)</td>
</tr>
<tr>
<td>18–64</td>
<td>194 (71.6)</td>
<td>251 (73.4)</td>
<td>286 (68.6)</td>
<td>1,020 (65.1)</td>
</tr>
<tr>
<td>65 and over</td>
<td>19 (7)</td>
<td>23 (6.7)</td>
<td>71 (17)</td>
<td>222 (14.2)</td>
</tr>
<tr>
<td><strong>Sex</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>130 (48)</td>
<td>169 (49.4)</td>
<td>254 (60.9)</td>
<td>744 (47.4)</td>
</tr>
<tr>
<td>Female</td>
<td>141 (52)</td>
<td>173 (50.6)</td>
<td>163 (39.1)</td>
<td>824 (52.6)</td>
</tr>
<tr>
<td><strong>Employment status</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Employed</td>
<td>130 (54.4)</td>
<td>168 (49.1)</td>
<td>216 (58.9)</td>
<td>780 (49.4)</td>
</tr>
<tr>
<td>Unemployed or outside workforce</td>
<td>109 (45.6)</td>
<td>174 (50.9)</td>
<td>151 (41.1)</td>
<td>532 (50.5)</td>
</tr>
<tr>
<td><strong>Profession</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Farmer/entrepreneur/white- or blue-collar worker</td>
<td>139 (58.2)</td>
<td>175 (51.2)</td>
<td>214 (51.3)</td>
<td>699 (44.6)</td>
</tr>
<tr>
<td>Parental leave/pensioner/conscript</td>
<td>43 (18.0)</td>
<td>56 (16.4)</td>
<td>111 (26.6)</td>
<td>341 (21.7)</td>
</tr>
<tr>
<td>Student</td>
<td>36 (15.1)</td>
<td>53 (15.5)</td>
<td>28 (6.7)</td>
<td>181 (11.5)</td>
</tr>
<tr>
<td>Schoolchild</td>
<td>16 (6.7)</td>
<td>58 (17)</td>
<td>55 (13.2)</td>
<td>280 (17.9)</td>
</tr>
<tr>
<td>Other</td>
<td>5 (2.1)</td>
<td>0</td>
<td>9 (2.2)</td>
<td>67 (4.3)</td>
</tr>
<tr>
<td><strong>Car ownership</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>223 (82.6)</td>
<td>283 (82.7)</td>
<td>366 (87.8)</td>
<td>1,393 (88.8)</td>
</tr>
<tr>
<td>No</td>
<td>47 (17.4)</td>
<td>59 (17.3)</td>
<td>51 (12.2)</td>
<td>175 (11.2)</td>
</tr>
<tr>
<td><strong>Driver’s license</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>178 (82.4)</td>
<td>243 (71.1)</td>
<td>331 (79.4)</td>
<td>1,138 (91.6)</td>
</tr>
<tr>
<td>No</td>
<td>38 (17.6)</td>
<td>99 (28.9)</td>
<td>86 (20.6)</td>
<td>104 (8.4)</td>
</tr>
<tr>
<td><strong>DMA category</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban fringe</td>
<td>143 (52.8)</td>
<td>173 (50.6)</td>
<td>239 (57.3)</td>
<td>1,121 (71.5)</td>
</tr>
<tr>
<td>Outer urban area</td>
<td>76 (28)</td>
<td>110 (32.2)</td>
<td>110 (26.4)</td>
<td>297 (18.9)</td>
</tr>
<tr>
<td>Inner urban area</td>
<td>52 (19.2)</td>
<td>59 (17.3)</td>
<td>68 (16.3)</td>
<td>150 (9.6)</td>
</tr>
</tbody>
</table>

As shown in Table 5, a one-unit increase in DMA score was associated with a 20% increase in walking trips (OR 1.20; 95% CI: 1.16, 1.25; p < 0.001), an 8% increase in cycling trips (OR 1.08; 95% CI: 1.01, 1.16; p = 0.018), and a 27% decrease in car trips (OR 0.73; 95% CI: 0.70, 0.77; p < 0.001) in the models adjusted for socioeconomic factors. On the contrary, DMA score was not associated with public transportation use.
Table 5. The association between DMA-score and transportation mode (OR, 95% CI) among 2,598 participants living in Oulu.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Walking</th>
<th>Cycling</th>
<th>Public transport</th>
<th>Car</th>
</tr>
</thead>
<tbody>
<tr>
<td>DMA-score</td>
<td>1.24 (1.19, 1.30)$^2$</td>
<td>1.06 (0.99, 1.12)</td>
<td>1.01 (0.92, 1.13)</td>
<td>0.76 (0.73, 0.80)$^3$</td>
</tr>
<tr>
<td>(crude model)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DMA-score</td>
<td>1.20 (1.16, 1.25)$^2$</td>
<td>1.08 (1.01, 1.16)$^1$</td>
<td>1.02 (0.92, 1.14)</td>
<td>0.73 (0.70, 0.77)$^3$</td>
</tr>
<tr>
<td>(adjusted model$^4$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^1$ p < 0.05, $^2$ p < 0.01, $^3$ p < 0.001

$^4$ Adjusted for age (continuous), sex (male/female) and employment (employed/outside workforce)

Similarly, there was an association between the DMA categories and walking, cycling, and traveling by car, as shown in Fig. 7. Walking increased according to increase in DMA class (OR 2.53; 95% CI: 1.69, 3.79; p < 0.001 for the outer urban area; OR 10.82; 95% CI: 6.45, 18.15; p < 0.001 for the inner urban area) when the urban fringe was the reference category. In terms of cycling, there was a similar pattern, but the difference between the outer (OR 2.75; 95% CI: 1.21, 6.23; p = 0.015) and inner urban areas (OR 3.4; 95% CI: 1.28, 9.01; p = 0.014) was not as large. Correspondingly, traveling by car decreased (OR 0.12; 95% CI: 0.07, 0.20; p < 0.001 for the outer urban area; OR 0.02; 95% CI: 0.01, 0.03; p < 0.001 for the inner urban area), but there were no significant difference between DMA classes in relation to public transportation.
5.3.3 Synthesis of qualitative and quantitative evidence

Oulu’s land use and transportation planning policies emphasized densifying urban form, mixing functions in local centers, developing the city center, and increasing active transportation modal shares during 1998–2016.

Infill and densification were sought particularly within a north-south development corridor according to the 2004 land use masterplan. The results showed that density increased in the inner urban area, but new regional centers in the urban fringe also increased urban sprawl and car dependency. Thus, it is questionable whether the infill and densification goals were reached in the outer urban area and the urban fringe. Moreover, infill development emphasized dwellings but not the diversity of amenities.

Different functions were mainly separated with clearly defined zones for commerce, housing and workplaces according to modernist planning principles.
The policies focused on convenience stores and municipal services, but functional mix was generally not examined, nor did it improve in most postal code areas. Balanced land use was only found in the city center, and the other postal code areas were mainly for housing or work. It appeared that the plans to develop the city center were successful. The components of the urban DMA improved in the inner urban area, which was associated with increased walking and cycling and decreased car use. Despite this positive development, the city wanted to guarantee undisturbed car traffic flow on major roads in the city center, which was also reflected in the development of parking capacity.

Even though walking and cycling modal shares increased in the inner urban area, altogether, car dependency increased, and active transportation modal share decreased 2 percentage points during the follow-up. Moreover, public transportation use remained minimal, and there was no association with urban DMA.
6 Discussion

The goal of the present study was to examine the BE as a determinant of PA with a specific focus on longitudinal associations, residential relocation, and the results’ policy relevance. The results showed that changes in the BE were associated with changes in PA and might play an important part in adopting an active lifestyle. In that regard, better access to destinations, mixed use neighborhoods, and higher street network connectivity seem crucial factors that may enhance cities’ walkability and bikeability, increase TPA and overall regular walking and cycling, and decrease private motor vehicle use at a population level.

The present study’s results are promising considering the endeavor for increased population PA (I, II, and III) and reduced private motor vehicle use by changing the ways urban forms are developed (III). They could imply that behavior is responsive to changes in the BE and that it is possible to induce demand for active modes of transportation. The results have direct implications for community planning and zoning policies. They support the planning of dense and diverse neighborhoods where daily destinations are easily accessible (I, II, and III). They also support greater investments in high-quality infrastructure for walking, cycling, and public transportation (I). Together, these could make the modal shift from private motor vehicles to active modes of transportation possible and enable increases in population PA with long-lasting effects.

6.1 Urban form density, functional mix and access networks as predictors of physical activity (I, II, and III)

According to the results of study I, the possible predictors of PA included the creation of new infrastructure for walking, cycling, and public transportation and higher amount of objectively assessed destinations and better public transportation accessibility. These findings were most consistent for TPA. In study II, when neighborhood DMA was used as a continuous predictor, a one-unit increase was observed to be associated with a 17% increase in regular cycling and a 3% increase in regular walking. In study III, a one-unit increase in the DMA score was associated with a 20% increase in walking, an 8% increase in cycling, and a 27% decrease in car use. Moreover, when the urban fringe was compared to the outer and inner urban area in study III, there was a dose-response association with increased walking and decreased car use. The odds for cycling were also higher in the inner and outer urban areas compared to the urban fringe.
Urban form characteristics related to density, street connectivity, land use mix, and non-residential destinations have been consistently and positively associated with active transportation in cross-sectional studies (Bird et al., 2018; Saelens & Handy, 2008). The results of the reviews of studies with more advanced designs, such as retrospective and prospective longitudinal studies and natural experiments, point in the same direction. Increased residential density, destinations density, land use mix, and street connectivity seem supportive factors for PA and especially transportation-related walking (Ding et al., 2018; McCormack & Shiell, 2011; Smith et al., 2017). Moreover, the provision and improvements of parks and playgrounds and constructing or upgrading active transport infrastructure have been associated with increased PA (Smith et al., 2017). A gap in the literature does exist in terms of understanding how changes in the BE might affect cycling behavior, however (Smith et al., 2017).

The results of the present study (I, II, and III) support the findings of previous reviews (Bird et al., 2018; Ding et al., 2018; McCormack & Shiell, 2011; Saelens & Handy, 2008; Smith et al., 2017). Urban form characteristics related to DMA seemed to predict walking behavior (II, III). This study also showed that cycling behavior (II) and private motor vehicle use might be responsive to changes in these characteristics (III).

In this study, the strength of the associations between the exposures and outcomes were moderate (II and III). Effect sizes of comparable magnitude have also been observed in other longitudinal studies (Bentley et al., 2018; McCormack et al., 2017). For example, an Australian study found that any walking for transport (vs. none) was associated with increased street connectivity (+10 intersections OR 1.19; 95% CI: 1.07, 1.32), residential density (+5 dwellings/ hectare OR 1.10; 95% CI: 1.05, 1.15), and land use mix (10% increase, OR 1.12; 95% CI: 1.00, 1.26; Bentley et al., 2018). Moreover, another study showed that exposure to a new guided busway that comprised a traffic-free walking and cycling route was associated with increased weekly cycle commuting time (RR 1.34, 95% CI: 1.03, 1.76; Panter et al., 2016).

In general, the findings have been most consistent for adults from high-income countries. There is a lack of studies focusing on different settings, such as low- and middle-income countries, rural areas, and different age groups (Ding & Gebel, 2012), though some mixed evidence is available. For example, a Danish study noted that the urban renewal of a disadvantaged district was associated with increased time spent in both LPA and MVPA for local adolescents (Andersen et al., 2017). However, another study found no association between a new urban
greenway and PA in a disadvantaged high-crime urban community (Auchincloss et al., 2019).

The current evidence suggests that exposure to DMA-related urban form factors is particularly associated with transportation domain of physical activity (McCormack & Shiell, 2011; Smith et al., 2017). However, a recent longitudinal study showed that recreational walking was also associated with higher street connectivity, in addition to more LTPA domain specific factors such as access to parks or beaches, and perceived aesthetics and safety (Christian et al., 2017). Moreover, internationally comparable evidence reports that the factors associated with TPA might be supportive of LTPA behavior (Sallis et al., 2020). In this study (I, II, and III), changes in BE factors were associated with changes in both overall and transportation-related walking and cycling.

6.2 Residential relocation and causal inference (II)

Over the previous two decades, the number of studies that assess the association between the BE and PA has grown extensively. As the evidence base is still largely comprised of cross-sectional studies, there is a lack of longitudinal studies (McCormack & Shiell, 2011). Hence, residential self-selection has been presented as one of the main factors that might bias the findings, which refers to the attitudinal factors influenced by life situation and lifestyle preferences that affect residential location choices (van de Coevering et al., 2015). According to a review about residential relocation, the evidence from retrospective longitudinal studies is still more clear than that from prospective longitudinal studies (Ding et al., 2018).

This study advanced the field with its longitudinal design and robust methods. Residential preferences were not adjusted for directly, but time-varying sociodemographic variables associated with PA and residential location were selected as potential confounding factors, and current evidence has indicated that these might account for residential self-selection (Næss, 2014). Moreover, the residential relocation trajectories modeled based on neighborhood-level factors could demonstrate preferences and possibilities related to residential location choices during the follow-up, as a trajectory-based approach enables the quantification of exposure to different residential environments (Coulter et al., 2016).

Study II’s findings contributed to the understanding of residential relocation patterns according to 16 years of time-varying data on the urban form among adults. Stable residential relocation trajectories based on neighborhood DMA were
observed in four out of five participants between 31 and 46 years of age, which supports previous evidence telling that residential mobility declines when people reach their 30s and 40s (Geist & McManus, 2008). Previously, motivations for residential relocation have been shown to be interconnected with age, family status, and the timing of life events and originate from factors related to quality of life (Geist & McManus, 2008). Some sociodemographic variation between the residential relocation clusters was also observed in the present study, which was most obvious between the stable very high DMA and stable very low DMA clusters. At 46 years of age, the stable very high DMA cluster comprised more women, more participants with higher education, and fewer participants who were in a relationship and had children, whereas good self-rated health was lowest in the stable very low DMA cluster.

The key life events that trigger residential relocation choices and subsequent changes in the BE have also been demonstrated to induce changes in car ownership and travel behavior (Scheiner & Holz-Rau, 2013). Previous evidence has argued that relocating to suburban areas is associated with increases in car use and decreases in public transportation use, cycling, and walking, whereas the opposite is true for relocating to the inner city (Scheiner & Holz-Rau, 2013). In the present study, relocation was more often from higher to lower DMA neighborhoods than vice versa. However, the participants who relocated from lower DMA neighborhoods to the highest quintile had three times higher odds to start both cycling and walking regularly, as compared to those with the opposite relocation trajectory.

It is highly plausible that walking and cycling are more common in environments where a variety of amenities exist within a short distance and street networks do not constrain movement between them. Randomized controlled trials are neither feasible nor ethical, but a lack of such evidence does not nullify the results of other epidemiological observational studies (Hill, 2015). As more longitudinal studies that account for temporal order between exposures and outcomes are available, it can be argued that changes in the BE are associated with changes in PA. Nevertheless, also longitudinal observational studies are vulnerable to different types of biases, and the evidence from this study, does not per se imply causal associations between exposures and outcomes.

Even if a causal association between BE and PA cannot yet be ascertained (Hill, 2015), it can be argued that the evidence base in this field has grown much stronger. Future studies could benefit from a combination of qualitative and quantitative research methods to integrate knowledge about causal influences at the individual
or city level (Næss, 2015, 2016). As an example, a recent qualitative study derived data from in-depth interviews and concluded that the inability to reach destinations by walking, cycling, or taking public transportation have a decisive impact on suburban residents’ decision to relocate to more urban environments (Bruns & Matthes, 2019). Moreover, the residential biography that shapes perceptions of and emotional links to residential environments was identified as an important factor for location choice, while daily destinations density and parking restrictions seemed important to reducing the kilometers traveled by car (Bruns & Matthes, 2019).

Finally, besides prospective longitudinal studies examining residential relocation, population- and system-wide natural experiments are an important and often the only method to study how to shift population behavior patterns toward a healthier direction (Ogilvie et al., 2020). Accordingly, a practice-based evidence pathway, in which intervention studies assess reducing critical uncertainties, embracing non-randomized study designs, and appraising the utility of different types of evidence is crucial (Ogilvie et al., 2020). Natural experiments concerning changes in the BE have provided promising results regarding inducing changes in PA behavior, as this study illustrated as well (I).

6.3 Active transportation policy and practice (III)

Information is growing increasingly more available on how to create urban form that enhance citizens’ health, but its implementation in policies and urban planning practices has proven difficult. Hence, a gap between research and practice does exist, and it has been suggested that research translation requires context-specific, policy-relevant evidence on the implementation of local policies (Giles-Corti et al., 2015; Hooper et al., 2019; Sallis, Bull, Burdett et al., 2016). Street-scale urban design, land use policies, and community-scale urban design and transportation policies have been associated with PA but the level of evidence remains low (Puggina et al., 2018).

The present study took a step closer to practice by integrating local community planning policies with urban form and transportation modal share development with a mixed method approach to enhance utility of the findings. In study III, the results showed that during the last 20 years, developing density, functional mix, and the city center and increasing active transportation modal shares were emphasized in all of Oulu’s land use and transportation planning policies. Still, in practice the urban form development was not fully in line with policies that did not
attempt to hinder the flow of private motor vehicles. The components related to density, functional mix, and access networks increased mostly in the inner urban area, which was associated with increased walking and cycling and decreased car use, but not public transportation use.

However, as a whole the urban form development did not support active transportation modal share growth, as it decreased 2 percentage points, possibly due to an inadequately assessed functional mix outside the inner urban area, increased urban sprawl, and building more capacity for cars. Increased inner urban area density and the overall increase in car dependency as different functions are located further away from each other, is in line with the development of other Finnish cities (Rehunen et al., 2018). Good communication between land use and transportation was regarded as the starting point for Oulu’s urban development targeting to increase the modal shares of walking, cycling and public transportation. However, based on the results, it could be argued that no common language was found, and the actions in transportation and urban form development were not fully in line with the goals.

In Oulu, having specific zones for different functions such as housing, workplaces, and amenities is most likely to increase car travel. Moreover, the service structure outside the inner city relied on large regional hypermarkets, and planning regulations for big-box stores, such as maximum sizes for a single store and a maximum number of stores under one roof, could promote smaller-scale shops and nearby service accessibility (Schipperijn, 2017). It is noteworthy that land ownership and political and economic reasons set the boundaries of where land use related to new growth areas and service and workplace locations occur. Many large development plans and projects were also related to car infrastructure, which undermined the focus areas of all urban policies in the last 20 years.

Accessibility concepts have been increasingly utilized to explore the relationships between land use and transportation infrastructure in cities and urban regions (te Brömmelstroet et al., 2016). A variety of instruments exists but they are not widely used in planning practice because of user-friendliness problems, organizational barriers, and lack of institutionalization of accessibility instruments, which are the main reasons for the implementation gap (Silva et al., 2017). Identifying which measures could successfully serve different user needs is required for their wider acceptance and usage in accessibility planning (te Brömmelstroet et al., 2016).

Major decisions related to land use and transportation networks are political, which highlights the importance of strong political leadership to successfully
implement policy goals. It has been indicated that besides design policies, especially their successful implementation is important to change the BE to promote active transportation and reduce car dependency (Hooper et al., 2020). Movement on a policy needs, first of all, for decision makers to recognize the issue as a problem (Kingdon, 1995). Second, various feasible solutions need to be identified and proposed, and finally, politicians need to be willing to make a decision (Kingdon, 1995).

In the future, a proactive approach is required for increasing density and combining infill and mixed-use development in Oulu. High-quality walking environments and cycling infrastructure, greater investments in public transportation, and stronger political leadership are also necessary to reach policy goals and increase active transportation modal share.

6.4 Strengths and limitations

The present study has multiple strengths. In study I, an extensive search of publications was conducted from six databases and the quality of the evidence was evaluated. The primary measure of the effects was assessed according to changes in the BE and their association with changes in PA. Moreover, the analysis was stratified according to PA domain and BE measurement type. Study II was among the first to model and visualize residential relocation trajectories based on neighborhood DMA and assess the longitudinal associations of neighborhood DMA and regular walking and cycling in a representative prospective cohort population. Study III combined qualitative and quantitative data to provide an integrated longitudinal local analysis of land use and transportation policies, and the association between urban form and transportation modal share development to enhance utility of the findings.

The present study’s results need to be interpreted according to the following limitations. Given that the review (I) focused solely on peer-reviewed publications without gray literature, publication bias is possible. Due to the heterogeneity and diversity of the studies and their measures, a meta-analysis was not feasible. Furthermore, the resulting BE categories included measures that might have been defined differently. In study II, there were limitations to the measurements. The main outcome was self-reported and did not account for domain, intensity, or duration of the activity. Moreover, a circular buffer was used to calculate the exposure variables, which is a less accurate method compared to road network buffers. An additional limitation was attrition bias because some of the
sociodemographic characteristics differed among those who dropped out of the study compared to the participants who completed the follow-up. In study III, there were large rural areas that merged with Oulu during the follow-up, which hindered the full implementation of the policy goals. The policy documents that were analyzed had different meanings, time spans, political scopes, and legal consequences as well. In addition, recognition of the complexity of all the urban form characteristics used in this study is warranted, as reducing morphological properties to a distinct index might lead to misinterpreting how cities work (Dovey & Paška, 2020). This study’s results are not generalizable to other settings and populations as such because the study populations were derived from high-income countries, and in study II, the population consisted solely of adults. Moreover, study III was conducted in a single Finnish city, which limits the results’ applicability to other cities.

6.5 Implications for future research

Based on the empirical studies (II and III) included in the present dissertation, more people relocated from inner to outer urban areas than vice versa and environmental interventions to facilitate active transport in urban areas will not be effective if residents are moving away from such areas. Further understanding of how people choose where to relocate could better inform policy initiatives. Future studies could benefit from a combination of qualitative and quantitative research methods to integrate knowledge about causal influences at the individual or city level.

Further studies with rigorous study designs that assess changes in the BE and their effects on PA are needed to strengthen the evidence base and more research is also needed of the effects of other BE factors besides density, land use mix and intersection density on PA. Thus far, longitudinal studies assessing the association between changes in the BE and changes in PA have mostly relied on self-reported PA data. It is advised that future longitudinal studies use activity monitors and a measurement protocol that can detect cycling.

Moreover, only a few longitudinal studies have focused on different settings (such as rural and sparsely populated areas) or on low-income countries, which are recommended areas of research for future research. Rapid urbanization in countries such as India, China and Nigeria in the global south requires specific attention also regarding the creation of healthy communities and sustainable transportation patterns (United Nations, 2015b). Finally, given that the results of studies focusing on specific regions and cities might not be generalizable to other settings and
populations as such, more policy relevant research in different countries and cities is warranted.
7 Conclusions

The results of this study suggest that urban and transport planning have an influence on citizens’ physical activity. Based on this study’s aims, it can be concluded that:

1. Improved objectively assessed accessibility, measured according to the number of different types of destinations, access to public transportation, and land use mix, was associated with increased transportation-related physical activity. Moreover, the creation of new infrastructure for walking, cycling, and public transportation was associated with increases in transportation-related physical activity and overall physical activity.

2. Increases in neighborhood characteristics related to urban form density, mixed land use, and access networks were associated with increased regular walking and cycling. Between 31 and 46 years of age, over 80% of the participants lived in a neighborhood with the same level of DMA. More often, relocation focused on less dense and diverse neighborhoods, but relocating to neighborhoods with the highest population density, mixed land use and intersection density increased the odds of starting both regular walking and cycling.

3. Increasing urban form density and diversity, developing the city center, and increasing active transportation modal shares were central policy goals for the city of Oulu during the period 1998–2016. Community planning outcomes were not fully in line with these goals, and no consensus was established to limit the dominance of private motor vehicles. During the follow-up, urban form became denser and more diverse in the inner urban area, which was associated with increased walking and cycling and decreased private motor vehicle use, but not with public transportation use. However, active transportation modal share decreased 2 percentage points overall, possibly due to increases in urban sprawl and car dependency in outer urban area and the urban fringe.

A global modal shift from private motor vehicles to sustainable modes of transportation is required to manage increasing levels of urbanization and meet the environmental and health-related demands of future cities (Intergovernmental Panel on Climate Change, 2018; United Nations, 2015b). Better access to destinations, mixed use neighborhoods, and higher street network connectivity seem important factors in adopting an active lifestyle. They may enhance transportation-related physical activity and overall regular walking and cycling, as well as decrease private motor vehicle use at a population level. The present study’s
results have implications for zoning and transportation policies, suggesting designing dense, compact, and diverse neighborhoods and greater investments in active transportation infrastructure, which both require strong political leadership and could reduce the global disease burden caused by physical inactivity.
References


Ding, D., & Gebel, K. (2012). Built environment, physical activity, and obesity: What have we learned from reviewing the literature? *Health & Place, 18*(1), 100-105. doi:10.1016/j.healthplace.2011.08.021


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Appendices

Appendix 1

Medline search strategy:
1. Motor Activity/
2. Bicycling/ or Transportation/ or Walking
3. Exercise/
4. 1 or 2 or 3
5. Environment/ or Residence Characteristics/ or City Planning/ or
   Environment Design
6. walkability.mp.
7. Cities/
8. 5 or 6 or 7
9. Longitudinal Studies/
10. Observational Study/
11. Prospective Studies/
12. Follow-up Studies/
13. Cohort Studies/
14. Causality/
15. residential relocation?.mp.
17. 9 or 10 or 11 or 12 or 13 or 14 or 15 or 16
18. 4 and 8 and 1
### Appendix 2

Table 6. Characteristics of Oulu’s postal code areas (mean values during the period 1998–2016).

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<th>Dwellings (n)</th>
<th>Residents (n)</th>
<th>Jobs (n)</th>
<th>Dwelling floor area (ha)</th>
<th>Workplace floor area (ha)</th>
<th>Amenities floor area (ha)</th>
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<th>Intersections (n)</th>
<th>DMA-score</th>
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Original publications


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THE BUILT ENVIRONMENT AS A DETERMINANT OF PHYSICAL ACTIVITY

LONGITUDINAL ASSOCIATIONS BETWEEN NEIGHBORHOOD CHARACTERISTICS, URBAN PLANNING PROCESSES, AND PHYSICAL ACTIVITY