DOCTORAL THESIS

Urban Planning and Transport Walking

Examining the effects of built environment, psychological factors and socio-demographics on walking as a transport mode in a Swedish context

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Architecture

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ABSTRACT

This thesis addresses how built environment characteristics shape walking behavior by examining the relationship between GIS-based built environment measures and GPS-tracked transport walking, along with self-reported socio-demographic and psychological characteristics of individuals, in two medium-sized Swedish cities, Umeå and Linköping, across multiple datasets collected in 2019 and 2021.

A methodological foundation for the empirical work is established by evaluating two emerging data sources for pedestrian study: a Wi-Fi-based flow measurement system (Bumbee Labs) and a GPS-enabled travel survey application (TravelVu), finding that the two methods are complementary, with the former capturing large-scale pedestrian flow patterns and the latter providing individual-level route, distance, and attitudinal data suited to behavioral analysis. Built environment exposure, in this thesis, is operationalized at two spatial scales: 1) potential exposure, measured within a 750 m radius of each participant's home location, and 2) realized exposure, measured within a 15 m buffer along GPS-traced actual routes and their shortest-path alternatives. This dual-scale design enables a direct empirical comparison of which environmental features predict how much people walk versus which features shape the paths they take when they do. Socio-demographic variables and psychological variables, derived from a Theory of Planned Behavior questionnaire integrated into the tracking application, are examined both for their direct associations with GPS-measured walking outcomes and as potential mediators and moderators of built environment effects. Analytical methods include bivariate correlation analysis, structural equation modelling, linear mixed models, and discrete choice analysis.

At the neighborhood level, building density, bus stop access, commercial land use, tree cover, paved surface area, and pedestrian network length show modest but statistically significant positive associations with walking distance and walking ratio. Structural equation modelling confirms that the built environment retains a significant direct effect on walking when attitudes are simultaneously controlled, though attitudes are the stronger predictor. Contrary to the mediation hypothesis, the built environment does not significantly influence walking through attitudes in the overall sample; however, moderated mediation analysis reveals conditional pathways by age, with a significant indirect effect via attitudes among middle-aged adults and a stronger direct environmental effect among young adults.

At the route level, about 96% of observed trips follow the shortest available path, confirming distance minimization as the dominant pedestrian strategy. For trips that deviate, commercial land use is the strongest positive predictor of route selection in the discrete choice analysis, while dedicated non-vehicular pedestrian infrastructure and low-speed streets are consistently negatively associated with route deviation across both linear mixed models and discrete choice models. Moderation analyses further show that income, age, and scenic motivation condition how specific built environment features influence route behavior, while no socio-demographic or attitudinal variable produces a significant unconditional main effect on route choice.

The comparison across scales reveals that the environmental variables associated with walking volume are indicated to be different from those shaping route selection, a finding that challenges walkability frameworks and suggests that planning interventions targeting modal shift and those targeting route quality require different built environment priorities. These results support further understanding of scale-dependent built environment effects on pedestrian behavior and provide an empirical basis for more targeted assessment of walking behavior in Nordic urban contexts. The results also indicate a continued need for more data on the topic, as well as methodological development to collect quantitative data on pedestrian travel.

Keywords: Walking behavior; Transport walking; Built environment; Psychological constructs; Theory of planned behavior; Route choice; GPS tracking; Structural equation modelling; Discrete choice analysis; Medium sized cities; Cross sectional study; Sweden

SAMMANFATTNING

I denna avhandling studeras hur den bebyggda miljön och den rumsliga utformningen påverkar gångbeteendet genom att undersöka sambandet mellan GIS-uppmätta egenskaper hos den bebyggda miljön och GPS-spårade fotgängarresor med nyttodestination. tillsammans med individernas självrapporterade sociodemografiska och psykologiska egenskaper. Studien genomförs i två medelstora svenska städer, Umeå och Linköping, baserat på datamängder som samlats in under 2019 och 2021.

Exponeringen för den byggda miljön studerades i två olika rumsliga skalor: potentiell exponering, mätt inom en radie på 750 meter från varje deltagares hemadress, och faktisk exponering, mätt inom en 15 meters buffertzon längs de faktiska rutterna som spårats via GPS och deras kortaste alternativa vägar. Detta utförande med två skalor möjliggör en empirisk jämförelse av miljöfaktorer i relation till hur mycket människor går, respektive vilka faktorer som påverkar vilka vägar de väljer när de går. Psykologiska och sociodemografiska variabler baserat på teorin om planerat beteende (TPB), som är i ett frågeformulär integrerat i spårningsapplikationen, undersöks som potentiella mediatorer och moderatorer av effekterna av den bebyggda miljön. Analytiska metoder inkluderar bivariat korrelationsanalys, strukturell ekvationsmodellering, linjära blandade modeller och diskret valanalys.

På stadsdelsnivå visar byggnadstäthet, tillgång till busshållplatser, kommersiell markanvändning, förekomst av träd, andel asfalterad yta och längden på gångvägnätet ett måttligt men statistiskt signifikant positivt samband med gångavstånd och andel gångtrafik. Strukturell ekvationsmodellering bekräftar att den bebyggda miljön har en direkt effekt på gång när attityder samtidigt kontrolleras, även om attityder är den starkare prediktorn. I motsats till medlingshypotesen påverkar den bebyggda miljön inte gång i någon utsträckning genom attityder i det totala urvalet; dock avslöjar modererad medlingsanalys villkorade samband beroende på ålder, med en indirekt effekt via attityder bland medelålders vuxna och en starkare direkt miljöeffekt bland unga vuxna.

På ruttnivå följer 96% av de observerade resorna den kortaste tillgängliga vägen, vilket bekräftar att avståndsminimering är den dominerande strategin för fotgängare. För resor som avviker är kommersiell markanvändning den starkaste positiva prediktorn för ruttval i den diskreta valanalysen, medan särskild infrastruktur för fotgängare och lågfartsgator genomgående är negativt associerade med ruttavvikelse i både linjära blandade modeller och diskreta valmodeller. Denna kontraintuitiva negativa association återspeglar den rumsliga strukturen i skandinaviska gångnätverk, där gångytor avskild från motorfordonstrafik utgör de mer direkta rutterna snarare än alternativa natursköna rutter. Effekterna av bebyggelsetätheten är stadsspecifika, med positiva samband i Umeå som vänds till negativa i Linköping, vilket pekar på den modererande rollen som den urbana rumsliga strukturen spelar. Moderationsanalyser visar vidare att inkomst, ålder och motivationen att uppleva naturen påverkar hur specifika egenskaper i den bebyggda miljön påverkar ruttbeteendet, medan ingen sociodemografisk eller attitydmässig variabel ger en signifikant ovillkorlig huvudeffekt på ruttvalet.

Jämförelsen mellan olika skalor visar att de miljövariabler som är kopplade till gångvolym i stort sett skiljer sig från dem som påverkar valet av rutt. Detta resultat ifrågasätter generella ramverk för gångvänlighet och tyder på att planeringsinsatser som syftar till val av färdsätt respektive ruttkvalitet kräver olika prioriteringar i den bebyggda miljön. Resultaten bidrar till en bättre förståelse av hur den bebyggda miljöns effekter på fotgängarnas beteende varierar beroende på skala och ger en empirisk grund för en mer målinriktad utvärdering av gångbeteendet i nordiska stadsmiljöer. Resultaten visar även på fortsatt behov av mer data på temat och metodutveckling för att samla in kvantitativa data gällande fotgängarresor.

Nyckelord: Fotgängarbeteende; Transportgång; Den byggda miljön; Psykologiska konstruktioner; Teorin om planerat beteende; Val av rutt; GPS-spårning; Strukturell ekvationsmodellering; Diskret valanalys; Medelstora städer; Tvärsnittsstudie; Sverige

LIST OF PAPERS INCLUDED IN THE THESIS

Paper 1 (published)

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Paper 3 (submitted)

Mandal, A., Johansson, C., & Lindelöw, D. Interacting effect of attitude and built environmental on objectively measured utilitarian walking: A case from subarctic Sweden, submitted to *International Journal of Sustainable Transportation*

Paper 4 (submitted)

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Contributions in the appended papers:

Main author, main responsibility for data analyses, main writing and review process. Shared data collection, planning, and writing the manuscript.

LIST OF ABBREVIATIONS

BE	Built Environment
DCM	Discrete Choice Model
GIS	Geographic Information Systems
GPS	Global Positioning System
IPAQ	International Physical Activity Questionnaire
LMM	Linear Mixed Model
MVPA	Moderate-to-Vigorous Physical Activity
PA	Physical Activity
PBC	Perceived Behavioral Control
POI	Points of Interest
PT	Public Transport
SEM	Structural Equation Modelling
SES	Socioeconomic Status
TPB	Theory of Planned Behavior
TPDW	Total per day walking
WR	Walking ratio

TABLE OF CONTENTS

1. INTRODUCTION

Walking constitutes the most basic form of human mobility and the only transport mode universally available across age, income, and social position. It requires no specialized technology, generates no direct emissions, and embeds physical activity within everyday routines. For these reasons, walking occupies a position at the intersection of public health, environmental sustainability, and urban planning. A body of epidemiological research demonstrates that regular walking is associated with reduced risks of cardiovascular disease, type II diabetes, obesity, and premature mortality (I. M. Lee & Buchner, 2008; Morris & Hardman, 1997). It is also associated with improved mental health outcomes, including reduced stress and enhanced psychological restoration, particularly when undertaken in supportive environmental contexts (Hsu et al., 2021; Roe & Aspinall, 2011). These benefits arise not only from recreational walking but also from utilitarian travel that is integrated into daily routines. At the urban scale, higher walking rates are associated with reduced greenhouse gas emissions, lower congestion, and improved air quality (Banister, 2008; Ewing & Cervero, 2010). Walking strengthens the functional integration of public transport systems by providing first- and last-mile connectivity, thereby enhancing overall network efficiency. It also supports social interaction, local economic vitality, and street-level urban life, contributing to what Gehl (2010) describes as human-scale urbanism. Economic evaluations indicate that investments in walking infrastructure yield returns through reduced healthcare expenditure and increased local commercial activity (Baker et al., 2021; Litman, 2013).

Despite its numerous advantages, the share of walking (and cycling) has reduced across much of the twentieth and early twenty-first centuries with rising car dependence. In the United States, automobile mode share increased from about 67% of trips in 1960 to over 85% by the mid-1990s, while walking declined from roughly 10% to below 8% (Pucher & Renne, 2003). The 2017 National Household Travel Survey still reports 83% of trips by private vehicle and 10.5% by walking, with provisional 2022 data indicating a further decline in walking to 6.8%, although pandemic related survey disruptions limit strict comparability (McGuckin & Fucci, 2018). Comparable shifts occurred in Europe. In the United Kingdom, car mode share rose from 38% in 1952 to over 60% by the 1990s, while walking fell from about 35% to 25% (Department for Transport, 2023; Pucher & Buehler, 2008). In Germany, car share increased from 36% in 1976 to 58% in 2017 as walking declined from 33% to 22% (Nobis et al., 2019; Pucher & Buehler, 2008). Sweden followed a similar trajectory, with car share rising from roughly 30 to 35% in the early 1970s to about 60% by the early 2000s, while walking fell from around 30% to near 20%; recent surveys report 59% to 63% of trips by car in the 2010s, compared to 15 to 18% walking and 9 to 12% cycling (Pucher & Buehler, 2008; Trafikanalys, 2015, 2023). In rapidly motorizing contexts, the substitution effect was sharper: in urban China, cycling fell from over 50% of trips in the 1980s to below 20% by the 2000s (Pucher et al., 2007).

Walking behavior varies across national and urban contexts, reflecting divergent urban forms and modal hierarchies. National travel surveys indicate that walking accounts for approximately

12% of trips in the United States (Buehler et al., 2023; McGuckin & Fucci, 2018), compared to 26% in the United Kingdom (Department for Transport, 2023) and roughly 30% in Germany (Nobis et al., 2019). In the Netherlands, walking represents about 18% of trips within a system strongly oriented toward cycling (KiM, 2020). Analyses at the city level reveal additional differentiation. Walking constitutes 19% of journeys in Amsterdam, 18% in Copenhagen, 25% in London, 28% in Vienna, 30% in Berlin, and 39% in Paris, while Warsaw reports 8% (Wiśniewski, 2021). Most walking trips are short, typically below 1–2 km, as demonstrated in national travel surveys across Europe and North America, where average walking-trip lengths cluster around 0.8–1.2 km and more than three-quarters of walking trips fall under 2 km (McGuckin & Fucci, 2018; Nobis et al., 2019; Risser & Šucha, 2021). This distance sensitivity aligns with psychological evidence showing that walking choices are strongly shaped by habit, perceived effort, and situational convenience (Risser & Šucha, 2021). Within the United States, walking accounts for roughly 25% of trips in New York City but less than 5% in highly automobile-oriented metropolitan areas, with extreme intra-urban variation (e.g., 54% in Manhattan versus 5% in Staten Island; Buehler et al., 2023). Consistent with psychological evidence, these patterns suggest that walking behavior is shaped not only by infrastructure and distance but also by habit formation, perceived convenience, and social norms embedded in car-oriented systems (Risser & Šucha, 2021).

In comparative terms, Sweden occupies an intermediate position within the international distribution of walking levels. Recent national travel survey data indicate that approximately 499 million main trips were made on foot in 2024 out of nearly 3.9 billion trips overall, corresponding to roughly 12–13% of all trips (Trafikanalys, 2025), a proportion similar to that observed in the United States but lower than in European countries such as the United Kingdom or Germany. Notably, this represents a decline, with walking trips decreasing by 20% relative to Göteborgs Stad 2019 and by 9% compared to 2023, suggesting a recent contraction in pedestrian activity at the national level (Trafikanalys, 2025). At the same time, earlier surveys indicate higher estimates of 20–25% depending on trip definitions, underscoring sensitivity to measurement frameworks (Trafikanalys, 2019, 2023). Intercity comparison reveals substantial spatial differentiation. In the Stockholm region, walking accounts for approximately 29% of trips, compared to 22 percent in Göteborg and 15 percent in Malmö (Göteborgs Stad, 2026; Malmö stad, 2024; Trafikförvaltningen, 2020). Seasonal dynamics further shape behavior, as observed in Umeå, where walking increases in winter due to modal substitution from cycling (Indebetou & Ahlmer, 2023).

Cross-national differences in planning systems, governance models, and cultural attitudes toward mobility have produced markedly different urban morphologies and walking environments. In North America, twentieth-century planning was strongly shaped by automobile-oriented policies, including federal highway investment, mortgage subsidies favoring suburban expansion, and single-use zoning, which collectively institutionalized low-density, segregated land-use patterns and large block structures (Ewing & Hamidi, 2015; Newman & Kenworthy, 1999). These spatial configurations systematically undermine pedestrian accessibility and continuity, reinforcing car dependence and reducing everyday walkability (Forsyth, 2015; Southworth, 2005). Although policy frameworks such as smart growth and Complete Streets seek to recalibrate these spatial trends, implementation remains uneven and constrained by infrastructural and regulatory legacies (Schlossberg et al., 2013). Cultural norms further mediate behavior, as transport walking in many suburban U.S. contexts remains socially marginal, reflected in relatively low daily walking distances (Pucher & Renne, 2003). By contrast, many European countries have maintained compact urban structures through stronger statutory planning, coordinated land-use regulation, and sustained investment in multimodal transport integration (Banister, 2005; Pucher & Buehler, 2008). The Netherlands, Germany, and Denmark exemplify established commitments to accessibility and human-scale design, producing dense networks of pedestrian and cycling infrastructure in parallel to robust public transport systems (Buehler et al., 2023; Gehl, 2010). Nevertheless, intra-European variation exists, as rapid motorization and weaker commitments in parts of Southern and Eastern Europe continue to privilege vehicular flow over pedestrian priority (Pojani & Stead, 2015; Tight et al., 2011).

The influence of the built environment concerns overall travel behavior, particularly mode choice. Evidence indicates that characteristics at both trip origins and destinations influence the likelihood of active travel. Gehrke & Wang (2020) and Hajrasouliha & Yin (2015) show that higher residential density, mixed land use, and traditional street network design increase walking and cycling, with destination environments more influential for work trips and residential contexts more relevant for non-work travel. Their findings also indicate that the influence of built environment characteristics varies with how the surrounding area is defined. Land use mix tends to show stronger associations with walking when measured at more localized neighborhood levels, whereas density and street connectivity show more consistent relationships when evaluated over broader areas. This aligns with prior work demonstrating that compact development, land use diversity, and network connectivity reduce travel distances and increase non-motorized mode shares (Ewing & Cervero, 2010; Frank & Engelke, 2001). A large body of research shows that planning factors and built environment characteristics influence both the level of walking activity and the spatial distribution of pedestrian movement. Studies using pedestrian counts demonstrate that environments with higher density, mixed land uses, and connected street networks generate greater pedestrian volumes, particularly in areas with accessible destinations and supportive streetscape design (Ewing & Cervero, 2010; Frank & Engelke, 2001; Hajrasouliha & Yin, 2015; Vale & Pereira, 2016). Similar relationships appear in studies measuring walking distance or total walking time. Individuals living in compact, mixed-use neighborhoods tend to walk longer distances and spend more time walking because daily destinations such as shops, services, and public transport are located within reachable distances (Duncan et al., 2010; Ewing & Cervero, 2010; Stevenson et al., 2016). Built environmental characteristics also influence the frequency of walking trips. Areas with smaller block sizes, higher intersection density, and safe pedestrian infrastructure are associated with a greater number of utilitarian walking trips, as these conditions reduce travel distances and improve route convenience (Boarnet et al., 2011; Saelens & Handy, 2008; Sallis et al., 2016). Recent studies using emerging mobility datasets further indicate that pedestrian activity increases in environments with higher accessibility and better-quality walking infrastructure, including continuous sidewalks, traffic calming measures, and pedestrian-oriented street design (Cervero & Duncan, 2003; C. Foster et al., 2004; Giles-Corti et al., 2005). In addition, research on pedestrian route choice shows that pedestrians tend to select routes that minimize distance and travel time while maximizing connectivity, safety, and environmental quality, often selecting streets with lower traffic volumes, active frontages, and aesthetic appeal (Guo & Loo, 2013; Helbing et al., 2001).

Walking levels vary among individuals due to differences in psychological dispositions and socio-demographic characteristics, and these patterns differ by walking purpose. For transport walking (i.e. walking for transportation), individuals who perceive walking as convenient, beneficial, and easy to perform tend to walk more frequently (Bamberg et al., 2003). Positive attitudes and stronger perceived control have been consistently associated with higher levels of walking for transport and with greater likelihood of choosing walking as a commuting mode (Bamberg et al., 2003; Gardner et al., 2011; Heinen et al., 2011; J. R. Panter et al., 2008). Studies focused specifically on commuting report similar patterns, showing that workers who believe walking is feasible and advantageous are more likely to walk to work (de Bruijn et al., 2009; Gardner & Abraham, 2008; Heinen et al., 2010; J. R. Panter et al., 2010). Similarly, Positive attitudes toward walking, enjoyment, and intrinsic motivation are consistently associated with higher levels of leisure-time (or recreational) walking (Reichert et al., 2007; Rhodes et al., 2017; Teixeira et al., 2012). Individuals who perceive walking as relaxing, pleasurable, or beneficial for mental well-being are more likely to walk regularly for recreation (Crone et al., 2005). Perceptions of the local environment further shape participation. Adults who perceive their neighborhoods as aesthetically pleasing, green, and safe report higher levels of recreational walking, even when objective conditions are not assessed (Cerin et al., 2013; Sugiyama et al., 2010; Van Cauwenberg et al., 2012). Recent studies confirm that perceived access to parks, low traffic stress, and social cohesion are positively associated with recreational walking frequency (Barnett et al., 2017).

Socio-demographic factors also shape these relationships. Older adults often walk less for transport due to health limitations, reduced mobility, or concerns about physical capability (Cerin et al., 2017; Y. Yang & Diez-Roux, 2012). However, they are particularly responsive to perceived safety, sidewalk quality, and access to resting places when engaging in recreational walking (Cerin et al., 2017). Gender differences are also widely documented, with women more strongly influenced by perceived personal safety and social support for both transport and recreational walking (Bennett et al., 2007; S. Foster & Giles-Corti, 2008; Loukaitou-Sideris, 2014). Similar dynamics appear among younger populations. In studies of children's travel behavior, parental attitudes toward walking and perceptions of neighborhood safety strongly influence whether children walk to school (McMillan, 2007; J. R. Panter et al., 2010; Pont et al., 2009). Socioeconomic status also conditions participation: individuals in disadvantaged groups often report fewer positive environmental perceptions and lower recreational walking levels (Beenackers et al., 2012).

In contemporary transport policy, walking is being framed as a central instrument within sustainable mobility transitions instead of a residual or necessity-based mode. This shift is institutionalized in European governance frameworks. The Transport, Health and Environment Pan-European Programme is currently preparing a dedicated master plan on walking, developed in partnership with the World Health Organization and advocacy networks including Walk21 and POLIS, for adoption at the Sixth High-level Meeting on Transport, Health and Environment in 2025 (United Nations Economic Commission for Europe, 2022). Across national and local scales, active travel is increasingly positioned as a lever for decarbonization, population health, and distributive justice.

A limitation in the walking literature concerns the uneven geographical and urban distribution of empirical studies. Based on the literature reviewed in this thesis (see Chapter 2, and Table 10 and in Appendix 5), research examining the determinants of walking behavior is heavily concentrated in high-income regions, particularly North America, Western Europe, and Australia, with comparatively limited representation from low- and middle-income countries. Many empirical studies are conducted in dense urban environments such as large metropolitan regions. In contrast, smaller cities, suburban municipalities, and rural contexts remain underrepresented. Similar observations have been made in previous reviews of walking and active travel research. Systematic reviews indicate that the empirical literature on walking behavior and built environment influences is dominated by studies from the United States, Canada, Western Europe, and Australia, a pattern likely shaped by uneven data availability and research funding distributions (Kerr et al., 2016; Sallis et al., 2016). A strong concentration of studies in large metropolitan settings, with limited representation of smaller cities or rapidly urbanizing regions has been identified in existing literature. This highlights the need for research that examines walking across a broader range of urban contexts and planning environments.

Understanding why and where people do or do not walk requires a multi-dimensional approach. Considering the complex and multi-dimensional nature of walking, more studies are needed, especially in the lesser studied parts of the world, such as the Nordic region. Sweden exemplifies a distinctive approach rooted in its social-democratic planning tradition and long-standing commitments to environmental stewardship and social equity. Since the post-war era, Sweden has embraced the principle of "decentralized concentration", encouraging polycentric urban development with satellite communities connected via high-quality public transport (Hersperger et al., 2018; Meijers et al., 2007). Comprehensive municipal planning systems (översiktsplanering) and environmental legislation have embedded walking-related planning factors, such as pedestrian accessibility, safety, and environmental quality, into everyday spatial governance (Pyddoke, 2023). Recent national policies continue this legacy. The Swedish Vision Zero strategy, adopted in 1997, prioritizes pedestrian safety within transport planning frameworks, while the 2018 strategy for sustainable cities set explicit targets to increase walking, cycling, and public transport to comprise at least 25% of total personal travel distance by 2025 (Löfven & Skog, 2018). Moreover, winter-specific measures such as prioritized snow clearance on sidewalks demonstrate how walking is operationalized as a year-round mode of transport.

This thesis conceptualizes walking not only as an outcome of urban form, nor merely as an expression of individual preference, but as a behavior emerging from the interaction between urban planning and form, personal conditions, and cognitive appraisal. By focusing on two medium sized urban areas of Sweden, it addresses the contextual and spatial gap in the existing literature. By integrating spatial analysis with individual-level psychological data, the thesis seeks to advance knowledge and empirical results regarding walking as a transport mode.

1.1 Research Aim and questions

Due to the growing interest from governments worldwide in promoting walking, revealed preference data and the need of walking behavior analysis, the past decade has seen a rise in research focused on walking, particularly in relation to the decision to walk and route choice associated with pedestrian movement. An overview of the existing literature (in chapter 2) reveals that aspects of these decision-making processes are still insufficiently understood. These knowledge gaps should be addressed to better support further advancements in walking research.

The overarching aim of this thesis is to investigate which planning factors support walking as a mode of transport in a Swedish context, and to explore the underlying mechanisms and reasons behind these relationships. To address this aim, two research questions were formulated:

RQ1: How does the built environment affect walking behavior, in terms of distance, choice to walk, and choice of route?

RQ 2: What other factors (such as demographics, attitude, self-efficacy, etc.) affect the relationship between the built environment and walking behavior? What is the mediating or moderating effect of these factors?

In addition to addressing the research questions, this thesis makes a methodological contribution regarding planning factors that support walking as a mode of transport by studying pedestrians and walking behavior. It begins with exploring the effectiveness of new methods for collecting data pertaining to pedestrian activity and walking behavior and identifying the different ways in which walking can be defined (paper 1). This is followed by the development of a questionnaire to measure the psychological correlates of walking behavior based on the theory of planned behavior (paper 2). This questionnaire contains attitude and perceived control questions pertaining to walking behavior, and specific questions related to the built environment.

1.1.1 Delimitations

This thesis has several delimitations that define its scope and distinguish it from similar areas of walking research. The focus is on transport (or utilitarian) walking, i.e., walking as a mode of transport, in urban Swedish contexts, examined through the lens of spatial planning and the built environment. This means the thesis does not address recreational (or leisure) walking as a primary outcome, nor does it engage with the governance, policy process, or political dimensions of walking promotion. Equally, while psychological factors are incorporated as explanatory variables, the thesis is not a study in health psychology or behavioral science: attitudes and perceived control are treated as predictors of transport behavior rather than as outcomes. These boundaries are the disciplinary framing of the research and the practical orientation of its findings in relation to planning for pedestrians and utilitarian walking.

As discussed in the previous section, there are cross-national differences in planning practices, urban form and walking behavior, and few studies on or of walking behavior studies of small and medium sized cities of the Nordic region. Since there is a drive to improve and encourage walking in Sweden, there is a need to understand walking behavior in a Swedish context. Since the built form and motivations for walking are also different in urban and rural areas, this study focuses on urban areas. Built environment and walking behavior data were collected and cleaned to include only areas within the urban limits. The boundaries of urban limits are defined by the municipalities.

Different types of walking are studied in different studies: transport, recreational or all walking. This thesis distinguishes between pedestrians and walkers, following conventions in transport and public-health research. A pedestrian refers to a person traveling on foot at a given moment and is a mode-based, situational designation. A walker, in contrast, refers to an individual characterized by their engagement in walking behavior over time and is a behavior-based classification (Jack & McCormack, 2014). In this thesis, we also focus on transport walking, also known as utilitarian walking. Transport walking is defined as any form of travel on foot, including the use of mobility aid for those with mobility impairments, undertaken to reach a destination from an origin. This thesis excludes recreational walking (e.g., trips with identical origins and destinations, such as home-to-home trips or those identified by participants as exercise) and indoor walking (e.g., within shopping centers or university buildings).

1.2 Thesis Outline

The thesis consists of six main chapters: Chapter 1 begins with a short description of the motivation for the research and the research aims and questions; Chapter 2 provides a discussion of the existing theoretical frameworks and methodologies related to walking and reflections from previous research; Chapter 3 describes the research design, study areas, data collection processes and data analysis methods; Chapter 4 summarizes the four papers (attached in full in appendices 1 to 4); Chapter 5 aggregates and synthesizes the results from the four papers, and provides insights based on the cross-paper results comparison; Chapter 6 recapitulates the research questions and presents the conclusions and discusses the contributions and limitations of the thesis. At the end of the thesis are a series of appendices consisting of the four papers, the two sets of questionnaires (for Umeå and Linköping), two literature review tables synthesizing literature on the relationship between walking behavior, psychological constructs and built environment, at the neighborhood and route levels and finally additional results that could not be included in the main text.

2. BUILT ENVIRONMENT AND WALKING BEHAVIOR

This chapter reviews theoretical frameworks based on quantitative studies that aim to explain how the built environment (BE) shapes walking behavior, providing a foundation for understanding walking as a multidimensional activity shaped by social, spatial, and cognitive processes. Further, it discusses deficiencies in conceptualizing walking behavior, focusing on methodological and measurement considerations. Subsequently, it reviews quantitative studies on walking behavior, identifying the environmental, psychological and socio-economic determinants mainly based on Theory of planned behavior (TPB). The chapter concludes with a summary highlighting gaps in current knowledge.

2.1 Existing Theoretical Frameworks

Walking as a mode of transport is understood through multiple overlapping theories linking urban form to human behavior (Gehl, 2010, 2011; Jacobs, 1961). Early frameworks in urban planning and transport focused on physical design: Jacobs observed that mixed-use, diverse neighborhoods with active street fronts encourage walking by enhancing safety and interest. Gehl's observational work similarly showed that pedestrian-scale features, such as sidewalks, street furniture, active ground-floor use, support walking for both errands and leisure. Models such as Cervero & Kockelman's (1997's) "3Ds" (density, diversity, design), later extended to 5Ds (destination accessibility and distance to transit; Ewing & Cervero, 2001) and 6Ds (demand management; Ewing & Cervero, 2010), propose that compact, connected, mixed-use environments are associated with higher walking rates. These frameworks treat the BE as the primary driver: walkable design reduces travel distances and increases destination options, making walking more feasible (Ewing & Handy, 2009; Leslie et al., 2005).

Behavioral theories, by contrast, emphasize individual cognition and motivation. TPB (Ajzen, 1991), for instance, holds that a person's intention to walk depends on their attitudes toward walking, perceived social norms, and perceived behavioral control (PBC). A well-designed streetscape will only produce walking if people believe they can and should walk there. Empirical reviews find that attitudes and perceived control are strong predictors of active travel intentions (Bamberg & Möser, 2007; Gardner & Abraham, 2008), suggesting that BEs affect walking or the choice to walk through psychological mediators rather than directly.

A central insight across both traditions is that both the BE and subjective perceptions matter. People's perceived walkability, such as their sense of safety, aesthetic appeal, and comfort, often predicts walking behavior better than objective measures of density or connectivity (J. A. Carlson et al., 2012; Leslie et al., 2005). Two neighborhoods with identical street networks may generate different walking levels if residents perceive them differently. Ewing & Handy (2009) identified urban design qualities, such as imageability, enclosure, human scale, that shape these perceptions of comfort and visual interest. Alfonzo's (2005's) Hierarchy of Walking Needs integrates these ideas, describing walking as a decision process in which basic needs (feasibility, safety) must be met before higher-order needs (comfort, pleasurability) become relevant. Lower levels depend on personal and demographic constraints (age, health) as well as basic infrastructure; higher levels depend on environmental conditions and how people subjectively assess them.

Figure 1 synthesizes the frameworks of Ewing and Handy (2009) and the TPB (Ajzen, 1991). BE attributes have both direct and indirect effects on walking. Direct effects occur when infrastructure or proximity reduces the effort of walking, for example grid-like street layouts shortening distances. Indirect effects operate through psychological pathways: a park may not generate trips by itself, but it can improve attitudes toward walking or provide pleasant routes that encourage pedestrian activity. Recent studies support this mediation view. Shi et al. (2025) found in an urban sample that both objective and perceived environmental features mediated the influence of residential preferences on commuting walking, while only perceived features mediated recreational walking, implying that people's values and preferences operate through both what the environment is and how it feels.

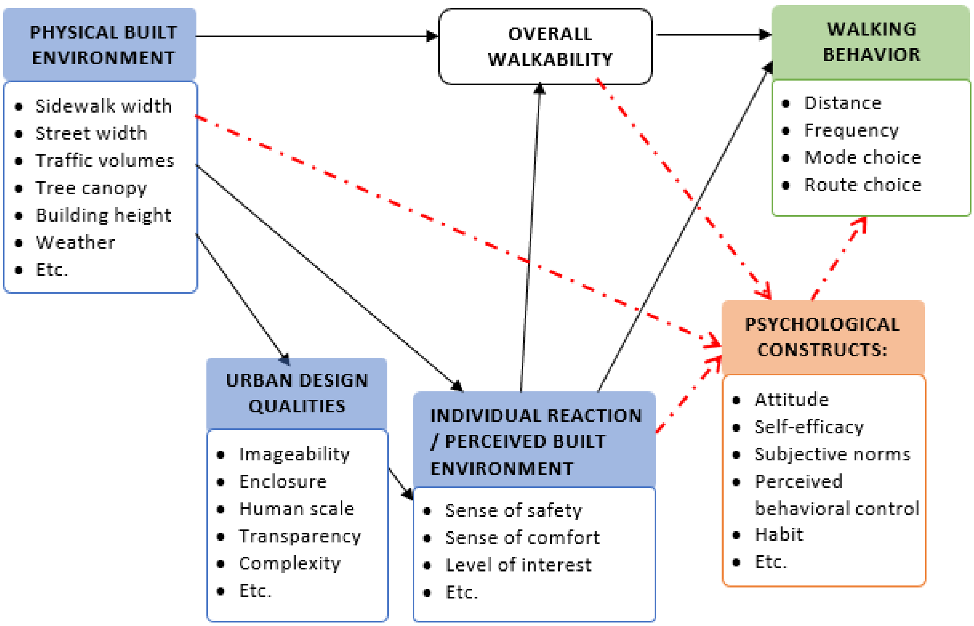


Figure 1: Integrating existing theoretical frameworks on the interaction between the built environment and walking

Moderation mechanisms are also recognized. The effect of the BE on walking may vary by demographic or contextual factors: improved sidewalks might increase walking more among older adults or women if they reduce safety concerns (J. R. Panter & Jones, 2010; Shi et al., 2025). These interactions are rarely tested explicitly, but according to the framework the link between street design and walking may be stronger or weaker depending on household car access, cultural norms, or climatic conditions. In the Swedish context, high baseline winter walkability and strong welfare norms suggest that psychosocial factors such as habit or perceived health benefits may play a relatively larger role than in some other countries (Chapman et al., 2017, 2019). Evidence on whether environment–walking relationships differ in Nordic cities remains limited, and this gap is an important motivation for the current thesis.

Existing theoretical frameworks thus unite planning and psychology. Urban design models (Cervero & Kockelman, 1997; Gehl, 2010, 2011; Jacobs, 1961) provide the structural context; TPB and other social-cognitive theories explain how that context is interpreted by individuals. Alfonzo's hierarchy illustrates the layered needs that shape walking decisions, and Figure 1 integrates these levels by showing how environmental attributes, perceptions, and intentions interact. This synthesis guides the analytical approach of the thesis: testing mediation (how perceptions translate design into walking) and moderation (for whom and when design matters), with particular attention to gaps in the Nordic research context.

2.2 Conceptualizing Walking Behavior

Walking has been studied across multiple disciplines, yet the precise definition of "walking behavior" remains conceptually contested. Across the behavioral literature reviewed in this thesis (refer to Table 10 and in Appendix 5) spanning more than two decades and contexts from suburban Australia to Chinese resettlement towns, researchers have approached walking through distinct disciplinary lenses, with different assumptions about what kinds of walking matter, how behavior should be described, and what units of measurement are appropriate. This section focuses on behavioral studies of walking, setting aside pedestrian counting and flow studies, which address aggregate infrastructure use and not individual behavior.

There is a clear division in the literature between walking undertaken for a specific destination (variously termed destination walking (C. Carlson et al., 2012), utility walking (Agrawal & Schimek, 2007), purposive walking (Rodrigue et al., 2024), or transport walking (Cerin et al., 2007; Hirsch et al., 2014; Van Dyck et al., 2012); utilitarian walking (Koszowski et al., 2024; Stewart et al., 2016)), and walking in which the journey itself is the primary purpose, such as strolling (also known as recreational walking (Giles-Corti et al., 2005; Van Holle et al., 2015) or leisure walking (Ball et al., 2001; H.-S. Lee & Shepley, 2012; Rhodes et al., 2006)). These types of walking have often been treated as exclusive, even though they frequently describe different aspects of the same trip: a walk to daycare through a park is simultaneously purposive, recreational, and neighborhood based. The classifications are also too blunt to capture what transport walking requires in practice.

The studies reviewed repeat this division. Many focus exclusively on leisure or recreational walking (Ball et al., 2001; Beenackers et al., 2013; H. S. Lee, 2016; Lovasi et al., 2008; Rhodes et al., 2006); others restrict attention to transport walking (Cerin et al., 2007; Kamruzzaman et al., 2016; Li et al., 2020; Turrell et al., 2014); and a growing number distinguish both in parallel (Koohsari et al., 2023; Owen et al., 2007; Shi et al., 2025; Van Dyck et al., 2012; Watson et al., 2020). More recently, purpose-specific breakdowns have become finer-grained, distinguishing commuting, errands, and leisure as separate categories (Cho & Rodriguez, 2015; Koszowski et al., 2024; Shi et al., 2025), while some studies capture all walking regardless of purpose (Almagor et al., 2024; Christie et al., 2022; Shen & Ryan, 2026).

Another ambiguity concerns whether walking segments are embedded in multimodal trips, i.e., the walk to a bus stop or station access, are included in or excluded from behavioral measures. Walking 250 meters to a bus stop is not behaviorally, environmentally, or motivationally equivalent to walking 1.5 kilometers directly to work; the two differ in purpose, spatial context, frequency, and physical effort. That is, four 250-meter access walks are not equivalent to a single 1-kilometer direct trip, even if daily totals are similar. This distinction matter for understanding environmental determinants, since the street conditions relevant to transit access walking may differ substantially from those shaping a direct pedestrian commute (Agrawal & Schimek, 2007; J. X. Liu et al., 2021).

Some studies make their scope explicit: Almagor et al. (2024) excluded walking legs forming part of continuous multimodal trajectories to avoid conflating modes within a single journey. National travel surveys in countries such as USA, UK and Netherlands (Agrawal & Schimek, 2007; Gao et al., 2023; Sarkar et al., 2015) capture all reported walking trips but cannot control for whether transit access walking is consistently included. Purpose-specific self-report studies such as Y. Yang & Diez-Roux (2017) rarely clarify whether transit access should be counted under transport walking. Most reviewed studies make no clear statement on this question. When scope is left undefined, survey respondents apply their own interpretive frameworks, which differ across individuals and contexts.

2.2.1 Methodological considerations

At the individual level, walking behavior is often measured primarily as aggregated volume data or as mode choice. Aggregated measures include distance per day, minutes per week, and trip or day frequency. Weekly minutes is the most common measure across the literature (Koohsari et al., 2023; Owen et al., 2007; Shi et al., 2025; Turrell et al., 2014; Van Dyck et al., 2012), while frequency-based measures are more common in transport-oriented studies (Koohsari et al., 2016; Lindelöw et al., 2017). Walking was measured through self-rating in the large majority of reviewed studies, using instruments such as the IPAQ (Van Dyck et al., 2012); Koohsari et al., 2016, 2023), national travel surveys and travel diaries (Almagor et al., 2024; Cervero & Duncan, 2003; Gao et al., 2023), or purpose-designed questionnaires (Shen & Ryan, 2026; Turrell et al., 2014; Watson et al., 2020). Distance is less common in survey-based research given the difficulty of accurate self-estimation, though GPS-based studies have increasingly enabled distance indicators at trip and daily levels (Almagor et al., 2024), including threshold-based classifications (e.g., less than 400 m, 400 to 800 m, more than 1 km) used to model distance-decay (Rodríguez & Joo, 2004). In studies using app-based travel data, walking distance is derived through algorithmically classified trip segments, with each walking trip automatically geocoded and its route and length inferred from GPS traces and spatiotemporal patterns (Technische Universität Dresden, 2020). These datasets allow for indicators such as average walking distance per trip, total daily walking distance, or the share of daily distance covered on foot, enabling both absolute and relative comparisons across individuals and populations. Mode choice operationalizations treat walking as a competing alternative within a trip decision. Many studies simplify this to a binary of walk versus no walk (or all other modes) (Adams et al., 2016; Ball et al., 2001; Beenackers et al., 2013; Cho & Rodriguez, 2015; Dalton et al., 2013; Jack & McCormack, 2014b; Orrego-Oñate & Marquet, 2025; Yu, 2024) while others model multiple alternatives including cycling, public transport, and car (Bondemark, 2023; Heinen et al., 2015; Lemieux & Godin, 2009; Molina-García et al., 2010).

Route choice research shifts focus from how much people walk to where and through what environments they choose to walk, offering a more direct link between BE attributes and pedestrian experience than aggregate volume measures can provide. Traditional travel surveys assume shortest-path routing or use street-network buffers to approximate exposure, but GPS-based research has shown that pedestrians frequently deviate from the shortest route due to aesthetics, perceived safety, and personal preference (Ewing & Handy, 2009; Rodríguez et al., 2015). Hoogendoorn & Bovy (2004) established a theoretical framework characterizing pedestrian route selection as a continuous spatial optimization trading off destination utility against perceived walking costs, compared to the more basic notion of distance minimization. Guo and Loo (2013) quantified pedestrians' willingness to detour toward active frontages and away from arterials across New York City and Hong Kong. Route-level indicators, including detour, perceived pleasantness, traffic exposure, and environmental quality along walking paths, provide a behaviorally salient representation of the environments encountered during movement. Evidence from route-based studies demonstrates that such attributes are associated with walking behavior (J. Panter et al., 2014; J. Panter, Griffin, et al., 2011), while a broader body of research highlights the importance of perceived environmental qualities such as aesthetics and safety (C. Foster et al., 2004; Van Dyck et al., 2012). These environmental influences operate in conjunction with psychological constructs, with studies grounded in TPB indicating that attitudes, PBC, and intentions mediate or condition environment–behavior relationships (McCormack et al., 2013; Rhodes et al., 2006).

2.2.2 Measurement considerations

Table 1 summarizes the methods used for measuring walking behavior. Early behavioral walking research relied often on recall-based surveys, typically covering the past seven days (C. Foster et al., 2004; Owen et al., 2007; Van Dyck et al., 2012). While efficient for large samples, self-report is subject to recall bias, rounding errors, and inconsistent definitions of walking bouts. Walking distance is particularly difficult to self-estimate accurately (Rodríguez & Joo, 2004). When survey instruments leave scope undefined, respondents apply their own interpretive frameworks, introducing systematic variance. GPS-assisted travel surveys suggest that walking trips are disproportionately underreported relative to motorized modes, and that underreporting worsens as the diary period extends (Bohte & Maat, 2009).

From the late 1990s, physical activity research adopted objective activity monitors to address these limitations. Pedometers measure cumulative step counts and have been used extensively in population-level walking research; Tudor-Locke & Bassett (2004) provided reference thresholds for interpreting step-count data. Accelerometers register movement intensity as acceleration counts and have been used in epidemiological and physical activity research (Stewart et al., 2016; Sundquist et al., 2011; Van Holle et al., 2015). Neither instrument captures trip purpose, origin-destination structure, or route, and variation across studies limits comparability. These limitations make both methods poorly suited to the trip-level questions central to transport walking research, which may partly explain their greater use in physical activity epidemiology than in transport-oriented behavioral studies.

Table 1: Summary of measurement methods

Method	What it Measures	Examples
Self-report (survey)	Frequency, duration, purpose of walking	Ball et al. (2001); Cerin et al. (2007); Van Dyck et al. (2012)
Accelerometer/pedometer	Steps, duration, intensity	Sundquist et al. (2011)
GPS/smartphone tracking	Routes, speed, distance, spatial exposure	Almagor et al. (2024); R. Basu & Sevtsuk (2022); Lieu & Guhathakurta (2025); Stewart et al. (2016); Sevtsuk et al. (2021)
GIS-BE overlay	Exposure to BE during trips	Feuillet et al. (2016); Van Dyck et al. (2014); Van Holle et al. (2015)

GPS tracking enables continuous, objective measurement of location, distance, duration, speed, and spatial trajectory. When integrated with travel diaries or smartphone apps supports trip detection, mode classification, and route reconstruction (Almagor et al., 2024; Stewart et al., 2016). GPS-based distance estimation has begun to reveal trip-level route distance distributions that challenge common planning thresholds regarding how long people actually walk (Almagor et al., 2024). However, signal accuracy degrades in dense urban environments due to building obstruction; indoor environments produce complete signal loss; and battery constraints in smartphone applications introduce temporal gaps. Mode detection requires additional sensor fusion or post-processing to distinguish walking from slow cycling or stationary bus travel (Huang et al., 2019). Continuous location tracking also raises ethical concerns around privacy, consent, and data security, GPS traces can reveal home locations, health facility visits, and daily routines, contributing to recruitment challenges. GPS-based samples therefore tend to be substantially smaller than survey-based studies, limiting statistical power and generalizability. For these reasons, GPS data collection is typically combined with survey instruments capturing trip purposes, sociodemographic characteristics, and attitudinal variables that location data alone cannot provide, and this pairing is likely to remain the methodological standard for the foreseeable future.

2.3 Behavioral and Spatial Determinants of Walking

A body of research has examined the psychological and environmental correlates of walking and other forms of active transportation, reflecting a rising interest in understanding the complex interplay of individual motivations, social influences, and BE characteristics. Table 10 (in Appendix 5) summarizes the studies analyzing the environmental, psychological and socio-demographic correlates of walking behavior and (in Appendix 5) summarizes the studies on pedestrian route choice (PRC). Together, the tables provide a structure for navigating the reviewed literature. By cataloguing each study's geographic context, sample characteristics, methodological design, and key findings, these tables enable cross-study comparisons that are difficult to convey in continuous text and render the empirical basis transparent, allowing readers to assess areas of convergence, divergence, and remaining gaps. These studies, conducted across diverse geographic and socio-demographic contexts, yield complementary findings that can be organized according to type of activity and methodological approach. This section reviews quantitative research on walking behavior, focusing on psychological, environmental, and socio-demographic determinants.

2.3.1 Psychological determinants

Psychological determinants of walking are commonly examined using social-cognitive frameworks, most notably TPB (Ajzen, 1991). At the same time, a growing body of research takes a broader psychosocial approach without explicitly anchoring analyses in a single theory, drawing on constructs such as self-efficacy, social support, perceived barriers, and affective dispositions. Across both traditions, walking is generally treated as a behavior shaped by cognitive evaluations, perceived capability, and motivational states, rather than being driven by external conditions alone.

Across the literature, a relatively stable set of psychological variables appears repeatedly. Attitudinal constructs, often separated into instrumental (utility-based) and affective (experience-based) components, are used to capture evaluative orientations toward walking (Beenackers et al., 2013). PBC, and its closely related conceptual analogue self-efficacy, represent perceived capability and are frequently identified as central predictors (Neto et al., 2020; Wilcox et al., 2003). When measured, intention is typically treated as a proximal motivational indicator of planned behavior (Huo et al., 2025; H.-S. Lee & Shepley, 2012). Beyond these constructs, studies often incorporate additional psychosocial dimensions. Social support and broader forms of social influence are commonly examined, particularly in health-oriented research (Beenackers et al., 2013; Wilcox et al., 2003). Perceived barriers and benefits reflect cognitive appraisals of constraints and rewards associated with walking (De Geus et al., 2008). Habit is sometimes introduced, especially in studies with longitudinal or repeated-measures designs, as a potential mechanism through which behavior becomes more stable over time (Bird et al., 2018). More recent extensions also include constructs such as willingness and social prototypes, reflecting more reactive and socially embedded decision processes that may operate alongside, or partly outside, deliberate intention (Huo et al., 2025). Although these constructs originate from different theoretical traditions, they overlap conceptually in several ways, particularly around perceived capability and evaluative judgement.

Three broad patterns repeat across studies. First, perceived capability, operationalized as PBC or self-efficacy, emerges as the most robust and generalizable predictor of walking. It shows associations with both intention and behavior across diverse contexts, including Brazil (Neto et al., 2020), China (Huo et al., 2025), and the United States (Wilcox et al., 2003). In several cases, it uses both direct and indirect effects, indicating its role in translating motivation into action. Second, attitudinal factors are often associated with higher levels of walking, particularly for leisure and optional trips. Positive opinions about walking predict walking in both European and North American contexts (Beenackers et al., 2013; Neto et al., 2020) and remain significant in longitudinal behavior change analyses (Bird et al., 2018). Third, intention demonstrates predictive value where explicitly modelled, but its role is less consistent than that of perceived capability. While intention is a significant mediator in several studies (H.-S. Lee & Shepley, 2012), its explanatory power reduces when habitual or situational processes are integrated (Bird et al., 2018; Huo et al., 2025). This suggests that walking is only partially governed by deliberate planning and may also reflect routinised or context-responsive behavior. In contrast, social influence variables show weak and inconsistent effects. Subjective norms rarely show statistical significance in TPB-based models (Bird et al., 2018; Neto et al., 2020), while broader constructs such as social support demonstrate context-dependent relevance, particularly in specific populations such as older adults (Wilcox et al., 2003). This indicates that walking behavior is less regulated by perceived social pressure than by individual capability and personal perception.

2.3.2 Environmental determinants

a. Early research

The relationship between the BE and walking behavior has been examined across multiple disciplines for several decades, with seminal contributions from transportation planning, urban design, and public health. The BE has been operationalized through both subjective and objective measures -transportation-origin research being almost entirely objective, while the public health literature has leaned more toward perceived measures. Owen et al. (2004) reviewed 18 studies focused specifically on walking, identifying aesthetic attributes, convenience of facilities, and destination accessibility as correlates of recreational walking, and sidewalk presence, proximity to stores, and traffic perceptions as correlates of transport walking.

They found that environmental correlates varied systematically by walking purpose. Saelens and Handy (2008) subsequently synthesized 13 existing reviews and 29 original studies published in 2005–2006, confirming positive associations between transport walking and density, land use mix, and proximity to destinations; findings for route connectivity, parks, and personal safety were equivocal, while those for recreational walking was notably weaker and less consistent. Across all three reviews, walking was assessed almost exclusively by self-report. Methodological limitations included near-universal cross-sectional designs, geographically concentrated sampling (predominantly the United States and Australia), limited attention to population subgroups, and insufficient behavioral specificity in both exposure and outcome measurement (Owen et al., 2004; Saelens & Handy, 2008). These reviews collectively called for prospective designs, objective measurement of both walking and the BE, multilevel modeling, and broader demographic and geographic coverage -gaps that have shaped the trajectory of the subsequent literature.

b. Measures of Built Environment

Studies since 2000 have used both objective and perceived measures of the BE independently, and increasingly in combination within the same study. Subjective measures rely on residents' perceptions of neighborhood attributes, safety, aesthetics, convenience, and proximity to destinations, often assessed through instruments such as the NEWS and its variants (Ball et al., 2001; C. Foster et al., 2004; Van Dyck et al., 2012), while objective measures use GIS-derived indicators.

Composite walkability indices became increasingly used from around 2010, reflecting improvements in spatial data infrastructure and computational capacity. They typically combine residential density, intersection density, land use mix, and proximity to transit or retail (Christie et al., 2022; Koohsari et al., 2016; Sundquist et al., 2011; Watson et al., 2020). Specific objective variables most commonly examined include population and employment density (Agrawal & Schimek, 2007; Almagor et al., 2024; Cervero & Duncan, 2003; Hirsch et al., 2014; Huang et al., 2019) land use diversity or entropy (Chen et al., 2024; Gao et al., 2023; L. Yang et al., 2024), street connectivity and intersection density (Koohsari et al., 2016, 2023), proximity to and quality of public open space (Cho & Rodriguez, 2015; Giles-Corti et al., 2005), street-level greenery and tree canopy (Sarkar et al., 2015; L. Yang et al., 2024), and transportation infrastructure (Gao et al., 2023; Heinen et al., 2015; Hirsch et al., 2014). Space syntax measures of street integration have been applied as an alternative connectivity operationalization (Almagor et al., 2024; Koohsari et al., 2016; Sarkar et al., 2015). A growing number of recent studies combine objective and perceived measures to compare their relative contributions (Orrego-Oñate & Marquet, 2025; Shen & Ryan, 2026; Stewart et al., 2016).

A further source of methodological variation concerns how the spatial unit of BE exposure is defined. The dominant approach across the reviewed literature is potential exposure, also termed residential or activity-based exposure, referring to the environmental conditions individuals could potentially encounter based on proximity to their home or other activity location such as work. Two operationalizations are common within this approach. Zone-based measures use pre-existing administrative boundaries such as census block groups (Watson et al., 2020), census collection districts (Cerin et al., 2007; Koohsari et al., 2016), postal code areas (Gao et al., 2023; Koohsari et al., 2023), or statistical zones (Almagor et al., 2024; Chen et al., 2024; L. Yang et al., 2024). These are computationally convenient and enable linkage to administrative datasets, but administrative units vary substantially in size, shape, and internal homogeneity across cities and countries, making cross-study comparisons problematic and potentially introducing aggregation bias when boundaries do not align with residents' functional neighborhoods.

Buffer-based measures, also termed egocentric, proximity-based, or distance-based, define the exposure area as a geometric zone of specified radius around the home address, ranging widely across studies: 400 m Euclidean buffers (Christie et al., 2022; Koohsari et al., 2023), 0.5-mile buffers ((Huang et al., 2019; Sarkar et al., 2015), 1 km buffers (Lovasi et al., 2008; Stewart et al., 2016), and 1-mile buffers (Hirsch et al., 2014). Euclidean buffers are simpler to compute but might overestimate accessible area by ignoring the actual street network. Isochrone-based delineation, defining the area reachable within a fixed travel time such as a 15-minute walk (Orrego-Oñate & Marquet, 2025), is conceptually appealing because it grounds spatial exposure in human movement directly, though the method is rare. A minority of studies report sensitivity analyses across buffer sizes (Hirsch et al., 2014), which is good practice given that the appropriate spatial scale of BE influence likely varies by outcome type, trip purpose, and urban context. Network-based or "sausage" buffers, an operationalization of realized exposure, follow the walkable path structure and provide more ecologically valid exposure estimates (Stewart et al., 2016) but require higher-resolution street data. Realized exposure, meaning the environmental conditions individuals actually encounter as they move through urban space, is primarily the domain of route choice research. Stewart et al. (2016) represent an important exception, integrating GPS tracking with accelerometry and travel diaries to characterize the environment along observed walking trajectories rather than around the home, enabling a more direct test of environment–behavior relationships during actual movement.

The heterogeneity in spatial exposure definitions is compounded by studies that provide no explicit definition of the neighborhood or measurement area. At least ten studies in Table 10 (in Appendix 5), including several using perceived BE instruments, specify no spatial boundary for the neighborhood construct (Ball et al., 2001; Cervero & Duncan, 2003; C. Foster et al., 2004; Koszowski et al., 2024; Stefánsdóttir et al., 2024; Sundquist et al., 2011; Turrell et al., 2014; Van Dyck et al., 2012). In surveys relying on perceived neighborhood ratings, this ambiguity is consequential: when respondents are asked to evaluate their "neighborhood" without a defined boundary, individuals vary widely in how they interpret the spatial extent of the term, some may consider a few surrounding blocks, others an entire suburb or administrative district. This variability introduces measurement error that is difficult to quantify and may attenuate or distort observed environment–walking associations (Saelens & Handy, 2008). Even where buffers are defined objectively, the choice of size is typically made on practical or conventional grounds rather than on evidence about the spatial scale at which the BE most strongly influences walking, a scale that likely differs between transport walking, which may respond to neighborhood-level accessibility patterns, and recreational walking, which may be more sensitive to streetscape conditions. The wide variation in spatial exposure definitions, spanning undefined perceptual neighborhoods, administrative zones of varying size, Euclidean buffers from 400 m to 1.6 km, network buffers, and isochrones, constitute a significant source of cross-study incomparability about which specific BE attributes, at which spatial scales, most reliably support walking behavior.

c. Key Results: Utilitarian or Transport Walking

The clearest pattern in the literature concerns transport or utilitarian walking. Higher residential and employment density, greater land use diversity, and better street connectivity have been repeatedly linked to more transport walking across countries and methods (Agrawal & Schimek, 2007; Cerin et al., 2007; Cervero & Duncan, 2003; Chen et al., 2024; Hirsch et al., 2014; Koohsari et al., 2016; Van Dyck et al., 2012; Watson et al., 2020; L. Yang et al., 2024). Destination access is a particularly robust predictor: Cerin et al. (2007) linked diverse destinations to transport walking frequency; Cho and Rodriguez (2015) showed destination-specific effects for walking to work, shopping, and entertainment; and Koohsari et al. (2023) found that street integration predicted transport walking partly by facilitating destination access, a mediated pathway. Watson et al. (2020) documented stepwise increases in transport walking across walkability categories in a large U.S. national sample. Objective walking data tell a similar story: Sundquist et al. (2011) linked neighborhood walkability to greater accelerometry-based activity; Huang et al. (2019) found residential and job density predicted more walking bouts near home (where over half of all bouts occurred); and Almagor et al. (2024), using GPS data across 21 cities, found intersection density and city population independently associated with longer routes. Results from longitudinal studies, though limited, aligns with this: Hirsch et al. (2014) found that higher baseline density, retail concentration, and connectivity predicted growth in transport walking, with increases in destination availability and connectivity independently predicting walking growth. A review of 23 longitudinal studies (Bandara et al., 2025) concluded that improvements in street connectivity, destination access, and transit availability increase transport walking. Road characteristics and residential density alone, however, show inconsistent associations.

However, the picture is not uniform. Christie et al. (2022) found negative associations between street connectivity and walking in their primary sample, a reminder that high connectivity does not automatically produce more walking, possibly because it correlates with socioeconomic neighborhood characteristics or unmeasured barriers. identified a socioeconomic paradox: residents of more disadvantaged neighborhoods walked more for transport, while lower individual-level education, occupation, and income were simultaneously linked to less walking, a distinction between neighborhood- and individual-level effects that aggregate analyses can miss. Heinen et al. (2015), studying new busway infrastructure as a natural experiment, found that proximity to the intervention raised the probability of shifting toward active commuting but did not affect trip frequency or total distance, suggesting new infrastructure can reshape modal choices without increasing overall walking volume. Gao et al. (2023) showed that weather moderated BE–walking associations in the Netherlands, with warm and dry conditions amplifying the positive effect of bus stop proximity on transit-related walking, a moderator that most studies ignore.

d. *Key Results: Leisure and Recreational Walking*

Evidence linking the BE to leisure or recreational walking is less consistent and involves a different set of environmental attributes. Perceived and objective aesthetic qualities, attractive scenery, greenery, pleasant settings, have been positively associated with recreational walking in multiple studies (Ball et al., 2001; Giles-Corti et al., 2005; Koszowski et al., 2024). Giles-Corti et al. (2005) found that access to large, high-quality, attractively designed public open space substantially increased the odds of high-volume walking; around 70% of observed pedestrians used the more attractive spaces. Personal safety perceptions are similarly relevant (Foster et al., 2004; Koszowski et al., 2024). Koszowski et al. (2024) also found that frequent pedestrians rated aesthetic "delight" higher than infrequent walkers, and that distance and directness dominated decision-making for transport trips but were secondary to comfort and aesthetics for recreational walks.

The structural BE attributes most predictive of transport walking, density, connectivity, and land use mix, show weaker and less consistent associations with recreational walking. Koohsari et al. (2023) found no association between street integration and recreational walking despite significant effects for transport walking. Lovasi et al. (2008) found that no individual or composite BE feature (including density, connectivity, destination access, or park proximity) predicted walking for exercise in a validation sample, with models explaining less than 1% of variance, a null result that points to the limits of applying transport-oriented BE frameworks to recreational walking. This dissociation between BE correlates of transport and recreational walking, noted earlier by Owen et al. (2004) and Saelens et al. (2003), is supported by more recent literature. Stewart et al. (2016), using accelerometer-GPS measurement, found that restaurant proximity was positively associated with transport walking in urban Seattle but inversely associated in small towns, where recreational walking predominated and perceived slow traffic speed was the only BE attribute that mattered, illustrating how context shapes which environmental attributes are behaviorally relevant. Yang et al. (2024) further identified non-linear and synergistic BE effects: recreational facility access and land use mix were most influential, but both interacted with intersection density in non-additive ways, so BE variables examined in isolation likely understate their combined influence.

e. *Socio-demographic Variables*

Socio-demographic variables appear across the reviewed literature, though their analytical role ranges from covariate adjustment to active examination of moderation and mediation. Most studies include age, gender, education, income, and car ownership as controls to isolate BE effects (Cervero & Duncan, 2003; Gao et al., 2023; Hirsch et al., 2014; Van Dyck et al., 2012; Watson et al., 2020). A smaller but growing subset treats these characteristics as substantively important moderators.

Gender differences in BE-walking associations have been reported across several studies. C. Foster et al. (2004) found that parks within walking distance predicted achieving recommended walking levels among men, while safety and local shops were more relevant for women. Shen and Ryan (2026) found that the path from walking to physical health outcomes was stronger among females, with gender moderating the walking-health pathway. Stefánsdóttir et al. (2024) similarly found that men and women differed in which walking environments they preferred and which barriers they reported. Research on older adults suggests that walking levels and their environmental correlates may shift with life stage: Turrell et al. (2014), tracking transport walking across three survey waves in a cohort aged 40–70, found that weekly walking minutes declined in follow-up data collection, with steeper declines at older ages and among retired and lowest-income individuals. Almagor et al. (2024) found that adolescents (12–17) had the longest walking routes across age groups, while greater household car access was associated with shorter routes at all ages.

Mediation analyses remain underrepresented. Koohsari et al. (2023) showed that destination availability partly mediated the street integration–transport walking relationship, and Orrego-Oñate & Marquet (2025) showed that perceived accessibility partially mediated objective environment effects on walking mode choice, with perceived proximity particularly influential for restaurant-trip walking. These are exceptions. The field has largely stayed at the level of demographic controls rather than moving toward theoretically grounded moderation and mediation frameworks.

f. Cultural and Climatic Context

Cultural setting and climatic conditions are sources of variability that complicate cross-study synthesis. Van Dyck et al. (2012) comparing BE-walking associations across countries using the NEWS, found that while land use mix, street connectivity, and infrastructure were broadly associated with transport walking, effect sizes varied across national contexts, pointing to cultural norms around car use, urban form traditions, and infrastructure investment as likely moderators. Weather has received limited but relevant attention: Gao et al. (2023) found that warm, dry weekday conditions amplified the positive effect of bus stop proximity on walking to transit in the Netherlands, while inclement weather suppressed these associations, an interaction most studies do not address. Stefánsdóttir et al. (2024), in a mixed-method study in Iceland, identified winter maintenance (snow and ice removal, gritting, lighting) as the most frequently cited walkability improvement needed, and found that car-oriented urban structure and dispersed amenities substantially constrained walking feasibility. These findings caution against assuming that relationships between the BE and walking are transferable across contexts without accounting for local cultural, climatic, and BE conditions.

2.3.3 Interaction between psychological, environmental and socio-demographic determinants

Early research on walking behavior drew primarily on social-cognitive frameworks, particularly the TPB (Ajzen, 1991), which treats walking as a function of attitudes, subjective norms, PBC, and intention. Within this tradition, BE attributes were proposed as theoretically important extensions: environmental features were argued to shape the psychological antecedents of behavior rather than operating independently of them (H.-S. Lee & Shepley, 2012; Rhodes et al., 2006). A parallel strand of environmental and transport geography examined associations between objectively measured urban form and walking in isolation, an approach criticized as physical determinism, meaning the assumption that the physical environment directly and uniformly determines behavior without accounting for individual psychological predispositions, values, or volitional processes (S. L. Handy, 1996; Riggs, 2014). The limits of both single-framework approaches have increasingly been recognized, and a growing literature now examines psychological and environmental attributes together, exploring how they interact to shape walking behavior.

a. Measurement Approaches

The psychological constructs measured across reviewed studies range from comprehensive multi-component TPB questionnaires to narrower attitude-only or self-efficacy measures. Full TPB operationalization, capturing attitude, subjective norm, PBC, and intention, is confined to studies explicitly testing the TPB as a theoretical framework (H.-S. Lee & Shepley, 2012; J. Lee, 2016; Lemieux & Godin, 2009; McCormack et al., 2013; Rhodes et al., 2006; Y. Wang et al., 2024). Studies outside that tradition often retain one or more TPB components as cognition proxies. Attitude toward walking is the single most commonly retained construct (Adams et al., 2016; Jack & McCormack, 2014; Y. Yang & Diez-Roux, 2012), consistent with the view that walking attitudes form the primary psychological link between environment and behavior. Self-efficacy, conceptually close to PBC but theoretically distinct, is prominent in studies drawing on Social Cognitive Theory or hybrid frameworks (Molina-García et al., 2010; Nguyen & Mertens, 2021; Van Holle et al., 2015; Y. Wang et al., 2024). Habit, measured via the Self-Report Habit Index, appears in active commuting studies where automaticity is relevant (Lemieux & Godin, 2009; J. Panter, Jones, et al., 2011). Social support, enjoyment, perceived benefits and barriers, and travel mode preferences are used inconsistently, typically reflecting individual research groups' theoretical commitments. Place attachment, decomposed into place identity and place dependence, is less common but appears in Eng & McCormack (2025). Attitudes remain the dominant psychological measure, and most environmental mediation hypotheses are articulated through them.

BE measurement spans three approaches: objective GIS-based indicators, perceived environment scales, and composite walkability indices. Objective measures most commonly operationalize the "5Ds" framework (Ewing & Cervero, 2010) using administrative GIS layers, land-use registers, and street network data (Dalton et al., 2013; Kamruzzaman et al., 2016; Nguyen & Mertens, 2021; Shi et al., 2025; Van Holle et al., 2015; J. Wang & Huang, 2025). Composite walkability indices, typically combining residential density, land-use mix entropy, and street connectivity into a single score, are used both as sampling frames and as analytical predictors, particularly in the NQLS/BEPAS tradition (Owen et al., 2007; Van Dyck et al., 2012;

Van Holle et al., 2015). Walk Score, a proprietary composite index, appears in Yang & Diez-Roux (2017) as a convenient objective proxy.

Perceived environment is most frequently measured using instruments derived from the NEWS (Saelens et al., 2003) or its adaptations, covering residential density, land-use diversity, access to services, street connectivity, walking and cycling infrastructure, aesthetics, traffic safety, and personal safety from crime (J. Lee, 2016; Lemieux & Godin, 2009; McCormack et al., 2013; Van Dyck et al., 2012; Y. Wang et al., 2024). A narrower safety construct, covering traffic safety, personal safety, or both, is retained as a single-variable measure in studies focused on the safety-walking relationship (Beenackers et al., 2013; Hong & Chen, 2014). Studies of active commuting often substitute route-level perceptions for neighborhood-scale items (Adams et al., 2016; J. Panter et al., 2013, 2014; J. Panter, Jones, et al., 2011). Jack & McCormack (2014), Shi et al. (2025) and Wang & Huang (2025) include both objective and perceived BE simultaneously, which allows their independent contributions to be compared directly.

b. Analytical Approaches and Key Results

A first generation of studies integrating BE and psychological constructs, added perceived and/or objective BE variables alongside psychological constructs in multivariable regression models, treating both as independent predictors of walking (Beenackers et al., 2013; Dalton et al., 2013; H.-S. Lee & Shepley, 2012; Molina-García et al., 2010; Owen et al., 2007). These additive approaches are informative about the relative magnitude of effects within a common model, but they cannot identify whether and how the two sets of determinants work together, whether the BE shapes psychology, whether psychological dispositions strengthen or reduce sensitivity to the environment, or whether the two pathways operate independently. Subsequent studies have addressed this through two main strategies: mediation, which tests whether psychological constructs transmit the effect of BE on walking; and moderation, which tests whether the strength of environment–walking or attitude–walking associations varies as a function of individual psychological characteristics. A smaller number of studies combine both strategies within a single structural equation model (Li et al., 2020; McCormack et al., 2013; Rhodes et al., 2006; Shi et al., 2025; J. Wang & Huang, 2025).

Socio-demographic characteristics (age, gender, education, income, and household or vehicle access) are included in integrated models primarily as control covariates rather than as theoretically motivated predictors, i.e., they account for background differences rather than explain why people walk. Car ownership and car access are the most substantively important of these controls, consistently reducing the likelihood of transport walking (Guinn & Stangl, 2014; Lemieux & Godin, 2009; J. Panter, Griffin, et al., 2011; Ton, 2019). A minority of studies use socio-demographic variables as moderators. Gender is explored as a moderator of environment–behavior associations in Guinn and Stangl (2014), where women rate security as a more important walking motivator than men, and in Van Dyck et al. (2014), which tests gender as a potential modifier of psychosocial–environment interactions. Neighborhood income is used as a moderator in (Van Holle et al., 2015).

Three direct associations are well-supported across the integrated literature. First, higher objective or perceived walkability is positively associated with transport walking, a finding that replicates across countries, measurement instruments, and analytical approaches (Dalton et al., 2013; Eng & McCormack, 2025; Jack & McCormack, 2014; Kamruzzaman et al., 2016; Owen et al., 2007; Van Holle et al., 2015). Second, positive attitudes toward walking are positively associated with walking frequency and duration, for recreational walking (J. Lee, 2016; Van Dyck et al., 2014), transport walking (Li et al., 2020; Larrañaga et al., 2016), and grocery-store walking (Yu, 2024). Third, higher self-efficacy and PBC are positively associated with walking intention and behavior across TPB studies spanning multiple countries and purposes (H. S. Lee, 2016; Molina-García et al., 2010; Wang et al., 2024).

The relative importance of BE versus psychological factors varies with context and walking purpose. Transport walking is more strongly associated with objective BE attributes, connectivity, land-use diversity, transit access, and distance, because the destination is externally defined and the decision to walk is more directly constrained by spatial structure (Dalton et al., 2013; Jack & McCormack, 2014; Shi et al., 2025). Lemieux and Godin (2009) find that cognitive variables outperform environmental ones in predicting active commuting: BE subscales that are significant when entered alone lose significance once attitude, PBC, and habit are included. Yu (2024), by contrast, finds that BE exerts a stronger direct effect on grocery store walking than attitudes, with sidewalk availability and distance dominating the model. Recreational walking is less sensitive to objective morphology and more responsive to perceived aesthetic quality, social environment, and motivational constructs (Eng & McCormack, 2025; Van Dyck et al., 2014; Van Holle et al., 2015; Zhao et al., 2019). and van Holle et al. (2015) find no significant main effect of objective walkability on recreational walking; Jack and McCormack (2014) find no neighborhood-type effect on recreational walking. Yet Van Dyck et al. (2014) document positive associations between perceived environmental attributes and recreational walking, and Feuillet et al. (2016) find density-walking associations for leisure as well as transport. These inconsistencies likely reflect both measurement heterogeneity (perceived versus objective, density versus composite walkability) and context-specificity.

Mediation analyses test whether the BE shapes psychological constructs, attitudes, PBC, or perceived safety, which in turn predict walking, thereby identifying a cognitive pathway through which physical conditions produce behavioral change. Rhodes et al. (2006) demonstrate via SEM that retail land-use mix, and neighborhood aesthetics are associated with walking through their effects on affective and instrumental attitudes: proximity to retail destinations makes walking instrumentally attractive, and aesthetically pleasant neighborhoods make it affectively rewarding, both operating through the attitudinal pathway. Lemieux and Godin (2009) find that perceived BE attributes lose significance when PBC and habit are entered, which suggests mediation, though they do not formally test indirect paths. McCormack et al. (2013) use logistic regression with mediation analysis and find that TPB variables, especially PBC, carry part of the effect of perceived access to services and social support on transport walking participation, supporting a partial cognitive mediation pathway. Hong and Chen (2014) establish perceived crime safety as a mediator of BE effects on walking via two-stage least squares: higher-density environments lower perceived safety, which in turn reduces walking; in high-density areas where perceived safety is maintained, walking rates are higher. H. S. Lee (2016), using SEM, finds that neighborhood quality and safety improve attitudes, norms, and PBC, which then predict recreational walking indirectly. Wang and Huang (2025) report that socio-environmental perceptions fully mediate the association between objective BE and walking in a Chinese resettlement town, an unusually strong result suggesting that, in this context, objective physical conditions have no direct behavioral effect independent of the subjective experience they generate. Yu (2024) introduces a mediation structure in which BE attributes (distance, sidewalk quality, obstacles) affect walking both directly and indirectly through attitudes. Shi et al. (2025) treat perceived BE as the mediator between residential preferences and walking, differentiated by purpose.

Moderation analyses address whether the strength of environment–walking or attitude–walking associations varies by individual psychological characteristics. Two theoretical frameworks structure this literature. Beenackers et al. (2013) propose dichotomous mechanisms: competitive and synergistic. In the competitive (compensatory) mechanism, the environment matters most for individuals with weaker psychological characteristics; whereas in the synergistic mechanism, supportive environments amplify the behavior of those already positively disposed. These are framed as competing empirical hypotheses about the direction of moderation. Yang (2015), drawing on Handy's (1996) earlier observation that strongly pro-walking individuals walk regardless of urban form while strongly anti-walking individuals remain inactive even in supportive environments, offers an integrative meta-framework that explains when each mechanism is likely to dominate. Yang (2015) argues that environmental conditions are most consequential for individuals in the middle of the attitude spectrum, those without a firmly established disposition, and that which mechanism dominates in a given study reflects where that study's population sits on the absolute attitude continuum. In low-walking, car-oriented contexts, few individuals are "very positive" to walking, so synergistic patterns are more likely; in high-walking, walking-normalized contexts, competitive patterns are more probable. The two frameworks are hierarchical rather than parallel: the Beenackers dichotomy becomes depending on Yang's meta-framework, not replaced by it.

The empirical record is broadly consistent with this dichotomous mechanisms. Synergistic patterns have been observed in several settings: walkability is positively associated with walking only among action-oriented individuals (Friederichs et al., 2013); Walk Score effects on travel walking are concentrated among those with the most positive walking attitudes (Y. Yang & Diez-Roux, 2017); individuals with weaker mode preferences respond less to walkability improvements (Bondemark, 2023); and self-efficacy amplifies the walkability–recreational walking association among older adults, with no walkability effect among those with low self-efficacy (van Holle et al., 2015). Lindelöw et al. (2017) similarly find that walkable design enables strong-preference individuals to walk more rather than compensating for weak preferences. Competitive patterns have also been reported: Van Dyck et al. (2014), across three countries, find perceived environmental attributes most strongly associated with leisure activity among adults with less favorable psychosocial profiles, with the pattern strongest at the Belgian site. Wang et al. (2024) report a compensatory interaction for purposeful campus walking, where walkability predicts behavior most strongly among those perceiving fewer benefits. (Beenackers et al., 2013), despite originating the dichotomy, find only four significant interactions out of sixteen tested combinations and conclude that neither mechanism was clearly favored, a null result that is itself consistent with Yang's (2015) prediction that intermediate-walking populations produce weak, inconsistent moderation effects rather than a clear directional signal.

Two patterns extend beyond the Synergistic and Competitive mechanism. First, moderation direction varies by walking purpose: synergistic effects appear more consistently for transport walking, where environmental affordances condition whether the behavior is feasible, while competitive effects are more common for recreational walking (Van Dyck et al., 2014; Van Holle et al., 2015). Second, which psychological construct is used as moderator matters: self-efficacy and action orientation produce more consistent synergistic effects (Friederichs et al., 2013; Nguyen & Mertens, 2021; Van Holle et al., 2015), while attitude and social influence yield more context-dependent results (Beenackers et al., 2013; Yang & Diez-Roux, 2012), consistent with Yang (2015) point that these constructs have different meanings and cannot be assumed to moderate environmental effects by the same mechanism.

2.3.4 Pedestrian Route Choice: Built Environment, Psychological Factors, and Behavioral Determinants

Pedestrian route choice (PRC), the selection of a path between an origin and destination from available alternatives, addresses the spatial expression of walking behavior: why individuals deviate from the shortest path and which street attributes attract or repel pedestrian movement. This is analytically distinct from the broader question of walking participation reviewed in the preceding section, operating at the micro-scale of street segments rather than the neighborhood scale. The field has expanded substantially since 2010, with 82% of the studies identified in Basu et al.'s (2022) systematic review published in the decade to 2021. Most studies focus on a single trip purpose, most commonly commuting to school or work and walking to transit (Agrawal et al., 2008; Z. Y. Liu et al., 2020; Ozbil et al., 2016; Sarjala, 2019), with recreational walking less frequently examined (Ge et al., 2023; Yuan et al., 2025). Purpose-specific disaggregation remains the exception rather than the rule, despite clear indications that the environmental correlates of route choice differ substantially by trip purpose.

Studies are concentrated in North America and Europe, though Asian contributions, particularly from China, South Korea, Japan, Singapore, and Hong Kong, are growing rapidly, and work from Australia (N. Basu et al., 2023; Shatu et al., 2019a, 2019b), and Turkey (Ozbil et al., 2016) has expanded coverage further. Most studies are set in urban areas, most commonly large metropolitan cities such as San Francisco, Boston, Chicago, Toronto, Hong Kong, and Istanbul, which dominate the big-data GPS literature (R. Basu & Sevtsuk, 2022; Lieu & Guhathakurta, 2025; Lue & Miller, 2019; Sevtsuk et al., 2021), though medium-sized cities, such as Brisbane (N. Basu et al., 2023; Shatu et al., 2019a) and Oulu (Sarjala, 2019) and suburban and campus settings also feature in smaller-scale survey and experimental work. Smaller towns and rural areas are almost entirely absent.

N. Basu et al. (2022) identify 105 factors associated with pedestrian route choice across 44 studies, organized under three PASTA framework domains: BE, trip characteristics, and socio-demographic factors. Three broad epistemic traditions structure the literature: behavioral-cognitive approaches that foreground environmental perceptions and decision heuristics; discrete choice frameworks that formalize route selection as utility maximization; and data-driven approaches that exploit passive GPS, Wi-Fi, and computer vision data to infer preferences at scale. These traditions increasingly converge in hybrid Integrated Choice and Latent Variable (ICLV) models (C. J. Jin, Li, Wu, Li, et al., 2025; Prato et al., 2011), where latent psychological constructs are embedded within discrete choice models.

a. Route distance and deviation from shortest paths

Route distance and deviation are most commonly studied through GPS-tracked actual routes compared against alternate paths (such as the shortest-path or multiple alternatives derived algorithmically) (Ge et al., 2023; Sevtsuk et al., 2021), or through map-tracing intercept surveys in which respondents draw their route at the point of travel (Agrawal et al., 2008; Guo & Loo, 2013). Distance minimization is the primary and most common principle of pedestrian route choice: Basu et al. (2022) identify trip distance as the most studied variable in the literature and confirm that pedestrians generally prefer shorter routes across contexts. Several of the reviewed studies nonetheless document systematic deviations when routes offer attractive walkability features such as retail frontage, parks, or greenery (R. Basu & Sevtsuk, 2022; Borst et al., 2009; Guo & Loo, 2013; Sevtsuk et al., 2021). Where deviations occur, Tong & Bode (2022) demonstrate they follow hierarchical rules, minimizing turns before minimizing distance, and their magnitude varies by trip purpose. Ge et al. (2023) find that recreational walkers show substantially larger deviations from the shortest path than transport walkers, who face time pressure and adhere more closely to direct routes; this pattern is consistent with the broader walking behavior literature showing that recreational walking is more sensitive to environmental quality than transport walking.

b. Built environment attributes

BE attributes along routes are most commonly measured through objective GIS coding applied to GPS-tracked or map-traced routes, with micro-scale features increasingly extracted via virtual street audits such as SWATCH or Google Street View-based machine learning (Shatu et al., 2019a; Li & Zhang, 2024). Three spatial measurement approaches dominate. The sausage buffer method generates a linear corridor, typically 15 to 100 meters wide, around the route polyline, within which BE characteristics such as greenery, sidewalk availability, and traffic proximity are measured and averaged (Broberg & Sarjala, 2015); buffer width varies substantially across studies and affects the granularity of environmental exposure (Krenn et al., 2014; Winters et al., 2010). The grid-based method divides the route into uniform spatial cells, typically 20×20 or 50×50 meters, each buffered at multiple distances, enabling fine-grained analysis of local variation along the path that area-averaged approaches miss (Sarjala, 2019). A third approach measures the BE as linear frontage, for example, meters of route adjacent to parkland or arterial roads, capturing the sequential character of the walking experience more directly (Lue & Miller, 2019). Each method involves trade-offs between spatial precision, data demands, and analytical tractability.

Beyond distance, three route attributes are consistently significant. Greenery, shade, and waterfront access increase route attractiveness and willingness to walk further (R. Basu & Sevtsuk, 2022; Borst et al., 2009; Ge et al., 2023; Sarjala, 2019; Sevtsuk et al., 2021). Traffic volume and road type reduce route attractiveness: pedestrians avoid arterials, high-speed traffic, and poorly separated pedestrian-vehicle interfaces even at the cost of longer paths (Agrawal et al., 2008; R. Basu & Sevtsuk, 2022; Ozbil et al., 2016). Slope is among the strongest negative route attributes where terrain varies, with pedestrians willing to walk substantially further to avoid steep gradients (Basu & Sevtsuk, 2022). Sidewalk quality, crossing facilities, lighting, and active land use frontage (shops, cafes, building entries) are also consistently positive route attributes (N. Basu et al., 2022; Borst et al., 2009; Sevtsuk et al., 2021), while litter, blank walls, vacant land, and pedestrian bridges over arterials are negative (Borst et al., 2009; Basu et al., 2023). Basu et al. (2022) note that natural environment factors such as topography and climate remain understudied despite their clear relevance, particularly for older adults at risk of falls.

Perceived BE measures, perceived safety from traffic and crime, perceived aesthetics, and perceived comfort, constitute a distinct dimension of route-level environmental measurement that frequently diverges from objective GIS-based assessment. Shatu et al. (2019a) show that objective and perceived measures of the same streets often differ, with these differences varying by gender and familiarity. Both types of measures independently influence route choice, so neither can substitute for the other in modelling. Perceived safety is the most studied perceptual variable and operates both as a direct predictor of route choice and as a mediator of objective environmental effects, particularly at night and for female pedestrians (N. Basu et al., 2022; C. J. Jin, Li, Wu, Li, et al., 2025). Integrated Choice and Latent Variable models provide the most theoretically coherent treatment of perceptual variables, formally establishing the cognitive pathway through which objective street attributes are translated into route selection decisions; incorporating latent safety and comfort perceptions into such models improves fit by approximately 15% over standard logit specifications (C. J. Jin, Li, Wu, Li, et al., 2025; Prato et al., 2011). Stated preference experiments using photographs or hypothetical route scenarios offer a complementary approach that enables direct manipulation of perceived attributes (N. Basu et al., 2022; C. J. Jin, Li, Wu, Xiu, et al., 2025), though hypothetical bias in SP designs has been shown to be substantial and requires explicit correction before estimates transfer to real-world behavior (C. J. Jin, Li, Wu, Xiu, et al., 2025).

c. Psychological factors and latent constructs

Psychological variables are measured through controlled wayfinding experiments or post-hoc survey instruments administered alongside route recording (Tong & Bode, 2022, 2023). TPB-inspired constructs are rarely examined in route choice research, and Basu et al. (2022) identify psychosocial factors as the least explored domain in the literature. The most substantive contributions come from Tong & Bode (2023), who demonstrate in controlled experiments that wayfinding anxiety and spatial ability independently predict route decisions beyond any physical or perceived environmental attribute, with females exhibiting higher wayfinding anxiety that systematically affects routing. Sense of place and place attachment emerge as additional psychological determinants in a small number of studies (Chan et al., 2024), with familiar and affectively meaningful routes chosen even when objectively longer. Habit remains almost entirely unexamined despite its theoretical relevance: if route choice is largely habitual rather than deliberate, environmental interventions may have limited effect on routing behavior unless they disrupt established routines (Basu et al., 2022).

d. Socio-demographic heterogeneity

Socio-demographic variables are predominantly collected through self-report survey items and entered as covariates in discrete choice or regression models. Most studies include age and gender as standard controls, while income, ethnicity, and companion status are examined in fewer studies (Basu et al., 2022). Population-specific designs, targeting children's school routes (Moran et al., 2018; Ozbil et al., 2016), older adults (Borst et al., 2009; Yuan et al., 2025), or stratified demographic groups (Lieu & Guhathakurta, 2025), tend to yield the most analytically informative results.

N. Basu et al. (2022) report six socio-demographic factors that show associations with route choice: age, gender, ethnicity, occupation, income, and companions. Gender moderation is most consistently documented: female pedestrians are more sensitive to lighting, personal security, and pleasantness, particularly at night (Agrawal et al., 2008; N. Basu et al., 2023), while male pedestrians favor quicker, less crowded routes (Wicramasinghe & Dissanayake, 2017). Children (Moran et al., 2018; Ozbil et al., 2016) and older adults (Borst et al., 2009; Yuan et al., 2025) exhibit systematically different route preferences, with safety from traffic as the binding constraint for school routes and a preference for greener, flatter, bench-equipped routes among older pedestrians. Lieu & Guhathakurta (2025) find that lower-income and minority pedestrians are more sensitive to safety and infrastructure quality, a finding with direct equity implications for infrastructure investment priorities.

2.4 Summary

The reviewed literature demonstrates that walking behavior emerges from the interaction of BE structures, psychological dispositions, and socio-demographic positioning, rather than from isolated determinants. Objective environmental attributes such as density, connectivity, and destination accessibility consistently predict transport walking, while perceived qualities, including aesthetics, safety, and comfort, are more strongly associated with recreational walking. Psychological constructs, particularly attitudes and PBC, represent the most robust individual-level predictors and operate both independently and in interaction with environmental conditions.

However, the mechanisms linking these domains remain theoretically and empirically unresolved. Evidence supports both mediation pathways, in which environmental attributes influence behavior through cognitive constructs, and moderation pathways, in which psychological predispositions condition responsiveness to environmental affordances. These interaction mechanisms are further complicated by non-linear sensitivity across the attitudinal spectrum and by competing versus synergistic interaction patterns.

Methodologically, the literature is characterized by substantial heterogeneity in the conceptualization and measurement of walking behavior, and data collecting and amount of data, including ambiguity in trip purpose, inconsistent treatment of multimodal walking, and variation in spatial exposure definitions. Despite advances in GPS-based and route-level analysis, studies integrating objective behavioral data with objective environmental measures remain limited. Furthermore, socio-demographic variables are predominantly treated as control factors rather than as theoretically grounded moderators. These limitations constrain cumulative inference and highlight the need for multi-dimensional, integrative research designs that jointly model behavioral, environmental, and cognitive processes.

3. METHODOLOGY

This chapter outlines the research design and methodological framework employed to investigate transport walking behavior in Swedish urban contexts. Adopting a quantitative, multi-level approach, it integrates psychological, sociodemographic, and built environment (BE) data with GPS-tracked walking behavior. The chapter details the development of a conceptual framework grounded in the Theory of Planned Behavior (TPB), and describes the measurement and modeling of psychological factors, objective BE exposures, and walking patterns, as described in chapter 2. It also explains the analytical techniques used to examine the relationships influencing walking, highlighting the thesis's methodological and theoretical contributions.

3.1 Research design

Walking behavior is a complex phenomenon influenced by multiple interacting factors, including psychological, socio-demographic, and BE aspects (Figure 2). Understanding this complexity requires making explicit the philosophical assumptions that underpin how the phenomenon is conceptualized and how knowledge about it is produced.

This thesis takes an objectivist ontological position, i.e., walking behavior and the BE exist independently of the researcher, but are studied through theory-based concepts and methodological measurements. Attitudes and perceptions are incorporated as explanatory variables but are treated as measurable psychological constructs rather than as the primary locus of reality. The BE is operationalized through GIS-derived objective indicators, and walking behavior is measured objectively via GPS tracking rather than self-report, a deliberate choice to capture behavior as it occurs rather than as participants recall or perceive it.

Epistemologically, the thesis is grounded in post-positivism (Phillips & Burbules, 2000), informed by the tradition of critical rationalism in planning methodology (Faludi, 1983). Post-positivism holds that an objective reality exists and can be studied empirically but departs from classical positivism by acknowledging that measurements are imperfect, findings are probabilistic, and observed associations require interpretation within theoretical frameworks. Faludi's application of critical rationalism to planning methodology is particularly relevant because it rejects the view of planning knowledge as a fixed technical prescription and instead understands it as a provisional, revisable, and critically testable basis for action. In this thesis, this position supports a research design in which hypotheses about the relationship between the BE and walking behavior are derived from existing theory and empirical literature before analysis begins but are treated as testable rather than confirmed claims. The empirical analyses therefore test whether these theoretically informed expectations withstand confrontation with GPS-measured walking behavior, GIS-derived BE indicators, and survey-based psychological constructs. This shapes the analytical design by requiring hypotheses to be specified in advance, tested through transparent statistical procedures, and interpreted in relation to uncertainty, measurement limitations, and rival explanations. It acknowledges that GPS data carry spatial noise, that network-based shortest paths are algorithmic approximations of real route alternatives, that samples drawn through app-based recruitment are not fully representative, and that cross-sectional associations cannot establish causal direction. These are not afterthoughts; they follow from the post-positivist recognition that measurement is inherently imperfect and that conclusions are provisional, subject to revision as knowledge accumulates.

The thesis also draws on critical realism (Bhaskar, 1997) in its concern with mechanisms rather than associations alone. The SEM-based investigation of direct, indirect, and conditional pathways linking the BE, attitudes, and walking reflects this: the goal is not simply to establish that physical BE correlates with walking, but to understand whether that relationship operates directly or through attitudinal mediation, and whether it holds across different population groups.

The research design is quantitative, combining a narrative literature review with multiple rounds of primary data collection and multivariate statistical analysis. The literature review, presented in Chapter 2, draws on two structured tables (Table 10 and in Appendix 5) covering studies on the environmental and psychological correlates of individual-level walking behavior and studies on pedestrian route choice respectively. These tables organize the existing literature by study context, behavioral measure, BE operationalization, psychological constructs, and analytical method, enabling systematic comparison of methodological approaches and empirical findings, and informing variable selection and hypothesis development for the empirical papers.

The quantitative component builds on this through the collection and analysis of site-specific pedestrian flow patterns and GPS-tracked travel data, alongside questionnaire responses measuring psychological constructs and socio-demographic characteristics. Walking behavior is operationalized in different ways, total distance walked per day, walking ratio, and route deviation from the shortest path, and studied at both the individual and route levels. This multi-level operationalization is deliberate: different measures capture different aspects of the behavior, and their comparison across datasets and spatial scales strengthens the validity of the findings and supports more nuanced, evidence-based conclusions relevant to transport planning and walking promotion policy. Psychological and socio-demographic variables are self-reported; walking behavior and BE characteristics are measured objectively, keeping these two measurement streams independent and avoiding the common method bias that affects studies where both behavior and environment are derived from the same questionnaire. The type of and quality of results based on the work described above is dependent on the amount and type of data that is obtained.

3.1.1 Conceptual framework

Based on the literature review, a conceptual framework was developed to evaluate the environmental and psychological factors affecting walking behavior (Figure 2). While McCormack et al. (2013) argue that "much of the research to date has focused mainly on what associations exist, rather than examining how and under which circumstances the built and social environments determine physical activity" (pg. 961) it is also true of walking. The presented conceptual framework helps to explore the "what" along with the "how and under which circumstances" questions related to walking behavior. While using TPB as the basis for the framework, the focus is on actual (revealed preference) walking behavior, rather than intention and on objectively measured BE rather than perceived BE.

Figure 2 provides an overview of the conceptual framework and the various relationships explored. Solid lines indicate direct effect, and dotted lines indicate moderating effect. The complex relationship between the various factors is based on existing literature. Although previous research has extensively examined the individual effects of BE characteristics, socio-demographic attributes, and psychological factors on walking behavior, few studies have explored their interactive effects. This thesis adds to the literature by integrating multiple measures of BE exposure and walking behavior within a multilevel analytical framework that reflects the hierarchical structure of the data. The analytical approach was developed across the four papers (in appendices 1 to 4). Paper 1 employs a comparative analysis of Wi-Fi-based flow data and app-based GPS travel data to assess their utility in capturing pedestrian movement patterns; Paper 2 uses non-parametric group comparison tests to explore associations between TPB constructs and walking; Paper 3 employs structural equation modelling to simultaneously estimate direct, indirect, and interaction effects among latent constructs; and Paper 4 uses mixed-effects models that account for the hierarchical structure of repeated routes nested within individuals, incorporating both fixed effects of BE, socio-demographic, and attitudinal variables and cross-level interaction effects.

Furthermore, a questionnaire was developed to measure psychological constructs. It is compatible with mobile app deployment and enables scalable, context-sensitive data collection, was developed particularly for this thesis. The thesis demonstrates a clear progression from a descriptive assessment of pedestrian flows to a theoretically grounded and multi-dimensional explanation of walking behavior. As a result, this research provides both methodological and theoretical advances in understanding walking behavior.

The conceptual framework is structured around three core components: (1) modelling walking behavior, (2) measuring BE exposure, and (3) measuring psychological and sociodemographic factors. These components are operationalized across datasets and empirical papers within the thesis, each of which contributes distinct but complementary insights. The measures for these three components are discussed in the following section. Each component has multiple aspects to it, with several variables, and multiple ways of analyzing the relationships between them. The gaps identified from the literature review (in chapter 2) have been delt with across the four papers and the kappa, as addressing with them in a single paper was not possible.

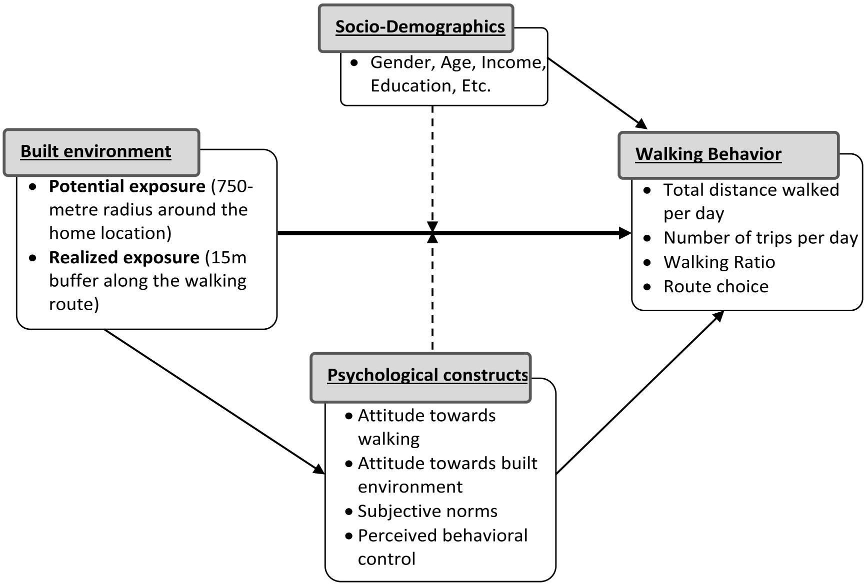


Figure 2: Conceptual framework for the thesis

Figure 3 illustrates the relationships explored in the four papers that are included in this thesis. In addition to these relationships, the discussion also covers comparing the BE correlates of walking behavior from the potential exposure (in paper 3) and realized exposure (in paper 4), as well as the psychological and socio-demographic variable from all the datasets (paper 2, 3 and 4). Through this integrated approach, the thesis contributes to both conceptual understanding and methodological tools for analyzing walking in urban contexts.

3.1.2 Measures of dependent and independent variables

a. Walking Behavior

The GPS data (see section 3.3 for description of data collection) was cleaned, aggregated and defined in different ways to form three variables at the individual level: 1) total walking distance per day, 2) number of trips and 3) walking ratio. Total walking distance and walking ratio are used as the primary dependent variables across Papers 2, 3, and 4. Number of trips is used as an additional dependent variable in Paper 2 only, where the aim is to characterize the full range of an individual's walking activity at the travel element level. This process highlights the importance of understanding the definition and measure of walking environment when comparing or generalizing results across different studies. At the route level, walking is measured in terms of distance walked and compared to the shortest route. All measures of the dependent variable are continuous.

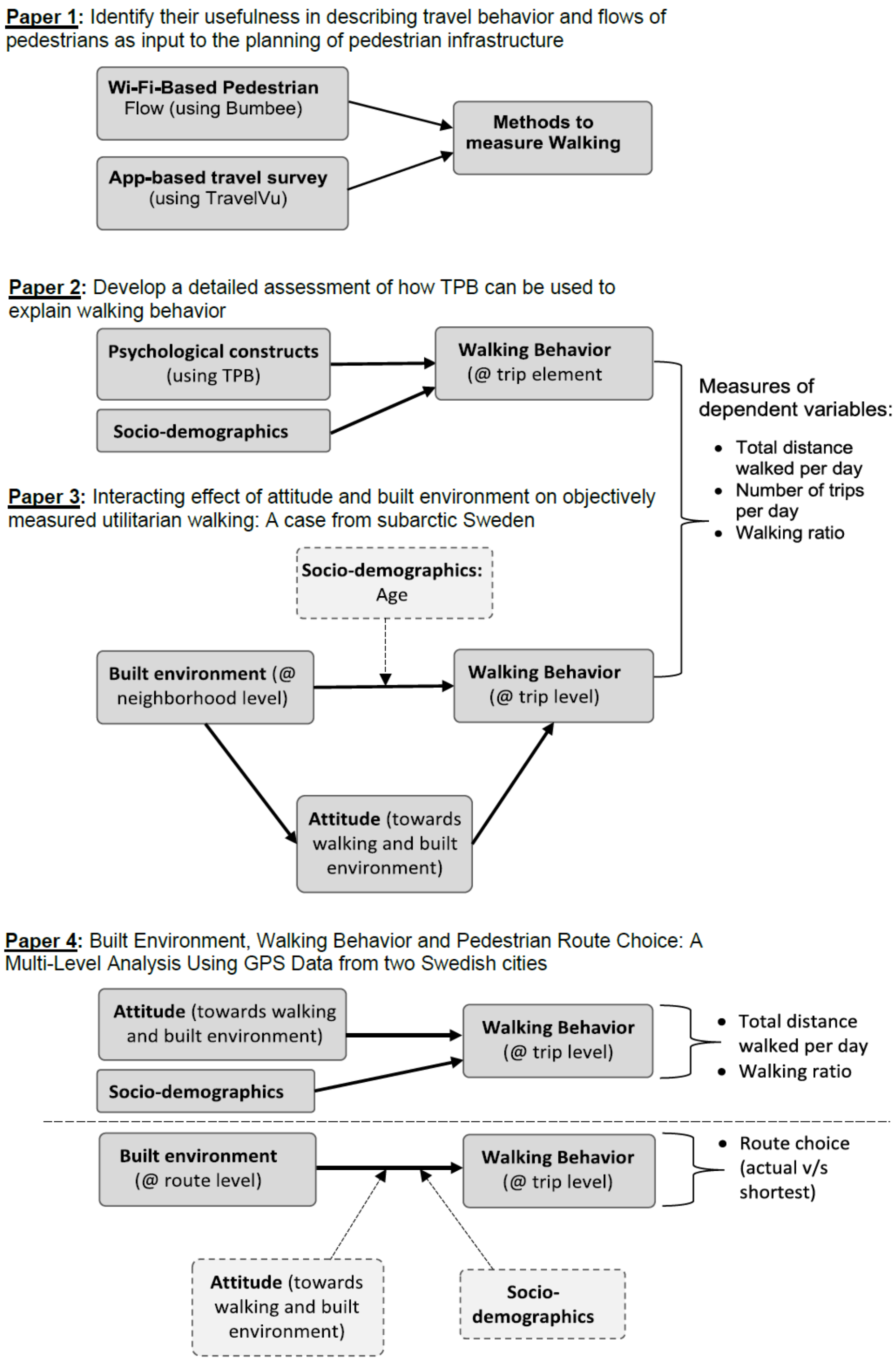


Figure 3: Aims of each paper and relationships explored in them

b. Psychological and Sociodemographic variables

This thesis employs psychological variables derived from TPB to investigate their relationship with everyday walking behavior. Psychological factors are measured using a questionnaire integrated into a mobile application (that also measures walking behavior using GPS-tracking). Based on the existing literature, the questionnaire was developed for this thesis, such that it was compatible with the mobile app. The questionnaire assesses attitudes and perceived control toward both walking behavior and the BE, along with subjective norms. Since the thesis focuses on objectively measured actual walking, there are no measures of intention (which is most commonly studied in TPB studies) in the questionnaire. For the complete list of variables/ questions, refer to the questionnaires in the Appendix 6.

Sociodemographic variables, including gender, age, education, income, employment status, and access to private and public transport, based on existing literature, are included to assess their direct and moderating effects on walking behavior. These variables are also drawn from survey data.

c. Built Environment Exposure

Perceived BE is the most commonly used measure in studies of walking behavior. However, these perceptions are not merely direct reflections of the objective environment; rather, they are shaped by cognitive, emotional, and socio-cultural filters, including personal experiences, values, and expectations (J. A. Carlson et al., 2012). As a result, individuals may perceive the same environment in vastly different ways. This subjectivity poses challenges for urban planning and policymaking, as interventions based on perceived environmental features are difficult to implement. Given these limitations, this thesis focuses on objectively measured BE features, which offer greater consistency and replicability for evaluating their relationship with walking behavior. The BE variables are selected based on the exiting literature and availability of data.

To assess the role of the BE, this thesis utilizes two exposure methods, potential exposure and realized exposure.

- **Potential exposure** is defined through a conventional buffer-based approach. BE characteristics are measured within a 750-metre radius around the home location, representing the accessible neighborhood, in paper 3. This method, widely used in travel behavior studies, serves as a baseline measure of the environmental context assumed to influence walking behavior. Buffer radii commonly range from 500 m to 1.5 km (Kamruzzaman et al., 2016; Koohsari et al., 2023; Nguyen & Mertens, 2021; Shi et al., 2025; Zhao et al., 2019; Zhu et al., 2024). Alternately measurement areas are defined by walking distance, usually 15 minutes from home (Eng & McCormack, 2025; Orrego-Oñate & Marquet, 2025).
- **Realized exposure**, in contrast, is operationalized using individual-level GPS tracking data aligned with observed walking routes. This approach captures the actual environmental conditions experienced during daily trips, offering a behaviorally valid

measure of exposure. In Paper 4, BE variables are calculated along the walked routes and the potential shortest route using a 15m buffer on both sides of the routes, enabling a direct analysis of environmental influences during movement through urban space (Krenn et al., 2014).

By comparing findings from both exposure types across separate analyses, the thesis evaluates the implications of different spatial representations of environment-behavior relations.

3.2 Description of study area

The empirical work in this thesis is based on data collected in two medium-sized Swedish cities: Umeå and Linköping. Both cities have committed to sustainable transport planning and have invested in pedestrian and cycling infrastructure, making them relevant and comparable contexts for studying walking behavior. While sharing these broad characteristics, the two cities differ in terms of geographic location, climate, urban structure, and the scope of the data collection area.

Umeå is a university city located in northeastern Sweden, with a population of approximately 131,000 as of 2021 (Befolkningsprognos: Umeå Kommun 2022 – 2033, 2022). Its demographic characteristics are broadly in line with national averages in terms of gender, age, and income, though the presence of Umeå University means the city has a notably higher proportion of students and residents with tertiary education and higher income levels. The city spans 5,277 km² and is recognized for its infrastructure supporting active travel and public transport, including 262 km of dedicated walking and cycling paths and 160 km of exercise tracks (Umeå Municipality (Gator och parker), 2019). Umeå adopted a new comprehensive plan with an integrated Sustainable Urban Mobility Plan in 2011 (*Umea | CIVITAS*, n.d.).Car ownership stands at 354 per 1,000 inhabitants in 2021 (Statistical database, n.d.).

Linköping is a growing city in southern Sweden, with a population of approximately 119,000 (Statistical database, 2021b), and is characterized by university presence and a high-technology industrial base. Covering 1,428 km², the municipality has actively pursued behavior-change initiatives aimed at increasing the share of sustainable travel since the late 1990s. Its current policy target is to increase the modal share of cycling from 28% to 40% by 2030 (Linköping Municipality, n.d.). To support year-round active travel, 130 km of pedestrian and cycling infrastructure are regularly cleared during winter. Car ownership is similar to Umeå at 353 per 1,000 inhabitants (Statistical database, n.d.).

The two cities thus offer a useful comparative basis: they are similar in size, car ownership rates, and commitment to active travel infrastructure, but differ in climate, geographic context, urban form, and the institutional context of data collection. These similarities and differences are relevant to the interpretation of results in Papers 3 and 4, and comparison of results in this thesis.

3.3 Data collection and Processing

This thesis employs two complementary data collection methods to study pedestrian behavior. The first is a Wi-Fi-based sensing system (Bumbee Labs, 2022), used to passively capture site-specific pedestrian flow patterns. The second is a smartphone-based travel survey application (TravelVu by Trivector, 2022), which combines GPS-based passive tracking with an integrated questionnaire, enabling the simultaneous collection of objective travel behavior, psychological constructs, and socio-demographic data from the same individuals. All data were collected anonymously in accordance with the European General Data Protection Regulation (GDPR). Each method is described in detail in the subsections below, followed by an account of the data processing steps.

3.3.1 Data collection methods

a. Wi-Fi-Based Pedestrian Flow Data.

To capture site-specific pedestrian flow patterns, Wi-Fi-based sensing technology provided by Bumbee Labs was deployed as part of the Umeå pilot study (Paper 1). Bumbee measures and visualizes visitor flows by capturing anonymized Wi-Fi signals from smartphones. Each sensing unit detects the passage of a mobile device within a radius of approximately 25 meters. When a device passes through two or more measuring ranges within 60 minutes, a path is created for that device, enabling both pedestrian counting and path-tracking across multiple points. This represents a significant advantage over manual or infrared counting methods, which can only record numbers at a single location and cannot reconstruct inter-point movement patterns.

Fourteen measuring points were installed in the vicinity of the two intervention sites in Umeå city, and data were collected continuously over 8 days (15th–22nd October 2019), yielding a total of 279,791 entries. Sensor locations are mapped in Figure 4. The placement and number of measuring units were determined by a combination of site-specific planning considerations and financial constraints. Crucially, all data captured by the Bumbee system were mode-unspecified, meaning the system could not distinguish between pedestrians, cyclists, or other users carrying Wi-Fi-enabled devices. As discussed in Paper 1, what the Bumbee system loses in precision relative to individual-level data, it compensates for through the large volume of registrations it can capture passively and automatically over extended periods.

b. App-based travel survey

The primary data source for this thesis is the TravelVu smartphone application, developed by Trivector AB (Sweden). TravelVu combines GPS-based passive tracking with an integrated survey interface, enabling the simultaneous and integrated collection of objective travel data and self-reported psychological (based on TPB) and socio-demographic data from the same participants. This dual-collection capability was central to the research design, as it allowed walking behavior and its psychological and demographic correlates to be linked at the individual level without relying on separate or independently administered instruments.

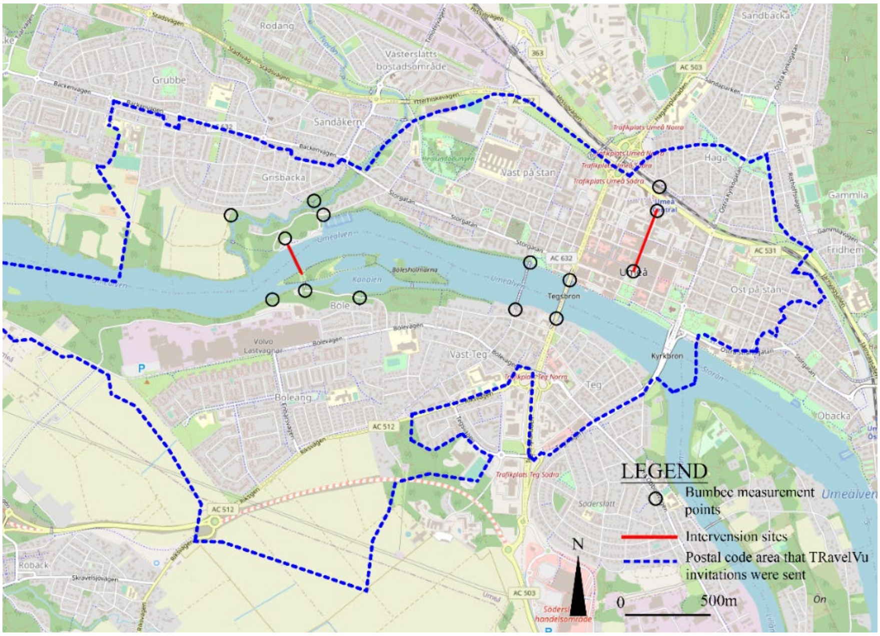


Figure 4: Map of Umeå focusing on the study area

Data were collected across two Swedish cities, Umeå and Linköping, in multiple rounds. In Umeå, two separate data collection rounds were conducted and administered by researchers at LTU: the first in autumn 2019 (used in Paper 2) and the second in autumn 2021 (used in Papers 3 and 4). Recruitment materials (e.g., postal invitations) were distributed to residents living within a 1-kilometer radius of the study areas, although participation was open to all residents of Umeå. In Linköping, a single data collection round was conducted in autumn 2021, commissioned and administered by Linköping municipality (used in Paper 4), but additional questions related to attitude were added to the survey in discussion with the researchers at LTU. Table 2 provides a detailed overview of the three data collection efforts using TravelVu, including the geographic focus, data collection period, recruitment methods, and the papers in which each dataset is used.

i. Objectively Recorded Travel Data

For each travel segment within a participant's travel chain, referred to as a travel element, TravelVu records information on the time, means of transport, activity type, distance, latitude and longitude of origin and destination, and GPS-traced path traveled. The application uses the smartphone's GPS and motion sensors to detect movement automatically and algorithmically classify the mode of transport. Crucially, users are required to identify the type of activity at the origin and destination once for every new location (e.g., home, work, shop, etc.) and review their recorded days and manually correct any misclassifications or missing entries before they are submitted. Only days that have been reviewed and approved by participants are used in the analysis, ensuring a high degree of data accuracy. Each smartphone used in the study was assigned a unique phone ID so that all recorded trips could be linked to the respective participant while maintaining full anonymity for the research team.

Table 2: Details of data collected using the TravelVu app

Location	Umeå		Linköping
Data collection period	1st November to 22 December 2019	24th November 2021 to 31st January 2022	13th September to 31st October 2021
Participant recruitment method	Unaddressed flyers (in round 1), personally addressed postcards and A3 posters in some key locations (in round 2)	Personally addressed postcards, shared on municipality's social media page	Advertised on social media, in newspapers and on municipality's website (Crowdsourcing)
Data collection area	Post codes within 1km of the two intervention sites		Linköping municipality
Focus/Purpose of study	Pedestrians/walking		Soft mobility (walking and cycling)
Variables included (in questionnaire)	All TPB and demographic variables	All TPB and demographic variables	Demographic and attitude variables
Number of participants	88	104	444
Articles using the data	Paper 2	Papers 3 and 4	Paper 4

Note: The Umeå Round 1 questionnaire was developed entirely by the research team and includes all TPB variables. The Umeå Round 2 questionnaire was similarly developed and administered by the research team. The Linköping questionnaire was developed by the municipality in consultation with the research team; due to a deliberate effort to keep the survey short for public participants

ii. Self-Reported Socio-Demographic and Psychological Data

In addition to GPS travel data, TravelVu was used to deliver a structured questionnaire to participants. Survey responses were collected at the individual level and covered both socio-demographic characteristics (age, gender, educational attainment, driving license, bicycle ownership, etc.) and psychological constructs derived from TPB, (including attitude towards walking, attitude towards the BE, subjective norms, and PBC). The questionnaire was designed to be completed once by each participant at the start of, or during, their participation period. The app also supported trip-level pop-up questions in the Umeå data collections, which were triggered automatically when a participant completed a walking trip of 500 meters or more, enabling the collection of PBC-related data at the trip level (used in Paper 2).

iii. Built environment data

BE data were sourced from both national and municipal repositories, such as, the Swedish Transport Administration's road and rail database (Swedish Transport Administration, 2023) and the geodatabase of the Swedish University of Agricultural Sciences (Swedish University of Agricultural Sciences, 2023), and the OpenStreetMap, with additional datasets provided directly by the municipalities of Umeå and Linköping upon request.

3.3.2 Processing and modelling walking behavior

a. Structure of App-Recorded Travel Data

Consistent with Ambrey & Bitzios (2018), a trip in this thesis is defined as beginning and ending with an activity that is not transitional, such as waiting for public transportation or parking. A trip is segmented into travel elements when there is a change in the mode of transport or activity. Ambrey and Bitzios (2018) refer to these segments as "walking episodes" when discussing walking mode. Travel elements may start or end with a transitional activity. Consequently, the mode for a trip is determined by the mode of the longest segment (or travel element) of the trip (see Figure 5). TravelVu collects travel data at the travel element level, each representing continuous travel by a single mode, which is linked to the PBC related pop-up questions. The travel element data is aggregated to form the trip data.

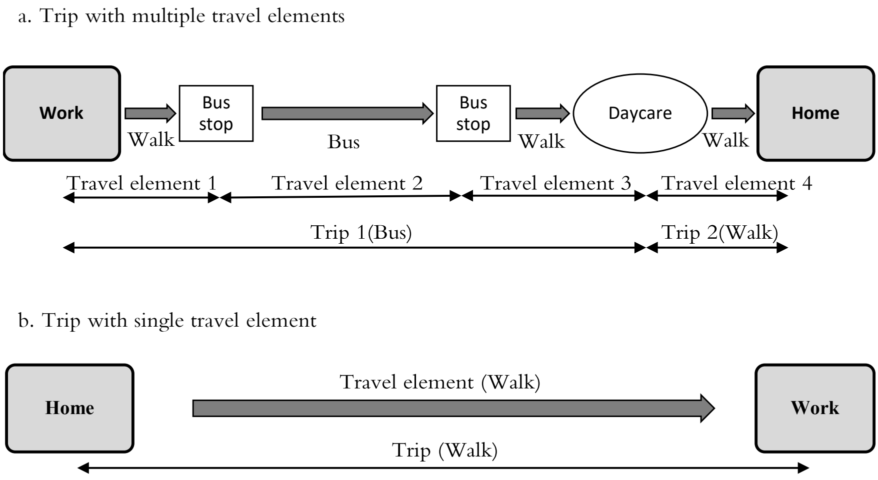


Figure 5: Parts of a trip chain

b. Common Data Processing Steps

TravelVu provided two datasets at the two levels: travel element and trip. Paper 2 operates at the travel element level and includes all walking, capturing walking as a component of multi-modal trips as well as standalone walking trips. Papers 3 and 4 operate at the trip level, including only trip where walking is the main mode of transportation. However, the processing applied was consistent in its foundational steps. Specifically, the following filters were applied to all datasets:

- Only corrected/approved days were retained for analysis;
- All recreational walking trips (i.e., trips where the origin and destination were identical, such as home-to-home, or those explicitly identified by participants as exercise or recreation) were excluded;
- Indoor walking trips within large, enclosed spaces (e.g., universities, hospitals, or shopping centers) were excluded;
- Trips occurring outside the city limits of the respective study areas were excluded;
- Trips shorter than 10 meters and trips exceeding twice the shortest possible network path (classified as recreational; Lue & Miller, 2019) were removed;
- To avoid over-representation by participants who used the app for extended periods, participation was standardized to a maximum of seven days per person.

Following these foundational processing steps, the cleaned travel data were further processed differently depending on the aim and research questions of each paper:

- For aggregating data at the individual level, days with incomplete entries (i.e., days not fully reviewed and approved by the participant) were excluded from analysis;
- When analyzing the BE in the home-based neighborhood, only the participants with known home address were included in the analysis;
- For route choice analysis, all walking routes that did not follow the street networks (probably due to issues with GPS tracking) were delete, since the BE along the route could not be gathered.

After processing, the walking mode was filtered out and three variables were aggregated at the individual level for use in quantitative analysis:

- **Total walking distance per day (km)** is the cumulative distance walked per participant per day across all valid days. In Paper 2 this includes all walking travel elements; in Papers 3 and 4 it includes only walking trips where walking is the primary mode.
- **Number of walking trips per day** is the average number of walking records per participant per day, again defined at the travel element level in Paper 2 and at the trip level in Papers 3 and 4.
- **Walking ratio,** serving as a proxy for mode choice, is the proportion of a participant's walking records relative to all records within the applicable distance range: measured at travel element level and unrestricted in Paper 2; and at trip level and between 0.5 and 1.5 km in Papers 3 and 4. Trips below 0.5 km are excluded on the grounds that walking at such short distances is largely a necessity rather than a mode choice, while 1.5 km represents the upper bound of distances generally considered walkable in the literature (G. Sun et al., 2015).

c. Route Selection and Shortest Route Generation

In Paper 4, the GPS-traced actual walking routes recorded by TravelVu were used alongside computationally generated shortest routes to examine pedestrian route choice behavior. The actual routes were extracted directly from the GPS data logged by the app. The corresponding shortest-path routes, i.e., the minimum-distance path between each trip's origin and destination within the pedestrian street network, were generated using the Network Analyst extension in ArcGIS Pro 3.2, based on local pedestrian network data sourced from the Swedish Transport Administration's road and rail database (Swedish Transport Administration, 2023), the geodatabases of Umeå and Linköping municipalities, and the Swedish University of Agricultural Sciences' geodatabase. To minimize false distinctions arising from GPS noise or minor navigational deviations, trips were classified as having taken the “same” route if the actual route exceeded the shortest route by less than 20% in relative length or less than 0.1 km in absolute distance. Only trips with meaningful deviations from the shortest path were retained for subsequent route-level analysis using Linear mixed models, resulting in a data set of only 156 trips for the analysis using LMM. The Discrete choice model, however, used all the walking trips.

3.3.3 Developing and processing the questionnaires

Two versions of the questionnaire were developed for use in this research. The Umeå questionnaire (used in both rounds) was designed and administered by the research team at Luleå University of Technology. It was developed from scratch, as no standard TPB questionnaire for walking existed in the literature at the time. The instrument was built on a systematic review of TPB-based studies across BE research, pedestrian studies, and cycling studies, resulting in a survey that captures major TPB constructs as well as socio-demographic variables (for the full questionnaire, see Appendix 6).

a. Psychological Constructs

The psychological constructs measured in the questionnaire were developed based on the TPB literature review (see section 2.3) and adapted to the specific context of transport walking and the BE. Four main constructs were assessed:

- Attitude towards walking: reflecting individuals' evaluative stance toward walking as a mode of transport, including both affective (enjoyment, pleasantness) and instrumental (usefulness, efficiency) dimensions;
- Attitude towards the BE: reflecting the importance individuals associate with their walking environment. This is distinct from the perceived BE, more commonly used in walking behavior studies. This construct is not commonly used in the existing TPB literature, though some examples of individual variables have been noted in previous studies;
- Subjective norms: reflecting perceived social pressure from significant others regarding whether one should walk;

- Perceived Control: over the behavior reflecting the perceived ease or difficulty of walking and the perceived control over the BE reflecting the route alternatives and BE along the selected route

Attitudes and subjective norms were always measured at the individual level, but perceived controls were collected at both the individual and trip level. Because the Linköping questionnaire was designed and administered by the municipality, in consultation with the research team but with a deliberate intention to minimize participant burden and maximize response rates through a shorter survey, it was agreed to include only attitude-related questions in addition to the standard demographic variables. As a result, the full set of TPB constructs (subjective norms and PBC) is only available from the Umeå datasets. Both questionnaires are included in the Appendix. This difference in questionnaire coverage between the two cities has implications for the comparative analyses in Paper 4, where only attitude and demographic variables common to both datasets could be used in the city-level comparisons. This is acknowledged as a limitation of the g study design and is discussed in the respective paper.

Questions were administered using a 4-point Likert scale (rather than the more common 5-point scale) for two reasons: to simplify response on small smartphone screens, and to avoid the neutral midpoint and encourage participants to take a directional stance. None of the questions were mandatory, and the questionnaire was prepared in both English and Swedish, with both versions vetted by researchers and transport planners.

b. Socio-Demographic Variables

Socio-demographic information was always collected at the individual level using the app-based questionnaire (refer to Appendix 6). Standard demographic variables collected in both Umeå and Linköping include age, gender, educational attainment, employment status, and access to a driving license, private car, and bicycle.

3.4 Data analysis

The analytical approach progressed across the four papers from descriptive and exploratory methods to multivariate and spatial modelling, reflecting the evolving research questions. Statistical analyses were conducted using IBM SPSS Statistics version 26 (Paper 2) and R version 4.3.3 in RStudio 2024.04.2 (Papers 3 and 4). Spatial analyses were performed in ArcGIS Pro 3.2.

3.4.1 Descriptive and Comparative Analysis

All papers begin with descriptive statistics characterizing sample demographics and walking behavior. Paper 1 used descriptive and graphical comparison of the two data sources to evaluate their complementarity for pedestrian planning. Paper 4 extended this to formal inter-city comparisons using chi-square tests for categorical variables and Mann-Whitney U tests for non-normally distributed continuous variables, both to characterize differences between Umeå and Linköping and to assess whether the datasets were suitable for combined analysis.

3.4.2 Bivariate Analyses

Papers 2 and 4 examined associations between walking behavior and attitudinal and socio-demographic variables using non-parametric group comparison tests, chosen because the independent variables were measured primarily at the ordinal level and sample sizes were relatively small. The Mann-Whitney U test was applied for binary variables (e.g., a variable with two response categories) and the Kruskal-Wallis test for variables with three or more ordered levels (e.g., four-point Likert scale items), with each predictor examined individually (Field, 2018; Pallant, 2016). In Paper 2, where a number of variables were tested separately, Bonferroni corrections were applied to alpha values where necessary to control for Type I error.

Paper 3 used bivariate correlation analysis to explore associations between walking behavior and the continuous BE, attitudinal, and socio-demographic variables, with results informing variable selection for subsequent structural equation modelling. Pearson's correlation coefficients were computed for continuous variables and Kendall's Tau for ordinal or non-normally distributed variables, with bootstrap resampling applied throughout to improve the robustness of confidence intervals.

3.4.3 Structural Equation Modelling

Paper 3 employed structural equation modelling (SEM) as its primary analytical framework, chosen for its ability to estimate direct, indirect, and interaction effects among latent constructs (including attitude, the BE, and walking behavior) while accounting for measurement error (Bollen, 1989; Kline, 2016). Four models were estimated sequentially, moving from individual observed indicators to aggregated latent construct scores to manage sample size constraints. All models were estimated using maximum likelihood with bootstrapped robust standard errors, and fully standardized coefficients (Std.all) are reported to facilitate comparison of effect sizes. The framework tested direct effects of the BE and attitude on walking, the mediating role of attitude, and the moderating role of socio-demographic characteristics, with post-hoc power analysis conducted to assess the risk of Type II error.

3.4.4 Mixed-Effects Models

Route choice was modeled using two complementary mixed-effects approaches, both incorporating a random intercept per participant to account for the hierarchical structure of repeated routes nested within individuals. Linear Mixed Models (LMMs) assessed differences in BE exposure between actual and shortest routes, with and without individual-level moderators, providing an associational perspective on the environmental context of route selection.

Mixed-effects logistic regression modeled route choice directly as a binary outcome (binary Discreet choice model or DCM), whether the actual route coincided with the shortest route, using standardized BE variables as predictors. Highly correlated variables ($r > 0.5$) were excluded prior to modelling. A baseline model with BE predictors alone was compared with a moderated model incorporating attitudinal and socio-demographic interaction terms, with only statistically significant interactions retained, allowing assessment of whether individual-level heterogeneity improved explanation of route choice beyond environmental attributes. In discrete route choice analyses based on conditional logistic regression, route attributes are often interpreted using odds ratios, which indicate how changes in route characteristics affect the likelihood of a route being chosen relative to competing alternatives (Rodríguez et al., 2015), whereas conditional logit models typically report utility coefficients and distance-equivalent trade-offs to express these effects (R. Basu & Sevtsuk, 2022; Sevtsuk et al., 2021). In this thesis, results are presented as odds ratio.

4. SUMMARY OF PAPERS

This chapter summarizes the four papers included in this thesis. Table 3 gives an overview of each paper, followed by a summary of the findings. As discussed in section 3.1, each empirical paper within the thesis addresses a different aspect of walking behavior within the same research design. Together, they build from describing where and how much people walk, to explaining why they walk, to identifying how individual dispositions and planning contexts at multiple levels jointly can be understood to shape both the amount and the route of walking.

4.1 Paper 1

Title: How useful are new data sources in pedestrian planning? Lessons from Umeå, Sweden case study

This study used two complementary methods, Wi-Fi-based sensor data (Bumbee Labs) and a smartphone-based travel diary app (TravelVu by Trivector), to examine pedestrian movement patterns in Umeå, Sweden. For detailed description of the two methods see sections 3.3.1. The Bumbee system recorded 279,791 entries across 14 measuring points within the city, providing insights into spatial traffic flows and movement intensity. These data revealed a high volume of pedestrian traffic within and around the central zones, confirming established findings that walking tends to concentrate in neighborhoods within a 10–15-minute radius from home or work (Agrawal & Schimek, 2007). The TravelVu app, used by 88 participants over approximately 6.5 days on average, yielded more than 3,500 trip records, of which 51% were walking trips. The sample socio-demographics characteristics were broadly representative of the general population in terms of age, gender, and income.

Comparative analysis demonstrated a positive correlation between pedestrian flows derived from Bumbee and TravelVu data, affirming the reliability of the respective methods despite inherent differences. Bumbee data were particularly valuable for estimating the relative volume of pedestrian flows between zones, while TravelVu offered detailed trip characteristics, including route choice, purpose, and origin-destination information. TravelVu data captured nuanced route preferences, such as pedestrians favoring river-adjacent paths over arterial roads, underscoring the influence of environmental quality on walking behavior.

However, each method exhibited limitations. Bumbee's effectiveness is constrained by the detection limitations of mobile devices, the inability to distinguish travel purpose, and its mode-agnostic nature, despite filtering by speed to approximate walking. Its utility is further limited when measuring points are sparse or widely spaced. Conversely, TravelVu data suffer from low response rates (1.95%) and participant dropout, partly due to battery concerns, privacy issues, and digital literacy barriers. Although TravelVu enables rich behavioral insights, the dataset may be biased towards individuals with a pre-existing preference for walking, as demonstrated by the high proportion of walking trips reported (48%) and the self-selection of participants.

Table 3: An overview of papers

	Paper 1	**Paper 2**	**Paper 3**	**Paper 4**
Aim and focus	Identify their usefulness in describing travel behavior and flows of pedestrians as input to the planning of pedestrian infrastructure	Develop an assessment of how TPB can be used to explain walking behavior	Explore how attitudes mediate the relationship between the BE and walking behavior	Identify the planning factors that affect walking behavior at the individual and route level
Dataset/study area	Umeå (2019)	Umeå (2019)	Umeå (2021)	Umeå and Linköping (2021)
Measures of walking behavior	Wi-Fi data: number of people at each measuring point; number of trips between any two measuring points App data: frequency measured at trip element level	Individual level: total distance walked per day; frequency; walking ratio Trip level: distance measured at trip element level	Individual level: total distance walked per day; walking ratio (within 1.5km) measured at trip level	Individual level: total distance walked per day; walking ratio (within 1.5km) Route choice: actual versus shortest route measured at trip level
Measures of Built environment	-	-	Neighborhood level (750 m radius around home location): Land use areas (in sq. m); Areas under different building uses (in sq. m); Areas under different housing types (in sq. m); Pedestrian network length (in m); Streetscape elements	Route Level (15 m buffer along the route): Land use areas (in sq. m); Areas under different building uses (in sq. m); Areas under different housing types (in sq. m); Pedestrian network length (in m); Streetscape elements

	Paper 1	**Paper 2**	**Paper 3**	**Paper 4**
Measures of Psychological factors	-	Measured at individual level: Attitude towards walking; Attitude towards BE; Subjective norms Measured at trip level: Perceived (behavioral) control over walking; Perceived control over BE	Measured at individual level: Attitude towards walking; Attitude towards BE	Measured at individual level: Attitude towards walking; Attitude towards BE
Socio-demographic characteristics	-	Gender; age; family structure; education; employment; income; driver's license; access to private car, motorcycle, bicycle, public transport pass; and physical activity level	Gender; age; family structure; education; employment; income; driver's license; access to private car, motorcycle, bicycle, public transport pass	Gender; age; family structure; education; employment; income; driver's license; access to private car, bicycle
Analysis method	Spatial comparisons; Pearson product-moment	Mann-Whitney U test; Kruskal-Wallis	Kendall's Tau and Pearson's correlations; Structural equation modelling	chi-square test, Mann-Whitney U test; Kruskal-Wallis; Linear Mixed Models and Discrete choice modelling

Note: For complete list of variables, refer to Table 12 and Table 13 in the Appendix 7)

Cost analysis revealed significant financial implications. Bumbee data cost approximately 75 Euros per measuring point per day, while TravelVu cost about 105 Euros per participant, with both methods proving considerably more expensive than traditional survey options offered by national statistical authorities. Although richer in content and spatial accuracy, the scalability of these newer technologies is limited by cost, response rates, and technical feasibility in larger or less pedestrian-dense urban areas.

Overall, the findings highlight the potential of combining Wi-Fi sensor data and app-based surveys for capturing urban walking patterns, while also highlighting methodological trade-offs. Future applications may benefit from hybrid approaches that balance costs, spatial coverage, and behavioral detail, alongside strategies to improve participation rates and data representativeness.

4.2 Paper 2

Title: Exploring Walking From The Perspective Of Theory Of Planned Behavior

The research, using the theory of planned behavior (TPB), sought to determine the extent to which personal attitudes, environmental factors, and individual perceptions of control affected walking patterns, with the aim of contributing to the understanding of how various factors shape transportation choices, particularly walking as a mode of transport. This paper makes a methodological contribution towards using TPB to analyze walking. The study analyzed 88 participants, measuring individual-level walking behavior per person per day as total distance walked (mean = 1.57 km, SD = 1.53) and walking ratio (mean = 0.46, SD = 0.26).

Personal socio-demographic variables such as gender, age, and income matched Umeå's population characteristics, but no significant relationship was found between these factors and walking behavior. Attitude was a strong predictor of walking behavior. A positive attitude, measured by general liking for walking, preference over other modes, reasons for walking, and purposes, was associated with higher walking frequency, longer distances, and greater modal share. Mann-Whitney U Tests showed that participants who liked walking had significantly higher scores across all three behavior measures. Furthermore, those who liked walking for more reasons (e.g., environmental or economic) walked more frequently and longer distances. Walking for transport or both transport and recreational purposes correlated with more walking compared to walking for recreation only.

Attitudes toward the built environment (BE), such as valuing direct connections, safety, and pleasant surroundings, were popular. However, only perceived importance of connectivity showed a statistically significant, albeit inverse, relationship with walking ratio, participants who rated it as very important walked less often.

Subjective norm, measured by perceived social expectations, showed no significant association with walking behavior, aligning with previous studies suggesting weak or inconsistent influence of social norms in travel behavior.

Perceived behavioral control (PBC) was assessed through self-reported health, reasons for walking, and route choice. Although most participants considered themselves healthy, those with self-rated poor health walked more often, possibly viewing walking as beneficial. At the trip level, PBC-related variables such as health and route safety significantly influenced walking distance. Walking for health reasons or choosing routes due to safety or dedicated paths were associated with longer distances, while choosing routes for shortness or necessity corresponded to shorter walks.

4.3 Paper 3

Title: Interacting effect of attitude and built environment on objectively measured utilitarian walking: A case from subarctic Sweden

This study investigated the influence of measured BE features and self-reported attitudes on walking behavior among Swedish adults in Umeå. A total of 3,623 trips recorded by 80 individuals were analyzed, of which 1,487 (41%) were walking trips, yielding a mean total daily walking distance per day of 1.93 km (SD = 1.40) and a mean walking ratio of 0.68 (SD = 0.35). While respondents indicated a willingness to walk for an average of 26.2 minutes (SD = ±11.9 minutes) for utilitarian (or transport) purposes, the objectively measured average trip duration was 10.70 minutes (SD = ±6.53 minutes), corresponding to 0.76 km (SD = ±0.50 km). This discrepancy illustrates a substantial gap between stated willingness and actual behavior. Bivariate analyses showed that walking ratio was significantly associated with a wider range of neighborhood-level BE variables than total daily walking distance.

Structural equation modeling indicated that both the BE and attitudes toward walking were predictors of walking behavior. Attitudes consistently demonstrated a stronger direct effect on walking behavior than the BE when both variables were included in the same model. In the simple mediation model, although the BE maintained a significant direct association with walking, the path from the BE to attitudes was not statistically significant, and the corresponding indirect effect was also non-significant. Therefore, attitudes did not mediate the relationship between the BE and walking behavior in the overall sample.

To assess heterogeneity across life stages, a moderated mediation model was used with age as a moderator of both direct and indirect pathways. The results showed conditional effects: the direct effect of the BE on walking behavior was statistically significant only among young adults, not among middle-aged and older adults. Additionally, a small but statistically significant indirect effect of the BE on walking via attitudes was found among middle-aged adults, whereas the corresponding indirect effects in younger and older groups were not significant. These results indicate that the mediating role of attitudes is conditional on age and that environmental effects on walking vary across life stages. However, the relatively small effect sizes and limited explanatory power for attitudes require cautious interpretation.

These results contribute to the ongoing debate concerning environmental and psychological determinants of walking. Some studies have reported mediation through attitudes or related constructs (Rhodes et al., 2006), whereas others highlight the predominant influence of psychological factors over objective(Li et al., 2020; J. Panter et al., 2011; J. Wang & Huang, 2025)l., 2011; J. Wang & Huang, 2025). Consistent with (Li et al., 2020), the present study did not identify strong support for simple attitudinal mediation. In conclusion, this study reinforces the independent and interacting roles of environmental and psychological factors in shaping transport walking, suggesting that life-stage differences should be considered when designing interventions to promote active mobility, especially in medium-sized urban centers.

4.4 Paper 4

Title: Built Environment, Walking Behavior and Pedestrian Route Choice: A Multi-Level Analysis Using GPS Data from two Swedish cities

This study examines the combined influence of individual socio-demographic characteristics, attitudinal factors, and objectively measured BE attributes on transport walking behavior and pedestrian route choice in two Swedish cities: Umeå and Linköping. The study analyzed 341 participants (72 in Umeå and 269 in Linköping), measuring individual-level walking behavior per person per day as total distance walked (mean = 1.40 km, SD = 1.16) and walking ratio (mean = 0.55, SD = 0.30).

The comparison between Umeå and Linköping reveals statistically significant differences in walking behavior, even though attitudinal profiles are largely similar across the two cities. In Umeå, participants report higher total daily walking distances and higher walking ratios, while demographic differences are mainly observed in age and employment status. The city context also moderates certain BE effects, particularly those related to building exposures, suggesting that the influence of urban form on walking practices varies by location. At the individual level, walking behavior is modestly but consistently associated with specific socio-demographic and attitudinal variables. Females and those without access to a bicycle tend to walk longer distances per day, and positive attitudes towards walking, such as enjoyment of walking and willingness to walk further for transport purposes, are positively associated with both total distances walked and the walking ratio.

To analyze pedestrian route choice, two complementary modelling approaches are applied. Linear Mixed Models (LMMs) are used to compare environmental exposures along actual and shortest routes, accounting for repeated trips by the same individuals. In addition, mixed-effects discrete choice models (DCMs) estimate the probability of selecting a particular route based on its attributes. The LMMs offer insight into how environmental characteristics differ between route types, whereas the DCMs identify which specific attributes are associated with the likelihood of deviating from the shortest path.

Linear Mixed Models

The results indicate that the vast majority of trips (95.65%) follow the shortest route, reflecting a strong preference for minimizing distance. For the small proportion of trips (i.e., 156 trips made by 98 individuals) that deviate from the shortest path, the actual routes are associated with higher total building area and slightly greater water area, but lower residential and apartment area, shorter non-vehicular pedestrian networks, fewer low-speed vehicular streets, and fewer streetlights. No significant main effects are observed for commercial area, park area, trees, pedestrian amenities, bus stops, or single-family housing. Several moderation effects are identified: the effect of building area is moderated by both income and walking motivations, while the influence of non-vehicular pedestrian networks and vehicular streets is moderated by age and attitudinal variables. Water area also shows moderation by income. Streetlights have a significant main effect, but no moderation is found.

Discrete Choice Models

The analysis shows that residential area, commercial area, trees, and bus stops are positively associated with the probability of selecting the observed (non-shortest) route. In contrast, non-vehicular pedestrian networks, low-speed vehicular streets, and pedestrian amenities are negatively associated with deviation from the shortest path. Park area and streetlights do not exhibit significant effects, and water area is significant only through interaction effects in the final model. Total building area and apartment area are excluded from the analysis due to collinearity. Several significant interaction effects are identified, suggesting heterogeneity in preferences, particularly for water, non-vehicular pedestrian networks, and bus stops. No significant main effects are found for socio-demographic or attitudinal variables.

Similarities and Differences

Both modelling approaches consistently find that non-vehicular pedestrian networks and low-speed vehicular streets are negatively associated with deviation from the shortest route. Residential area is significant in both models, although the interpretation of its effect differs between the two methods. Water area is significant as a main effect only in the LMM, and only through interaction effects in the DCM. Commercial areas, trees, pedestrian amenities, and bus stops are significant only in the DCM, whereas total building area, apartment area, and streetlights are significant only in the LMM. In summary, the LMM results describe how environmental exposure differs between route types, while the DCM results clarify which attribute independently influence route choice behavior when multiple factors are considered.

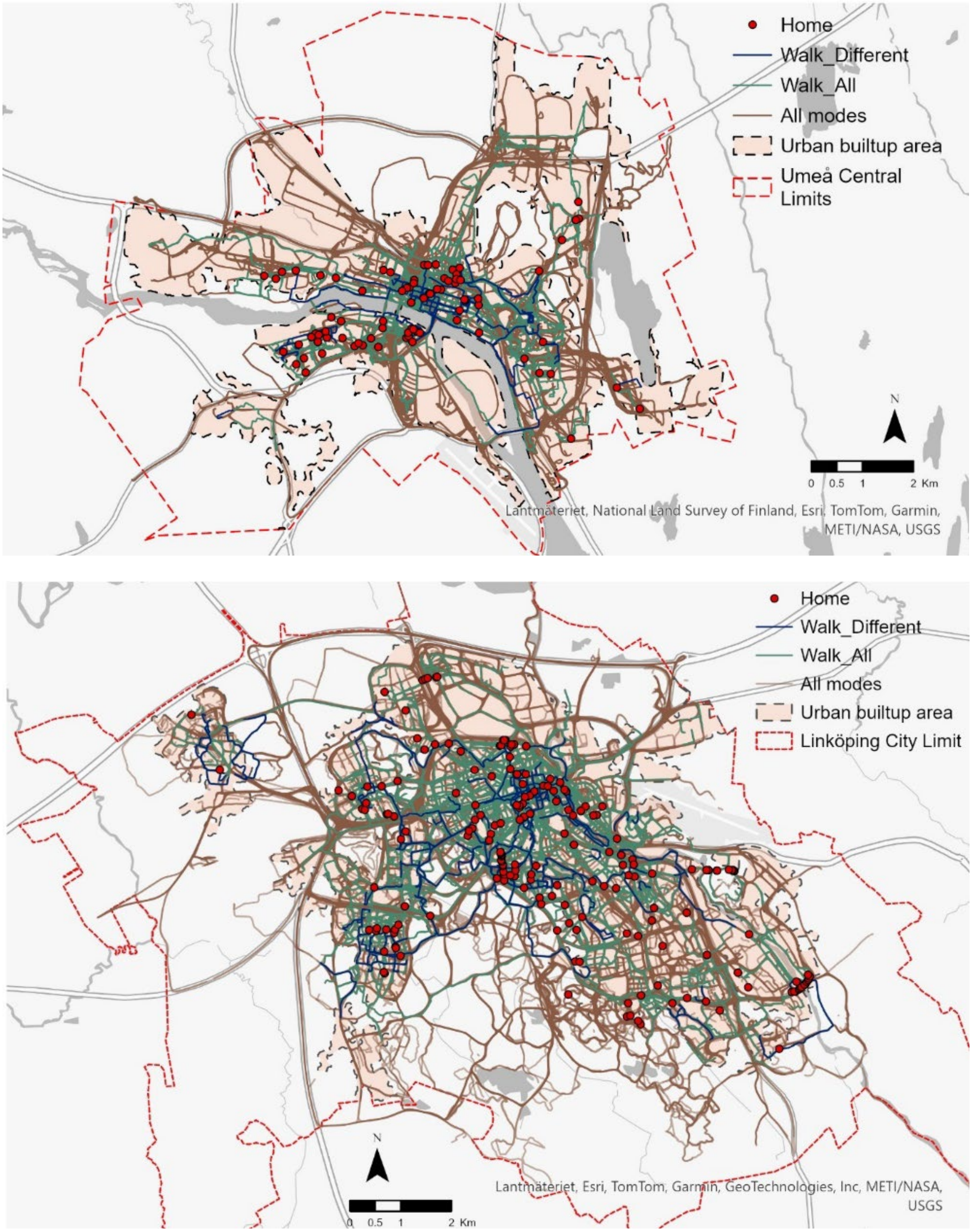
5. FINDINGS

This chapter presents and synthesizes the empirical findings across the four datasets of this thesis: Umeå 2019, Combined 2021, Umeå 2021, and Linköping 2021. The chapter is organized around three main analytical themes. It begins by comparing descriptive measures of walking behavior across datasets, examining both absolute indicators such as daily walking distance and relative indicators such as the walking ratio. It then turns to bivariate analyses of individual-level correlates, exploring how socio-demographic characteristics, attitudes toward walking, and attitudes toward the built environment (BE) relate to walking outcomes across temporal and geographic contexts. Finally, the chapter examines BE influences at two complementary spatial scales, the neighborhood level and the route level, drawing on structural equation models, linear mixed-effects models (LMM), and discrete choice models (DCM) to assess how environmental characteristics shape both the volume and the spatial patterning of walking. Throughout, findings are contextualized against international literature, with attention to where results converge with or diverge from existing literature.

5.1 Walking behavior: Comparison across datasets

This thesis examines walking behavior at the individual level using both absolute measures (e.g., total distance walked per day) and relative measures (e.g., walking ratio). Table 4 presents the operationalization of walking behavior across the various datasets employed in the thesis, while Figure 6 provides a graphical overview of travel behavior in the two cities based on the 2021 datasets.

While indicators such as trip count and distance are common in active travel research, the walking ratio, remains relatively underexplored, making direct comparisons with other studies challenging. One exception is the study by Sun et al. (2015), which reported a mean walking ratio of 0.90 (± 0.09) among university students in Hong Kong. This high ratio likely reflects the specific campus context, a predominantly walkable environment for a young cohort (mean age 18.6 years). In comparison, the walking ratios in this thesis were notably lower: Umeå 2021 showed a walking ratio of 0.77 (± 0.25), significantly higher than Linköping 2021 (0.49 ± 0.29). This discrepancy may reflect contextual differences such as age diversity, urban form, climate, and trip purposes (Prins et al., 2014), but also a result related to data collecting and (lack of clear) representativeness.



Note: Walk_All stands for all waking trips included in calculations of the walking behavior at the individual level, whereas Walk_Different stands for walking routes that are different from the shortest route (i.e., those included in route choice analysis)

Figure 6: Travel pattern of respondents in 2021: Umeå (above) and Linköping (below)

Table 4: Measures of walking behavior at the individual level

Description	Mean ± SD or percentage			Comparison of cities (2021)
	Umeå 2019	Umeå 2021	Linköping 2021	
Mean Distance per trip (km)	1.2 (±0.86)	0.80(±0.46)	0.65(±0.60)	W = 7217, p < 0.05
Total distance per day (km)	1.57 (±1.53)	2.05 (±1.25)	1.23(±1.07)	W = 5775, p < 0.05
Walking ratio	0.46 (±0.26)	0.77(±0.25)	0.49(±0.29)	W = 4483.5, p < 0.05
Number of trips	2.44 (±1.65)	_	_	_

The higher walking ratio observed in the 2021 Umeå dataset is partially attributable to a modification in the operational definition of the indicator. In the 2019 dataset, the walking ratio was computed as the proportion of all walking trips relative to total trips across all transport modes, irrespective of distance. In contrast, the 2021 calculation introduced a 1.5 km upper threshold, thereby restricting the denominator to trips within a distance range more plausibly classified as walkable. This adjustment produces a structurally higher walking ratio by excluding longer, non-walk-competitive trips from the comparison set. By contrast, differences in mean trip distance and total daily walking distance are not artefacts of measurement inconsistency. These indicators are derived directly from observed trip-level data and remain methodologically comparable across the two datasets. Consequently, variation in these measures likely reflects behavioral differences rather than definitional or computational changes.

In terms of total daily walking distance, participants in Umeå walked 2.05 km/day on average in 2021, significantly more than participants in Linköping (1.23 km/day). These results are broadly consistent with those of Zhang et al. (2023) in Australia, who reported 1.2 km/day of transport-related walking among university students, and G. Sun et al. (2015), who observed a daily walking distance of 3.29 km in a university setting.

In summary, while absolute metrics such as walking distance and trip frequency in Umeå and Linköping are broadly comparable with international benchmarks, the walking ratio introduces an additional metric for understanding modal preference at the individual level. These findings emphasize the importance of context, such as urban design, socio-demographic composition, and local climate, in shaping walking behavior and highlight the need for more nuanced, comparative studies that include both relative and absolute measures of active travel.

5.2 Bivariate correlates of walking behavior at the individual level: Comparison across datasets

Individual-level variables are analyzed across the three empirical papers included in this thesis. The analyses draw on four datasets collected in two Swedish cities: Umeå 2019, Combined 2021 (Umeå + Linköping), Umeå 2021, and Linköping 2021. These datasets enable within-city comparisons (Umeå 2019 vs. 2021) and cross-city comparisons (Umeå 2021 vs. Linköping 2021), as well as pooled analyses using the combined 2021 sample. Total distance walked per day (km) and walking ratio were analyzed against three clusters of individual-level predictors: socio-demographic characteristics, attitudes towards walking, and attitudes towards the BE. Results are contextualized through relevant literature, drawing on both converging and diverging studies to examine how consistently individual characteristics predict walking behavior across temporal and geographic contexts in Sweden.

5.2.1 Socio-demographic variables

The four samples are internally consistent on several socio-demographic characteristics, particularly in their elevated levels of educational attainment (63–74% university-educated) and near-universal access to mobility resources, driver's license holding (93–99%) and car access (~78–80%). Several variables nonetheless vary meaningfully across subsamples, reflecting temporal and spatial differences in composition. For a detailed comparison of results, refer to Table 12 (in Appendix 7).

First, gender composition varies across datasets, with the male share declining from parity in Umeå 2019 (50%) to lower levels in the 2021 samples (35–44%). Second, age structure differs markedly: Umeå 2019 has a relatively balanced distribution including a substantial older population (25%), whereas the 2021 samples are concentrated in the middle-aged group (50–61%), with older participants sharply underrepresented, particularly in Linköping 2021 (2%). This age difference between Umeå and Linköping 2021 is statistically significant. Third, family structure shifts toward households with children in 2021 (38–48%), compared to a more even distribution in Umeå 2019. Fourth, income distributions differ across contexts: Umeå 2019 skews toward lower-income groups (57%), while Linköping 2021 is dominated by middle-income households (56%). Fifth, employment composition changes as well, with the non-working category dropping from 30% in Umeå 2019 to 8–15% in 2021, alongside fluctuations in the student share (8–18%). The employment difference between Umeå and Linköping 2021 is statistically significant. Car access and bicycle access, by contrast, remain stable across all samples.

When benchmarked against national statistics, the sample is partially representative but shows several systematic deviations. In Sweden, the adult population is approximately gender-balanced (~50% male) and adults aged 65 and above make up roughly 20% of the population (Statistical database, 2020). The present samples underrepresent older adults and, in the 2021 datasets, overrepresent women, a pattern common in similar research (Basu, 2022; Ton, 2019).

Single-person households make up approximately 40% of Swedish households (Statistical database, 2020) but only 27–31% of the 2021 samples.

The largest deviation concerns educational attainment: approximately 40–45% of the Swedish population aged 25–64 has tertiary education (Eurostat, 2021), compared to 63–74% in the sample. This reflects both the university-city character of Umeå and Linköping and the well-documented participation bias in app-based data collection (Bricka et al., 2009; Cottrill et al., 2013). Employment rates in the sample (~75–76%) align closely with national labor force participation (~75–77% for ages 15–64; Statistical database, 2021a)). Car access also approximates national levels, with around 80–85% of Swedish households having at least one car (Statistical database, 2020) though the near-universal driver's license holding in the sample exceeds national averages (~80–85%).

Overall, the sample represents labor market participation and baseline transport resources reasonably well, but skews toward highly educated, middle-aged, and mobility-capable individuals, while underrepresenting older adults and single-person households. These patterns are consistent with known participation biases in app-based and voluntary travel surveys, where individuals with higher socioeconomic status, digital literacy, and active daily mobility are more likely to take part (Cottrill et al., 2013).

Socio-demographic factors are weak and inconsistent predictors of walking in this thesis. Table 5 summarizes the key associations across the four datasets. For a detailed comparison of statistical test results, refer to Table 12 (in Appendix 7).

Table 5: Summary of inferences of socio-demographics characteristics on walking behavior

Variable	Effect on total distance walked per day	Effect on walking ratio
Gender	Combined 2021 and Linköping 2021	Umeå 2021
Age	Not significant	Not significant
Family Structure	Not significant	Not significant
Education Level	Umeå 2021	Not significant
Employment status	Not significant	Not significant
Income	Not significant	Not significant
Bicycle Access	Combined 2021 and Linköping 2021	Combined 2021, Umeå 2021 and Linköping 2021
Driver's license and Private Car Access	Not significant	Not significant

a. Gender

Gender showed limited and inconsistent associations with walking across the four datasets. In Umeå 2019 (Paper 2), no significant gender difference was found for any outcome, total distance, walking ratio, or frequency. This null result stands out given the extent to which the international literature links gender to walking. Men typically walk longer distances per day, often for work-related purposes (Balarezo et al., 2024; Chamseddine & Ait Boubkr, 2021; Y. Yang & Diez-Roux, 2012) while women walk more frequently, especially for errands and short trips linked to caregiving (Chamseddine & Ait Boubkr, 2021; Evenson et al., 2002; Sloboda & Yao, 2005).

Our results only partially agree. Women in the samples walked slightly longer distances and chose walking more often than men, but the associations were limited and inconsistent. In the 2021 data, Umeå showed a borderline association between gender and walking ratio, while Linköping and the combined dataset showed a small but statistically significant effect on total distance. Where significant, effect sizes were uniformly small, accounting for less than 2–3% of variance in walking outcomes. Stefánsdóttir et al. (2024) found gender-differentiated perceptions of barriers and preferred walking environments in Nordic cities, but no large differences in overall walking volume. Ton (2019) also found gender non-significant as an explanatory variable of active mode choice in the Netherlands. In the relatively safe, high-equity urban environments of Swedish mid-sized cities, gender differences in walking volume may simply be smaller than in contexts where safety barriers are more pronounced (Guinn & Stangl, 2014).

b. Age

Despite notable compositional differences in age across datasets, age is not a significant predictor of any walking outcome, a finding that may seem to contradict studies documenting age-related declines in transport walking (Turrell et al., 2014) and age-differentiated BE sensitivities (Van Holle et al., 2015; Yuan et al., 2025), though some studies have also found age non-significant (Ton, 2019). App-based recruitment likely introduced a self-selection bias favoring younger, more digitally active, and more physically active individuals even within the older age category. Moreover, walking is deeply embedded in Swedish daily life regardless of age (Bondemark, 2023; Sundquist et al., 2011), which may genuinely reduce age's discriminating role compared to more car-dependent contexts. F. Sun et al. (2013) found that older adults tend to walk less due to mobility limitations and safety concerns, and Moudon & Lee (2003) argued that age alone is insufficient to explain walking differences once personal habits and physical capability are considered.

c. Education

Education produced one significant finding: in Umeå 2021 (Paper 3), university-educated individuals walked significantly further on average. This did not replicate in Linköping 2021, the combined 2021 dataset, or Umeå 2019. Agrawal & Schimek (2007) documented education and income patterns in walking that differed by trip purpose in the US, with higher education linked to less transport but more recreational walking in car-oriented settings. Most studies, however, do not report education as a predictor of walking. Troped et al. (2010) found that when environmental variables are controlled, education no longer explains walking variation, suggesting it may proxy for unmeasured influences such as residential location or lifestyle. In the Nordic context, the direction and magnitude of educational gradients in walking are likely moderated by the high baseline walkability of Swedish cities and the universal coverage of pedestrian infrastructure, which reduces walking's dependence on individual socioeconomic resources. That the education effect failed to replicate across cities and time points suggests it reflects a sample-specific feature of the Umeå 2021 recruitment rather than a robust structural relationship.

d. Employment status, Income and Family Structure

Employment status, income, and family structure showed no significant associations with walking in any dataset. The absence of income effects is consistent with European studies finding that income's role in walking is largely mediated by car ownership and residential location rather than directly shaping behavior (Christie et al., 2022; Turrell et al., 2014). In the present samples, car ownership was uniformly high (78–80%) and invariant across income groups, which likely absorbed any income gradient in walking. This nonetheless carries an equity implication: lower-income individuals in these Swedish datasets do not walk substantially more for transport, contrary to the pattern Turrell et al. (2014) identified in Australia, where more disadvantaged neighborhoods generated more transport walking. The likely explanation is the higher quality and more equitable distribution of pedestrian infrastructure in Swedish cities, which reduces the compensatory role of walking for those without reliable private transport.

e. Driving license, Car Access and Bicycle Access

Driver's license and car access showed no significant relation to walking. Bicycle access, however, emerged as a consistent and significant predictor in the 2021 datasets: people with bicycle access walked less. This pattern, absent in Umeå 2019, is theoretically coherent, in a cycling-rich culture like Sweden, a bicycle is a viable substitute for short-to-medium trips that might otherwise be made on foot. Sahlqvist et al. (2013) found that people with bicycle access are more likely to cycle even for distances that could feasibly be walked, particularly in cycling-friendly cities. Rietveld & Daniel (2004) found that improved cycling conditions shift mode choice away from walking when time savings are perceived. Winters et al. (2010) suggest that where cycling infrastructure surpasses pedestrian infrastructure, cycling can substitute for walking on short transport trips. Some research takes a different view: Heinen et al. (2010) and Pucher et al. (2010) emphasize that walking and cycling are often complementary in well-integrated urban environments, with regular cyclists also tending to walk more than those who rely primarily on private cars.

5.2.2 Psychological factors

Attitudinal constructs are the only psychological dimension measured consistently across all datasets, enabling direct comparison between Umeå 2019, Umeå 2021, Linköping 2021, and the combined 2021 sample. Subjective norm (SN) and perceived control were operationalized only within the Umeå dataset, so they are analytically confined to Paper 2 and cannot be incorporated into cross-sample comparisons. Statistical tests found no consistent or robust associations between SN and walking outcomes. Perceived control at the individual level also produced no significant results, while perceived control measured at the route level (as reasons for mode choice and route choice) yielded several significant findings (see Paper 2), though the associations are modest and not uniformly observed across all outcomes. Paper 3, which uses only Umeå data, excludes attitudes towards the BE, subjective norm, and individual-level perceived control due to non-significant correlations, and excludes trip-level perceived control to avoid over-complicating the structural equation models with moderators and mediators.

Across attitudinal variables, attitudes directly related to walking exert a more consistent and stronger influence on walking behavior than attitudes about the BE. Table 6 summarizes findings across datasets. For a detailed comparison of results, refer to Table 12 (in Appendix 7).

a. Attitudes Toward Walking

The attitudinal items in this thesis differ in format and depth from those typically used in international walking research due to the limitations in the visual format being app based in phones, but the constructs they capture are parallel enough to permit comparison. Most studies use multi-item scales with 5–7 bipolar or Likert items, typically separated into affective and instrumental sub-scales within a TPB framework (Bird et al., 2018; J. Panter, Griffin, et al., 2011; Rhodes et al., 2006). Adams et al. (2016) used a checklist of reasons for walking, health, environmental, and practical motivations, closely parallel to the items in this thesis. Despite these measurement differences, the direction of findings is consistent: positive attitudes toward walking are associated with more walking, across contexts from Brazil (Larrañaga et al., 2016) to Korea (H. S. Lee, 2016) to the United States (Y. Yang & Diez-Roux, 2017), and this pattern holds here under GPS-based behavioral measurement.

Attitudinal distributions are closely aligned across all four datasets (see Table 6). Virtually all respondents reported liking walking (93–97%), and willingness to walk was consistently around 24 minutes across all samples (range: 23.9–25.9 min), with no cross-dataset variation reaching statistical significance. These distributions, while reflecting a walking-sympathetic sample, provide a stable baseline against which within-sample variance in walking outcomes can be examined. For a detailed comparison of results, refer to Table 12 (in Appendix 7). Basu (2022) reports 88% of their sample enjoy walking and 75% enjoy walking with others.

The most consistent finding across all datasets concerns attitude towards walking. Both the binary measure ("Do you like walking?") and the ordinal degree measure ("How much do you like walking?" rated 1–4) were significant predictors of walking across nearly all papers and outcome measures (see Table 6 for summary and Table 12 for details). The binary measure was especially powerful in Umeå 2019, where those who liked walking walked significantly further, had a higher walking ratio, and walked more frequently. The ordinal measure was even more consistent: significant across all outcomes and both cities in 2021, and for walking ratio in Umeå 2019. The difference between 2019 and 2021 results likely reflects how walking was conceptualized, at the travel element level in 2019, and at the trip level in 2021. The high overall positivity toward walking in this thesis likely reflects three interacting factors: the binary yes/no format suppresses variance compared to a 7-point bipolar scale; walking is normalized in Swedish urban culture (Bondemark, 2023; Sundquist et al., 2011) relative to more car-dependent Australian or US contexts (Basu, 2022); and the app-based platform self-selects for individuals already engaged in active daily mobility.

These findings are consistent with the international literature identifying attitude towards walking as the most replicable individual-level psychological predictor of walking behavior (Yang & Diez-Roux, 2017; Chan et al., 2021; Yu, 2024; Adams et al., 2016). Chapter 2 documented that positive attitudes toward walking are associated with walking frequency and duration across contexts from recreational walking in Korea (H. S. Lee, 2016) to transport walking in Brazil (Larrañaga et al., 2016) and grocery-store walking in the United States Yu (2024). The present findings extend this to a Nordic, GPS-based context, methodologically relevant because most existing attitude–walking associations rely on self-reported outcomes that share method variance with attitudinal measures in the same survey instrument.

Among motivational reasons for liking walking, only three items showed significant results, and only in the Umeå 2019 data: walking because it is economic, because it is environmentally friendly, and to enjoy the landscape or streetscape. Koszowski et al. (2024) found that frequent walkers are more likely to express non- transport, intrinsic motivations such as enjoyment and aesthetic appreciation. None of these reasons were significant in the 2021 datasets, except for the association between walking ratio and walking for health in Linköping 2021. This may reflect COVID-related disruptions in 2021, where reduced and irregular travel weakened the link between stated motivations and actual behavior. Alternatively, the Umeå 2019 sample's higher share of non-workers and older adults, groups for whom the economic and environmental arguments for walking may carry more weight as deliberate mode choices, could explain the stronger motivational specificity of that dataset.

Most respondents across all datasets reported walking for both transport and recreational purposes (73–79%), with no statistically significant difference between cities in 2021. Walking purpose predicted walking only in Umeå, affecting all outcomes in 2019 and walking ratio in 2021, suggesting context-specific effects. Willingness to walk to a destination (~24 minutes in all datasets) was a consistent and significant predictor of actual walking distance and ratio across all 2021 datasets, whereas willingness to walk for recreation (~55–78 min, more variable) showed no associations in any paper. This is expected, since the thesis's outcome variables cover only transport walking.

Table 6: Summary of inferences of attitude on walking behavior

Variable	Effect on total distance walked per day	Effect on walking ratio
Attitude (towards walking)		
Like walking?	Significant across all datasets, except Linkoping 2021	Significant in all cities, but not combined dataset
Preference for walking compared to other modes of transport	Significant across all datasets, except Umeå 2019	Significant across all datasets
Reasons to like walking: it is economic, healthy, environment friendly, enjoyment of scenery, and practical and hassle-free	Environment friendly and observe landscape/ streetscape are significant in Umeå 2019	Economic and environment friendly are significant in Umeå 2019; Healthy is significant in Linkoping 2021
Walking Purpose (activity type): transport, recreational, both	Significant in Umeå 2019	Significant in Umeå 2019 & 2021
How long are you normally willing to walk to a destination?	Significant across all 2021 datasets	Significant across all 2021 datasets
Attitude (towards built environment)		
Importance of BE factors while walking: short and direct connection to destination, room for walking on the walking path, free from other types of traffic such as bicycles and car, quality and maintenance of walking path, quality of pedestrian amenities, feeling of safety, mix of uses, pleasantness of the walking environment, and overall character or uniqueness of the streetscape	Short and direct connection is significant in combined dataset and Linköping 2021 Pleasantness of the walking environment is significant in Linkoping 2021	Short and direct connection is significant across all datasets, except Umeå 2021

b. Attitudes Toward the Built Environment

Respondents rated the importance of nine walking environment attributes on a scale of 1 to 4. For a detailed comparison of results, refer to Table 12 (in Appendix 7), while Table 6 summarizes the results of the bivariate relation between the attitude towards **BE** and different measures of walking outcome. Of these, only two were significant predictors across datasets: short and direct connection to destination and pleasantness of the walking environment. Table 7 shows the share of respondents rating each attribute important. i.e., lists the percentage of participants who selected the BE variable as being important to them when walking. Refer to Appendix 6 for the original questions.

The main finding regarding BE attitudes is the disconnect between what respondents say matters and what actually predicts their walking. Safety is the highest-rated attribute (78–88% across datasets), followed by pleasantness of the walking environment (79–84%). Yet safety showed no significant correlation with any walking outcome, and pleasantness was significantly correlated only with total distance walked in Linköping 2021. The absence of a safety effect is plausible in the context of Swedish mid-sized cities, where objective and perceived safety are relatively high, safety may function as a background expectation rather than a behavioral constraint, subject to a ceiling effect. Short and direct connection to destination, rated important by 55–68% of respondents, was a better predictor of walking than any other BE attitude variable, though still inconsistent: no effect in Umeå 2021, and only with walking ratio in Umeå 2019. Other attributes, pedestrian amenity quality, land use mix, and streetscape character, were not significantly associated with walking in any dataset.

Table 7: Respondents rating of importance of various built environment features to walking

Variable	Umeå 2019	Umeå 2021	Linköping 2021	Combined 2021
Short and direct connection to destination	65%	55%	68%	65%
Room for walking on the walking path	62%	61%	54%	55%
Free from other types of traffic	57%	50%	51%	50%
Quality and maintenance of walking path	52%	65%	48%	51%
Quality of pedestrian amenities	21%	29%	21%	23%
Feeling of safety	78%	85%	88%	87%
Mix of uses	32%	27%	30%	30%
Pleasantness of the walking environment	84%	79%	81%	81%
Overall character or uniqueness of the streetscape	41%	29%	36%	32%

Attitude towards the BE is rarely measured in the existing walking literature. The closest parallel is Guinn & Stangl (2014), who asked pedestrians and cyclists in a walkable Vancouver neighborhood to rate motivating factors for their mode choice. Among pedestrians, the top motivators were exercise opportunities, environmental concern, and visual appeal, with route security especially influential for women. Although framed as motivators rather than importance ratings, the construct is closely related: respondents identify which environmental and individual features matter most in their decision to walk.

5.3 Built environment variables: Neighborhood and route level analyses and comparison

BE variables are examined at two complementary spatial scales across the empirical papers. Paper 3 analyzes the residential neighborhood using a 750 m buffer around the home location, while Paper 4 examines the pedestrian route using a 15 m sausage buffer along GPS-tracked walking paths. The following sections present findings from the neighborhood-level structural equation models and the route-level linear mixed-effects and discrete choice analyses in turn, before drawing a cross-scale comparison of which BE variables reached statistical significance across analytical frameworks and datasets.

5.3.1 At neighborhood (individual) level

GIS data within a 750 m buffer around the home were used to examine associations between the BE and individual-level walking behavior in Paper 3. Three structural equation models of increasing complexity tested direct, mediated, and moderated pathways linking the BE, walking attitudes, and GPS-measured walking. Walking attitudes emerged as the most consistent individual-level predictor, while the BE played a complementary but structurally distinct role. Both the magnitude and pathway of built-environment effects varied by age group.

The base model shows a moderate positive direct association between the BE and walking: BE characteristics explain approximately 18.4% of variance in GPS-measured walking. This is comparable to, or slightly higher than, figures reported in other studies using objective behavioral outcomes and suggests that the residential environment contributes meaningfully to walking even when measured objectively rather than through perception.

When walking attitudes were introduced in the simple mediation model, they emerged as a stronger direct predictor than the BE, though the BE retained a smaller but still statistically significant direct effect. Contrary to the mediation hypothesis outlined in Chapter 2, however, the BE did not significantly predict walking attitudes, so no indirect effect through attitudes was observed. Given the relatively low statistical power for testing mediation effects, this null finding warrants caution.

The coexistence of significant direct effects from both attitudes and the BE is consistent with prior SEM work showing parallel rather than competing pathways. H. S. Lee (2016), Rhodes et al. (2006) and Neto et al. (2020) all report strong direct effects of psychological constructs, while environmental attributes tend to exert more distal or indirect influences once psychological variables are included. Yang and Diez-Roux (2017) found that attitudes were positively associated with walking across contexts, with built-environment effects most visible among individuals with particularly positive walking attitudes. Studies such as Kamruzzaman et al. (2016) confirms that built-environment characteristics can retain independent associations with walking even after accounting for individual preferences.

The absence of a significant BE–attitude pathway nonetheless diverges from a large body of behavioral research. Many TPB-grounded studies report that neighborhood characteristics influence walking indirectly through attitudes, norms, or PBC. Rhodes et al. (2006) and H. S. Lee (2016) both find positive links between perceived neighborhood quality and attitudinal constructs, and more recent work by Yu (20J. Wang & Huang (2025)5), and J. Wang & Huang (2025) treat perceived built-environment characteristics as mediators connecting residential context to walking. In J. Wang & Huang (2025), objective GIS and audit-based built-environment features influence walking exclusively through latent socio-environmental perceptions, producing full mediation.

The key distinction is that nearly all of these studies use perceived rather than objectively measured built-environment indicators. Orrego-Oñate & Marquet (2025) show explicitly that perceived accessibility is more likely to function as a mediator between environment and behavior, while objective built-environment measures tend to retain direct associations with walking. J. Wang & Huang (2025) also work in a markedly different urban context, Chinese resettlement towns, with a model architecture where perceptions explicitly absorb the influence of objective features. Lemieux & Godin (2009) similarly find environmental effects absorbed by cognitive variables, but again in a perceived-environment framework. The absence of attitudinal mediation here most plausibly reflects these measurement and model specification differences rather than a challenge to the underlying behavioral theory.

The final model introduces age as a moderator, revealing further heterogeneity in environment–behavior pathways. Among young adults, the BE 's direct effect on walking is strongest and most robust, with no significant indirect effect through attitudes. Environmental affordances appear to translate more directly into walking for this group, possibly reflecting more habitual or automatic responses to dense, connected, and pedestrian-supportive settings.

Among middle-aged adults, the BE operates both directly and through attitudes, yielding a significant mediated pathway. This points to a more deliberative process, where environmental characteristics shape perceived feasibility or attractiveness before influencing behavior. Structured daily constraints, work schedules, family responsibilities, may increase reliance on cognitive appraisal when making travel decisions. Kamruzzaman et al. (2016) found attitudinal mediation particularly salient in working-age and commuting-oriented contexts, which fits this pattern.

For older adults, neither direct nor indirect pathways reach statistical significance. This result should not be interpreted as indicating the absence of environmental or attitudinal influences in later life; rather, the very small share of older respondents in the 2021 sample renders the findings for this group inconclusive. Most moderation studies focusing on older adults examine psychosocial characteristics, such as self-efficacy, as moderators of environmental effects. Van Holle et al. (2015) find that walkability supports recreational walking only among older with high self-efficacy; Nguyen & Mertens (2021) find self-efficacy amplifying park-density effects on older adults' active transport. Though these studies use a different model structure, they support the broader conclusion that responsiveness to the BE varies across population subgroups.

A few contextual factors also help explain residual divergence from the international literature. Swedish mid-sized cities have relatively high-quality and homogeneous pedestrian infrastructure compared to the Australian, American, or Chinese contexts where much prior work was conducted. This relative homogeneity reduces within-sample variability in objective built-environment indicators, which affect their apparent predictive power. GPS-measured walking also differs from the self-reported outcomes used in most comparable research: it captures walking across all purposes, including incidental and habitual movement that is less consciously planned and therefore less tightly linked to explicit attitudes or environmental appraisals. Finally, the residential 750 m buffer only partially captures the built-environment exposure that shapes all observed walking: GPS data cover movement across the whole city and workday, which the home neighborhood buffer cannot fully represent, especially for working-age adults.

Walking attitudes are the most consistent individual-level predictor of GPS-measured walking in these models. The BE plays a real but more constrained role, largely through direct behavioral associations rather than attitudinal pathways, at least when perceptions are not explicitly modelled. The fact that both the strength and mechanism of environmental influence shift across age groups further cautions against applying a single model of the environment–behavior relationship uniformly across adulthood.

5.3.2 Pedestrian route choice analysis

Walking trips in this dataset most often follow the shortest available route. Of 3,617 trips recorded across 332 participants in the 2021 dataset, only 4.35% deviated from the shortest path: 156 trips made by 98 individuals. This aligns with the established literature showing that transport pedestrians strongly prefer direct, efficient routes (Guo & Loo, 2013; Hood et al., 2011).

Two complementary analytical methods, Linear Mixed-Effects Models (LMM) and Discrete Choice Modelling (DCM), were employed to examine pedestrian route choice, but were applied to different analytical samples reflecting their distinct objectives. The LMM analyses were restricted to the subset of trips that deviated from the shortest path and compared built-environment characteristics along actual versus shortest routes for these 156 trips. This exposure-oriented analysis identifies which environmental attributes systematically characterize routes chosen when pedestrians do not follow the shortest alternative. In contrast, the DCM analyses were conducted on the full route-choice dataset, including both shortest-route and deviating trips, by modelling the probability of selecting the observed route relative to the shortest-path alternative. This behaviorally grounded approach allows estimation of the joint influence of multiple built-environment attributes and their interactions with socio-demographic and attitudinal factors, even though deviations occur infrequently. Together, these two methods provide complementary insights: LMMs characterize how environmental exposure differs when pedestrians deviate from shortest paths, while DCM identifies which environmental attributes increase or decrease the likelihood of such deviations in the broader population.

Table 8 provides a summary of which BE variables have statistically significant effect on pedestrian route choice and the moderators that affect this relation.

a. Results of Linear mixed models

Table 8 provides a Summary of inferences for route choice analysis using Linear mixed-effects models. Three variables were significant across all datasets: total building area, non-vehicular pedestrian network length, and streetlight density. Building area was higher on actual than shortest routes in the combined dataset and Umeå, denser corridors reduce route resistance, but lower in Linköping, likely reflecting that city's more polycentric spatial structure. Income moderated this effect, with lower- and middle-income pedestrians favoring built-up routes, while environmentally and scenically motivated pedestrians preferred less dense corridors. Non-vehicular paths were consistently shorter on actual routes than on shortest alternatives across both cities and the combined sample. In Swedish medium-sized cities, dedicated off-road paths tend to follow direct alignments through parks and residential areas, forming much of the shortest-path network itself. Walkers motivated by scenery and environmental enjoyment used more of these paths; those prioritizing path width and comfort tended to avoid them. Streetlight density was also lower on actual routes, with no moderation by socio-demographics or attitudes, in high-safety Swedish cities, less-lit corridors are probably just corridors that pedestrians find attractive for other reasons.

A second group of variables showed context-dependent effects. Water proximity was significant in Linköping and the combined sample (higher-income pedestrians showed the strongest preference), but not in Umeå, where the city's spatial structure means water is already on many shortest routes. Residential and apartment building area were similarly significant in Linköping and the combined data only, without any attitudinal or demographic moderation. Low-speed streets (≤30 km/h) were less prevalent on actual than shortest routes in Umeå and the combined data, moderated by age and scenic motivation. Despite their calm character, these streets appear to function as part of the shortest-path network in compact Nordic city centers, avoided in favor of more connected main corridors.

a. Results of discreet choice analysis

In the base model, commercial area was the strongest positive predictor of route selection, followed by tree presence, residential area, and water area (which showed equal effect sizes). Non-vehicular paths and low-speed streets were negatively associated. Pedestrian amenities were mildly negative, plausibly because amenity-dense corridors in Swedish cities tend to be slower and less direct. The commercial area finding closely replicates (Sevtsuk et al., 2021) and R. Basu & Sevtsuk (2022), who identified active land use frontages as the most consistent route attractor across large GPS datasets.

Table 8: Summary of inferences for route choice analysis using Linear mixed-effects models

Variable	Effect on route choice	Moderators	
		Socio-demographic	Attitude
Land use areas			
Buildings (total)	Significant across all datasets	Income	Like walking for environment friendliness and enjoyment of scenery; prefer pedestrian paths free of other traffic
Residential buildings	Significant in combined data and Linköping 2021	None	None
Apartment buildings	Significant in combined data and Linköping 2021	None	None
Single-family houses	Not significant	None	Like walking; like walking for health reasons
Water	Significant in combined data and Linköping 2021	Income	None
Traffic and street amenities			
Non-vehicular pedestrian network	Significant across all datasets	None	Like walking for environment friendliness and enjoyment of scenery; activity type for walking; consider available space on the walking path important
Vehicular, less than 30km/hr	Significant in combined data and Umeå 2021	Age	Like walking for enjoyment of scenery; consider overall character or uniqueness of the streetscape important
Pedestrian amenities	Not significant	None	Consider overall character or uniqueness of the streetscape important
Bus stops	Not significant	None	Utilitarian purpose
Streetlights	Significant across all datasets	None	None

** Route choice analysis was not conducted for Umeå 2019*

In the final model, residential areas' and commercial area's effect strengthened, water area's effect became not significant, and bus stops' effect became significantly positive, a relationship that only emerged once individual heterogeneity was accounted for. No socio-demographic or attitudinal variable produced a significant unconditional main effect on route choice, consistent with Lieu & Guhathakurta (2025): demographic differences in environmental preference show up almost entirely through interactions. The most theoretically informative results were these interactions. Walkers who valued streetscape character showed 63% higher odds of choosing water-adjacent routes. Those who enjoyed landscape observation showed 20% higher odds of selecting routes with more non-vehicular paths, reversing the main effect, and mirroring (H. Y. Chan et al., 2024) finding that aesthetically motivated pedestrians deviate toward visually stimulating environments. Walkers attentive to surface quality were less likely to choose bus stop corridors, a nuance not previously documented.

c. *Cross-Method Comparison*

Both methods agree that denser, more mixed-use corridors are the dominant environmental attractor, and that dedicated pedestrian infrastructure does not increase route attractiveness in this Swedish context. Trees and bus stops diverge: trees are a significant positive attractor in both DCM models but not in the LMM, likely because their distribution across actual and shortest routes lacks sufficient differential for mean-level differences while still functioning as a utility signal in choice modelling. Bus stops emerge only in the final DCM model once individual heterogeneity is modelled explicitly. As (Shatu et al., 2019a) observe, GIS-based exposure measurement and the choice-based framing of DCM capture complementary but non-identical aspects of route preference, and conclusions about specific environmental features should rest on convergent results from both.

5.3.3 Neighborhood vs. Route-Level Characteristics

The overarching aim of this thesis has been to advance understanding of how the BE shapes walking behavior at two complementary scales: the neighborhood level (750 m radius around home) and the route level (15 m sausage buffer along actual walking paths). Table 9 summarizes which variables reached statistical significance at each level.

Built-up area was positively associated with both total distances walked per day and walking ratio at the neighborhood level, suggesting that denser built form around the home supports greater walking activity. At the route level, however, building area showed a positive association with actual route length in Umeå but a negative association in Linköping, suggesting that pedestrians in Linköping do not preferentially choose routes with more building. In Umeå, density thus operates consistently across both scales, a pattern not replicated in Linköping. This divergence likely reflects differences in urban morphology (buildings in Umeå sit closer to the street), spatial data distribution (Linköping participants were more dispersed across the urban area), or broader cultural differences between the two cities. The DCM produced no significant result.

The total area of residential use is associated with increased likelihood of choosing to walk for trips under 1.5 km at the neighborhood level. At the route level, greater residential land use is associated with less deviation from the shortest path, and pedestrians actively prefer residential routes in the DCM. Together, these results suggest that residential streets function as preferred but efficient pedestrian corridors, chosen when available but not sought at the cost of additional trip length. Residential land use is one of the few variables that produced significant results across all analytical frameworks.

Paved surface was positively associated with both neighborhood-level walking metrics but showed no significant effect at the route level. This divergence is perhaps unsurprising: paved surfaces are sufficiently ubiquitous in both study cities that they offer little discriminatory power between route alternatives, even if their aggregate presence across a neighborhood supports walking in general.

Table 9: Comparison of built environment results at different levels: Neighborhood versus route

		Neighborhood level (750 m radius around home)	**Route Level (15 m sausage buffer)**
Land use areas (in sq. m)	Buildings	Both (TPDW and WR)	LMM only
	Paved surface	Both (TPDW and WR)	NS/NA
	Water	NS	Both (LMM and DCM)
	Parks	WR only	NS
Areas under different building uses (in sq. m)	Residential	WR only	Both (LMM and DCM)
	Commercial	WR only	DCM only
	Mixed use	WR only	NS/NA
Areas under different housing types (in sq. m)	Single family dwelling	NS	NS/NA
	Multi-family dwelling	NS	LMM only
Street network length (in m)	All pedestrian network	Both (TPDW and WR)	NS/NA
	Pedestrian network with mixed traffic	NS	NS/NA
	Non-vehicular pedestrian network	NS	Both (LMM and DCM)
	Vehicular (≤30 km/h) b	NA	Both (LMM and DCM)
Number of Streetscape elements	Pedestrian amenities	NA	DCM only
	Points of interest	WR only	NS/NA
	Bus stops	Both (TPDW and WR)	NS
	Trees	Both (TPDW and WR)	DCM only
	Streetlights	NS	LMM only

Water bodies showed no neighborhood-level effect but emerged as a route attractor in both the LMMs (combined dataset and Linköping) and the DCM. Pedestrians choose routes with more water even when the overall proximity to water in their neighborhood does not predict how much they walk. This is consistent with literature on blue space as an aesthetic draw. The absence of a significant LMM effect in Umeå may reflect Umeå's more concentrated waterfront compared to Linköping's dispersed canal and lake edges.

Parks showed a modest positive association with walking ratio at the neighborhood level but no significant effect at the route level in either the LMM or the DCM. Parks may marginally tip mode choice toward walking for short trips, but they do not reliably attract pedestrians onto specific routes, possibly because park paths often deviate from direct trip lines.

Commercial land showed a limited neighborhood-level and route-level association. At the neighborhood scale, the total area of commercial land use was significantly associated with walking ratio only, indicating that residents of more commercially provisioned neighborhoods are slightly more likely to choose walking for short trips, but do not necessarily walk longer distances overall. At the route level, commercial land use produced no significant effect in the LMMs, but emerged as a strong positive predictor in the DCM, indicating that pedestrians actively prefer routes through commercial areas when choosing between alternatives, even though commercial density in their neighborhood does not independently predict overall walking volumes. This aligns with arguments about active frontages and street-level vitality as pedestrian attractors. The absence of a neighborhood effect likely reflects limited variation in commercial provision across neighborhoods in both cities.

Mixed-use areas and single-family dwellings produced no significant results at any level or in any model. For mixed use, this null result may reflect the category's heterogeneity, or that its behavioral effects are already captured by the residential and commercial variables. For single-family dwellings, the result is consistent with the broader literature associating low-density residential environments with car use, though a negative effect may have been suppressed by collinearity with the residential variable.

Multi-family dwelling area showed no neighborhood-level effect but was negatively associated with route deviation in the combined dataset, i.e. fewer or lesser multi dwelling along the actual route, and in Linköping, routes through multi-family areas tend to be more direct. This likely reflects the gridded, well-connected pedestrian infrastructure characteristic of Swedish multi-family residential developments, which appears to support efficient rather than exploratory movement.

Total pedestrian network length at the neighborhood level was positively associated with both walking metrics, reflecting a straightforward access effect: more paths mean more opportunities. This did not, however, translate to the route level, where network length was not significantly associated with any outcome. Network density thus enables walking at the neighborhood scale without directly governing individual route choices.

Pedestrian network with mixed traffic produced no significant result at either level, which is unsurprising given how common shared-traffic streets are in both cities. Any behavioral signal is likely absorbed by more specific predictors.

Non-vehicular pedestrian network showed no neighborhood-level effect but emerged as one of the more common significant, and counterintuitive, route-level findings. Routes with more car-free paths were associated with less deviation from the shortest path in the LMMs, and pedestrians were significantly less likely to choose alternatives with more non-vehicular network. In Swedish cities, non-vehicular paths tend to run through parks and green corridors that are pleasant but poorly connected to destinations, making them characteristic of indirect rather than efficient routes. This challenges the assumption that separating pedestrians from traffic is sufficient to generate route preference.

Low-speed vehicular streets (≤30 km/h) showed a parallel pattern: consistently negative associations in both the LMMs and the DCM across all three datasets. These roads tend to be residential access lanes or peripheral connectors with limited destination pull, such that high concentrations of them mark areas away from the main street network. Together, the non-vehicular and low-speed results suggest that traffic safety improvements alone do not translate into pedestrian route preference without accompanying destination density and spatial connectivity.

Pedestrian amenities were not assessed at the neighborhood level and the route level, showed no LMM effect, but the DCM produced a small negative association. Amenities tend to concentrate along leisure-oriented paths, so this negative coefficient likely reflects a route-type proxy effect rather than genuine pedestrian aversion to benches and shelters.

Points of interest showed a modest positive association with walking ratio at the neighborhood level—destination-rich neighborhoods may nudge residents toward walking for short trips—but no route-level effect in either model. This partial pattern, also seen with parks, suggests that some neighborhood attributes influence the decision to walk without subsequently shaping which routes are taken.

Bus stop density was positively associated with both neighborhood-level walking outcomes (i.e. total distance walked and walking ratio), consistent with the well-established link between transit access and pedestrian activity. At the route level, however, no significant LMM effect emerged, and the DCM coefficient was nominally significant but practically negligible given the confidence interval spanning unity. Transit infrastructure generates walking at the neighborhood scale without functioning as a route-level attractor.

Trees were positively associated with both neighborhood-level walking metrics. No LMM effect was found at the route level, but the DCM identified trees as a significant positive predictor of route preference. This combination suggests that trees influence which of similarly-distanced routes is chosen, without inducing pedestrians to walk further overall. In contrast to the negative DCM results for non-vehicular paths and amenities, trees appear to generate route preference without implying detour cost, consistent with established findings on the restorative and aesthetic value of street greenery.

Streetlights showed no neighborhood-level effect and a non-significant discrete choice result. The LMMs found that routes with more streetlights deviate less from the shortest path, i.e., well-lit corridors coincide with more direct routing, probably because lighting is concentrated along main streets that are inherently better connected. Once other route attributes are controlled in the DCM, lighting does not independently drive route selection, suggesting the LMM result reflects collinearity with main-street characteristics rather than a lighting effect per se.

6. CONCLUSION

This chapter synthesizes the findings of the four empirical papers against the thesis's stated research questions. The discussion here evaluates what the cumulative results actually suggest, where findings are robust, and where there are flaws. The chapter identifies the thesis's theoretical and methodological contributions, examines limitations that affect how far the conclusions can be taken, and draws out implications for future research and planning practice.

6.1 Limitations

The findings reported in this thesis are subject to several methodological and design limitations that affect the interpretation of results and the extent to which conclusions can be generalized.

6.1.1 Longitudinal versus Cross-Sectional Design

The thesis was originally designed as a longitudinal before-and-after study to evaluate the effects of urban infrastructure interventions, such as urban reconstructions characterized by densification of the built environment (BE) or improved connectivity through the construction of new pedestrian and cycling bridge. These interventions were to be evaluated through before-and-after studies conducted over an anticipated period of two to four years. To facilitate this objective, a collaborative partnership was established with the planning departments of different Swedish municipalities. At the outset of the thesis work in 2019, the municipality of Umeå had already initiated two major infrastructure projects:

- Rådhusesplanaden, a central pedestrian street undergoing a four-phase beautification and accessibility improvement project.
- Lundabron, a 179-meter-long bridge spanning the Ume River, was designed to enhance pedestrian and cyclist connectivity (see Figure 4 and
  Figure 7).

The COVID-19 pandemic affected the comparability of pre- and post-intervention data in Umeå and disrupted the planned intervention schedules in other cities. The research design was adapted to a cross-sectional format. The Umeå 2019 and 2021 datasets are available for descriptive comparison, but the pandemic period substantially complicates any behavioral inference from changes between the two waves. Consequently, the research design was adaptively revised to a cross-sectional format. In 2021, data collection was successfully expanded to encompass the entire municipality of Linköping without geographical constraints. For analytical rigor and comparability, data from the urban area were carefully extracted to enable focused and consistent analysis.

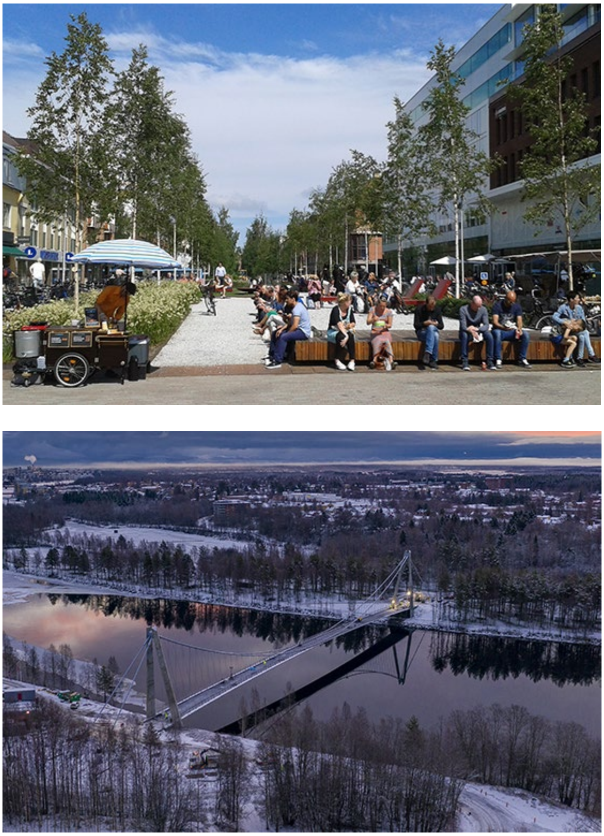


Figure 7: Rådhusesplanaden (top) and Lundabron (bottom)

Source: Umeå Municipality, 2020

The cross-sectional design places a specific constraint on causal inference. The language of effects and influences used throughout this thesis follows convention in the walking behavior literature and reflects more than correlation: the analyses are grounded in the extended Theory of Planned Behavior, which provides a theoretically motivated directional structure specifying attitudes and perceived behavioral control (PBC) as antecedents of behavior. The observed associations between attitudinal variables and GPS-measured walking are therefore interpretable as directional within this framework. What the cross-sectional data cannot establish is temporal precedence, i.e., the theorized antecedent was present before the observed walking behavior rather than co-occurring with it (Handy et al., 2005). The statistical association and the theoretical mechanism are in place; what is missing is empirical confirmation of the order of events. This limitation applies most acutely to the neighborhood-level BE findings. Residential self-selection is a well-documented confound in this literature: individuals with positive walking attitudes may systematically choose to live in more walkable areas, producing a positive association between environmental quality and walking that partially reflects residential preference rather than environmental influence (Mokhtarian & Cao, 2008). No instruments for addressing self-selection were included in the study design. Establishing temporal precedence at the neighborhood level would require longitudinal data or analytical approaches that exploit exogenous variation in neighborhood composition (S. Handy et al., 2005; Mokhtarian & Cao, 2008).

6.1.2 Theory of Planned Behavior Constructs in the Analytical Approach

The full set of TPB constructs, attitudes, subjective norms, and PBC, was collected only in the Umeå datasets. The Linköping questionnaire, developed by the municipality to minimize respondent burden, included only attitudinal items and demographics. As a result, Paper 4 and the combined 2021 analysis could not incorporate subjective norms or PBC, and the cross-city comparison is limited to attitudes and demographics. This restricts the ability to address RQ2 fully for the 2021 multi-city data. Answering attitudinal questions was also optional in the Linköping survey, which reduced the analytic sample for attitude-based analyses in Paper 4. The individual-level finding that subjective norms are non-significant (Paper 2) partially mitigates this limitation, in that the missing construct had no detectable effect where it was measured. However, trip-level PBC did produce significant effects in Paper 2, and that operationalization was not available for the 2021 data.

a. Habit and Residential Self-Selection

Two theoretically relevant constructs were deliberately omitted from the questionnaire. Habit, the degree to which mode and route choices become automatized through repetition, was excluded partly due to instrument length constraints: the questionnaire was already extensive relative to what could be comfortably administered through a smartphone travel diary application. There was also a deliberate conceptual rationale: by omitting habit items, respondents were encouraged to reflect actively on their choices rather than attributing them to routine, which would have obscured the attitudinal and environmental factors of primary theoretical interest. The absence of habit measurement means that the automaticity component of travel behavior remains unaccounted for in the analytical framework.

Residential self-selection, the tendency for walking-inclined individuals to sort into walkable neighborhoods, thereby confounding environment–walking associations, was likewise not addressed instrumentally, again due to questionnaire length constraints. No measures of residential preference or neighborhood satisfaction were included to permit adjustment for selection effects. The observed associations between neighborhood-level BE characteristics and walking behavior should be interpreted with this in mind.

6.1.3 Potential and practical quality of the data

The app-based data collection approach offers several notable advantages, including comprehensive capture of all travel data, enhanced precision in both location and route tracking, the ability to link questionnaire responses to specific travel events, and the capacity to collect large volumes of data efficiently. Nevertheless, some practical challenges emerged during implementation. The overall response rate was lower compared to traditional methods, potentially influenced by factors such as mobile phone battery limitations and privacy concerns (for a detailed discussion, see Papers 1 and 2). TravelVu achieved a response rate of approximately 1.95% in Umeå 2019 (Paper 1), with similarly low rate in Umeå 2021. While the exact response rate for Linköping 2021 data collection cannot be calculated due to the online promotion, the response rate, though better than Umeå, is still low.

The interpretation and of the findings in this thesis should be done in the light of the fact that response rates for walking-behavior surveys remain low in the field because data often relies on voluntary self-reporting, which people likely find time-consuming or irrelevant. Walking can be perceived as routine and unremarkable, and individuals may not see value in documenting it. Privacy concerns, especially with GPS or mobile tracking, which further discourages participation. Additionally, walking behavior is highly variable and context-dependent, making it still difficult to capture accurately through questionnaires. Seasonal changes, recall bias, and differences in definitions (e.g., leisure vs. transport walking) add complexity. As a result, collecting reliable, large-scale data on walking behavior is still both methodologically challenging and resource-intensive, which the research field needs to address.

a. Sample size and statistical power

The SEM analysis in Paper 3 was conducted on 80 individuals in Umeå 2021, which is a small sample for structural equation modelling. The moderated mediation models test conditional effects in three age group subsamples, which are smaller still. Post-hoc power analyses were conducted to assess Type II error risk. The moderated mediation finding for middle-aged adults is statistically significant, but the effect size is modest, and the null result for older adults most likely reflects insufficient statistical power rather than the genuine absence of an effect in that group. The Umeå subsample in Paper 4 (n = 72 individuals) similarly limits the route-choice analysis for that city. These constraints are a consequence of the response rates achievable through app-based data collection in medium-sized Swedish cities rather than a design choice, but they affect how far the SEM findings in particular can be generalized.

b. Self-selection and representativeness

App-based data collection consistently over-represents individuals with higher digital literacy and more active daily mobility. The high proportion of walking trips in the Umeå 2019 sample (51%) substantially exceeds population-level modal shares, pointing to self-selection toward walking-inclined participants. Educational attainment across all four datasets (63–74% university-educated) substantially exceeds national averages for the relevant age range (~40–45%), and older adults are markedly underrepresented, particularly in Linköping 2021, where only 2% of the sample was in the oldest age group. Single-person households are also underrepresented relative to Swedish national statistics.

These representativeness gaps have specific implications for the findings. The homogeneity in car access (78–80%), education, and attitudinal profiles compresses within-sample variance on variables that show larger variation in general population studies. Associations involving socio-economic factors may therefore be attenuated in these data relative to what would be found in population-representative samples. The null findings for several demographic variables should be interpreted in light of this.

c. Measurement constraints

The 4-point Likert scale, chosen to simplify smartphone-based completion, reduces response variance relative to the 5- or 7-point scales used in most comparable studies. This complicates direct comparisons of effect sizes and contributes to the ceiling effects observed in the attitudinal distributions: 93–97% of respondents across all four datasets reported liking walking. This high positivity reflects both the measurement format and the self-selection of participants, but it limits the within-sample attitudinal variance available for detecting attitude–behavior associations. The apparent dominance of attitudes over other predictors in this thesis should be interpreted with the awareness that the sample is drawn from the tail of the walking attitude distribution.

6.2 Methodological contributions

Despite the above-mentioned limitations, this thesis makes several methodological contributions alongside its empirical findings. Firstly, a TPB-based questionnaire, developed for integration into a GPS-enabled smartphone application, made a methodological contribution to existing literature. At the time of development, no standard TPB questionnaire for transport walking existed. The instrument was built by reviewing TPB-based work in BE research, pedestrian studies, and cycling studies, and covers attitudes toward walking, attitudes toward the BE, subjective norms, and PBC. Perceived control was operationalized at two levels: individual-level (general disposition) and trip-level (situation-specific, collected via pop-up questions during walking trips). A 4-point rather than 5-point response format was adopted to simplify completion on smartphone screens and to avoid the neutral midpoint. The questionnaire and its development rationale are documented in Papers 1 and 2.

Secondly, paper 1 also compared two emerging data collection methods applied in the same urban area: Wi-Fi sensor data (Bumbee Labs) and smartphone travel diary data (TravelVu). Wi-Fi sensor data capture aggregate pedestrian flow volumes across space with no participant burden, but cannot distinguish mode, trip purpose, or user attributes. Smartphone travel diary data provide route-level detail, linked survey responses, and individual-level behavioral records, but achieve low response rates and self-select for walking-inclined participants. The thesis tested both methods against each other and documents their complementary strengths and practical constraints, including cost. For pedestrian planning applications, the two methods answer different questions; when used in tandem, they can enhance urban mobility monitoring and planning. Their high costs and technical limitations do, however, require careful consideration of scalability and inclusivity, particularly in larger cities or contexts with limited digital infrastructure.

Thirdly, paper 4 also combines Linear Mixed Models (LMM) and Discrete Choice Model (DCM) for route choice. The LMM characterizes how BE exposures differ between actual and shortest routes, providing an associational account of environmental context. The DCM estimates the probability of selecting a given route as a function of its attributes, more directly approximating the structure of the choice. Where the two methods agree, for example on non-vehicular networks and low-speed streets, confidence in the findings is higher. Where they diverge, for example on commercial area and water, the divergence is informative: some features influence route preference in ways that do not reliably produce longer trips, and identifying this distinction requires both methods.

Fourthly, thesis also compares results across all four papers. The empirical findings from Umeå and Linköping show intra- and inter-city variability in walking behavior, particularly in total daily walking distances and modal preferences (walking ratio). Paired with individual-level socio-demographic and psychological data, these variations indicate that walking is shaped not only by the BE but also by attitudes, transport alternatives, and demographic factors. Finally, exposure to BE is measured at two scales. Paper 3 uses a 750 m neighborhood buffer around the home location to capture potential exposure; Paper 4 uses a 15 m buffer along GPS-traced routes and their shortest-path alternatives to capture realized exposure. Comparing findings across the two scales shows that different environmental variables are relevant at each level, and that even variables appearing at both scales may behave differently. This design is not common in the walking literature and treating the two analyses as a pair produces findings that neither could produce alone: the variables that predict whether someone walks more are not the same as the variables that shape which paths they take when they do walk.

6.3 Recapitulating the aim and research questions

The overarching aim of this thesis is to investigate which planning factors support walking as a mode of transport in a Swedish context, and to explore the underlying mechanisms and reasons behind these relationships. Four papers address these questions through different data, methods, and spatial scales.

Paper 1 evaluated two emerging data collection tools for pedestrian planning. Paper 2 applied the Theory of Planned Behavior (TPB) to characterize walking correlates in Umeå 2019. Paper 3 used structural equation modelling (SEM) to examine direct and indirect effects of the BE and attitudes on walking in Umeå 2021. Paper 4 extended the analysis to a two-city comparison of both individual-level walking and pedestrian route choice in Umeå and Linköping 2021. The cross-dataset comparison in Chapter 5, drawing on all four samples, provides additional context for how these findings hold across different temporal and geographic settings.

The discussion below evaluates how well the research questions have been answered and what the findings add to the field.

RQ1: How does the built environment affect walking behavior, in terms of distance, choice to walk, and choice of route?

RQ1 is addressed across Papers 3 and 4, which examine BE effects at two spatial scales: potential exposure (neighborhood level, 750 m radius around the home) and realized exposure (route level, 15 m buffer along actual and shortest-path routes). The two scales produce partly overlapping and partly distinct findings, that are compared in chapter 5 highlighting the scale-dependency of BE effects.

The direct and indirect effects of neighborhood-level BE characteristics on walking behavior are investigated in the third study (paper 3). Paper 3 identified several neighborhood-level associations, including positive relationships between walking outcomes and built-up area, paved surface, pedestrian network length, bus stop density, and tree presence, while selected land-use variables such as residential, commercial, mixed-use areas, parks, and points of interest were associated mainly with walking ratio. Paper 3 found that both neighborhood-level BE characteristics and walking attitudes had significant direct associations with GPS-measured walking. However, the hypothesized mediation pathway was not supported in the overall sample, since the BE did not significantly predict walking attitudes and the indirect effect via attitudes was non-significant. Mediation appeared only conditionally in the age-moderated model, where a small indirect pathway was observed among middle-aged adults.

Route-level BE effects on pedestrian path choice are examined in the fourth study (paper 4) through LMMs and a DCM applied to GPS-tracked trips across Umeå and Linköping. The analysis reveals that the overwhelming majority of observed transport walking trips follow the shortest available route, with meaningful deviations occurring in only a small minority of cases. In the LMMs, total building area, non-vehicular pedestrian network length, and streetlight density were significant across datasets, but their effects were not uniformly positive. Actual routes generally contained less non-vehicular pedestrian network and lower streetlight density than shortest-path alternatives, suggesting that these features may coincide with route structure rather than operate as independent attractors. The two-city design across Umeå and Linköping produced results that suggest that context matters even within Sweden and even between cities of similar size. Building density effects reversed direction between the two cities at the route level. Water proximity was relevant in Linköping and the combined dataset but not in Umeå, probably because the spatial distribution of water relative to participants' home locations and trip origins differs between the two cities. These variations show that findings from one city do not transfer straightforwardly to another, and they point to the value of multi-site study designs in research contexts where single-city studies still predominate. Commercial land use and tree presence were positive route-choice predictors in the DCM, while bus stops became positive only after accounting for individual heterogeneity and should be interpreted cautiously because the practical magnitude of the effect was small.

The comparative analysis of BE indicators shows that the strength, direction, and statistical significance of associations between environmental variables and walking outcomes varied considerably, despite the same environmental variables were assessed across both spatial contexts. That is, the BE features relevant to how much people walk are not the same as those that shape which paths they take. Several variables are significant at one scale only: paved surface, mixed land use, aggregate pedestrian network length, and points of interest at the neighborhood level; water, multi-family housing, non-vehicular network, low-speed streets, and street lighting at the route level. Residential land use is one of the clearest cross-scale variables, while commercial land use and trees also show cross-scale relevance, though through different model structures and outcome definitions. Building density appears at both scales, but its route-level direction differs between cities.

This partial asymmetry has a practical implication: environmental interventions aimed at increasing walking volumes and those aimed at improving route quality have different targets. Environmental interventions aimed at increasing walking volumes and those aimed at improving route attractiveness do not have identical targets. Some features, such as residential land use, commercial activity, and tree cover, matter across scales, but their mechanisms differ. Others, such as transit access or aggregate pedestrian network length, appear more relevant to neighborhood-level walking propensity than to route choice itself. Features that make neighborhoods more walkable overall are not necessarily the features that make specific walking corridors more attractive. Current walkability audit frameworks rarely separate these two objectives, and the tendency to treat them as equivalent is likely to produce mismatched policy targets.

Several variables hypothesized to attract pedestrians showed no significant effects at either scale: mixed-traffic paths, and safety-rated attributes failed to reach significance in any analysis. In Swedish medium-sized cities where pedestrian infrastructure is relatively uniform and perceived safety is high, these features may vary too little within the sample to generate detectable associations. Whether the same would hold in more varied or less well-maintained environments is an open question.

RQ 2: What other factors (such as socio-demographics, attitude, self-efficacy, etc.) affect the relationship between the built environment and walking behavior? What is the mediating effect of these factors?

RQ2 is addressed across Papers 2, 3, and 4, and through the cross-dataset comparison in Chapter 5. Evidence covers socio-demographic predictors, psychological predictors (based on TPB), and the mediating and moderating roles of these factors. Socio-demographic data are collected for all datasets and are tested across all papers, and some direct on walking and some moderating effect on the relation between walking and BE were observed. Similarly, data for attitude towards walking are collected for all datasets and are tested in all papers and consistently found to be the stronger direct predictor of walking, outperforming the built environment. Subjective norms and individual-level perceived control are tested in Paper 2 and found non-significant. Trip-level perceived control, assessed via pop-up questions triggered by walking trips of 500 m or more, health-related and safety-related perceived control were significantly associated with walking distance in Paper 2. Further, the results for socio demographic variables and attitude from across the three papers are compared in the thesis.

a. *Attitude*

Attitudinal variables are the most consistent individual-level predictors of walking in this thesis. Both the binary measure of whether someone likes walking and the ordinal degree of that preference were significant predictors of total distance and walking ratio across nearly all datasets and outcomes. Willingness to walk to a destination, approximately 24 minutes across all 2021 samples, was a consistent significant predictor of actual walking distance and ratio in all 2021 datasets. This not only supports the existing literature where attitude–walking associations rely on self-reported behavioral outcomes, but also contributes to it by providing the same pattern with objectively measured GPS data.

Attitudes toward the BE were less predictive. Safety was rated important by 78–88% of respondents across all datasets, making it the highest-rated attribute, but it showed no significant correlation with any walking outcome. Pleasantness was rated highly (79–84%) but was significant only for total distance in Linköping 2021. The item with the most consistent predictive power was perceived importance of short and direct connections, which was significant for walking ratio in multiple datasets. This disconnect between what respondents say matters and what actually predicts their behavior may partly reflect the high and relatively uniform safety and pleasantness levels in these Swedish cities, where variation in perceived environmental quality is insufficient to discriminate between individuals' walking levels.

Paper 3 directly examined whether attitudes mediate the relationship between the neighborhood-level BE and walking. In the overall sample, they do not: the path from the BE to walking attitudes was not statistically significant, and consequently the indirect effect via attitudes was also non-significant. The BE and attitudes each retained significant direct effects on walking when both were included, i.e., parallel pathways, not a sequential chain, with attitude towards walking outperforming BE variables. This null mediation result diverges from some TPB-grounded studies that treat perceived environmental quality as a mediator but is consistent with research distinguishing between perceived and objectively measured BE indicators: objective measures tend to retain direct rather than attitude-mediated associations with behavior.

At the route level (Paper 4), moderating effect of attitude was identified through interaction terms in the LMM and DCM. In the LMMs, building area effects were moderated by attitudinal variables related to environmental motivation, scenic enjoyment and pedestrian only path; area under single family housing effect was moderated by attitudinal variables related to general preference for walking and health; Non-vehicular pedestrian network effects were moderated by attitudinal variables related to environmental motivation, scenic enjoyment, transport purpose and sufficient pedestrian space; Low-speed street effects were moderated by age, scenic enjoyment, and the perceived importance of streetscape character or uniqueness; pedestrian amenities effects were moderated by attitudinal variables related to uniqueness of streetscape;

and finally bus stops were moderated by attitudinal variables related to transport purpose. In the DCM, attitudinal variable did not produced a significant unconditional main effect; attitudinal heterogeneity in environmental preference appeared only through interaction with specific route attributes: water area effects were moderated by attitudinal variables related to uniqueness of streetscape; Non-vehicular pedestrian network effects were moderated by attitudinal variables related to scenic enjoyment and sufficient pedestrian space; bus stops were moderated by attitudinal variables related to quality and maintenance of walking path.

Taken together, the moderation findings indicate that the BE does not operate uniformly across the population. Who the pedestrian is and what they value shapes which environmental features matter and how much. While this conclusion is conceptually expected, the thesis substantiates it through GPS-derived behavioral data across two cities and two analytical approaches, an empirical strategy that remains relatively uncommon in the walking literature.

b. Socio-Demographic Factors

Socio-demographic variables are generally weak and inconsistent direct predictors of walking in this thesis. Gender showed limited associations: in the 2021 data, women walked slightly more per day in Linköping and the combined dataset, but no gender effect was found in Umeå 2019 for any outcome. Age was non-significant across all four datasets and all walking outcomes. This null finding is worth noting given the substantial compositional differences in age across samples, but is plausible: app-based recruitment tends to select for more active and digitally engaged individuals even within older age categories, compressing within-sample age variance. Employment status, income, and family structure showed no significant associations with walking in any dataset. Education produced one significant finding: university-educated individuals walked longer total distances in Umeå 2021. Bicycle access was the most consistent socio-demographic predictor across the 2021 datasets: individuals with access to a bicycle walked less. One equity implication follows from the absence of strong income or car-access effects: lower-income individuals in these samples do not walk substantially more for transport.

However, the thesis has identified the moderating effect of several demographic variables. Age moderates how the potential BE exposure at neighborhood level affects walking behavior, in Paper 3. Among young adults, the relationship was direct: the BE shaped walking behavior without any attitude-mediated pathway. Middle-aged adults showed a small but significant indirect effect: environment influenced attitudes, which then influenced walking. Among older adults, neither pathway reached significance, though the subsample is too small to read as a clear null result. These conditional findings are of substantive interest but require caution. Effect sizes in the Paper 3 SEM are modest throughout, and the age-group subsamples used in the moderated mediation analysis are small. The age-stratified patterns point to the possibility that the mechanism through which the BE influences walking changes across life stages.

At the route level (in Paper 4), moderation was identified through interaction terms. In the LMMs, building area effects were moderated by income; water area effects were moderated by income, with higher-income pedestrians showing stronger preferences for waterfront routes;

low-speed street effects were moderated by age. In the DCM, socio-demographic variables did not produce significant unconditional main effects, indicating that gender, age, occupation, and car access did not independently predict route choice after accounting for route attributes and interactions. Demographic heterogeneity appeared mainly through bus stop interactions. Older respondents were less likely than middle-aged respondents to choose routes with more bus stops, while students were more likely than working respondents to do so. The interactions between non-vehicular pedestrian network and car access, and between low-speed vehicular network and gender, were directionally suggestive but not statistically significant because their confidence intervals included unity.

6.4 Implications for research and planning

6.4.1 Implications for Walking Research

The clearest methodological takeaway is that the findings from a single city are hard to generalize, even to another Swedish city with a similar profile. Umeå and Linköping are broadly similar cities, yet they diverged on key variables like building density effects and water proximity. That gap is a reason to invest in multi-site designs, particularly in the Nordic region, which is still underrepresented in the international walking literature despite having a distinctive urban character. It is also a reason to be cautious about generalizing any one city's findings elsewhere. The cross-temporal comparison between Umeå 2019 and 2021 is harder to interpret because of COVID-19. Trip patterns shifted, and part of the observed change in walking ratios came from how the indicator was calculated. Before further longitudinal claims can be made about these cities, a post-pandemic data collection round under stable conditions is needed. The focus should also be on methodological challenges regarding collecting reliable, large-scale data on walking habits and about pedestrians that are efficient regarding resources such as cost, and accuracy in data and interpretation, together with response rate. This especially holds true for studies opting for combining socio-demographic variables with travel behavior.

Regarding model specification: when the BE is measured objectively and behavior is tracked via GPS, direct pathways fit better than attitudinal mediation chains. Studies that find mediation tend to use perceived environmental indicators. Future SEM-based walking research should be explicit about this distinction from the start, it is not a minor methodological footnote, it changes how hypotheses should be designed. Related to this, small samples can reach statistical significance on effects that are too modest to mean much in practice. There is a need to prioritize larger samples for conditional analyses rather than repeating the same small-sample designs. The dual-scale approach used here, separating potential exposure at the neighborhood level from realized route choice, is worth adopting more widely. Neighborhood buffers alone miss what shapes where people actually walk; route-level analysis alone misses what drives whether they walk at all. Both scales are needed to get the full picture. Also, studies with different buffer size, at both neighborhood and route level, would help identify the level at which BE expose has most effect on walking behavior.

6.4.2 Implications for Urban Planning Practice

Infrastructure investment matters, but it is unlikely to produce large shifts in walking behavior on its own. The BE effects found here are real but modest, and they operate alongside attitudes rather than through them. Programs that pair physical improvements with behavioral or communication components are probably better positioned to reach people for whom environmental quality is not the main barrier. BE effects are stronger among people already positively disposed toward walking, which means walkability improvements may concentrate their benefits among existing pedestrians rather than converting non-walkers. Evaluation frameworks should account for this, measuring average effects across a whole population will likely understate impact within the motivated sub-group, and overstate it as a conversion tool.

The neighborhood-versus-route distinction has direct investment implications. Raising walking's modal share requires neighborhood-level changes: density, transit access, mixed land use, tree canopy. Improving the quality of trips people are already taking requires route-level work: waterfront access, active commercial frontages, adequate lighting. These are different problems and different budgets. Conflating them is a good way to invest in the wrong thing. Finally, the cycling substitution finding deserves more attention in Swedish planning discourse. Bicycle access consistently predicted less walking in the 2021 data. Walking and cycling are usually treated as complementary; the results here suggests that assumption is worth questioning.

6.5 Concluding remarks

This thesis examined the environmental and psychological correlates of transport walking in Swedish cities, combining GPS mobility tracking, psychological surveys grounded in TPB, and BE exposure data. The aim was to move beyond static walkability measures and treat walking as a spatially situated activity shaped by individual, social, and environmental systems. The results show, consistently, that walking behavior cannot be reduced to urban form. Attitudes toward walking and PBC both matter, though their relative weight shifts depending on context and who is being asked. The same street can register very differently depending on someone's motivations, constraints, and socio-economic position.

A methodological contribution worth highlighting is the move away from residential neighborhood proxies toward GPS-tracked route exposure. Where people actually walk, not just where they live, determines what environmental features they encounter. Analyzing realized exposure alongside greenery, connectivity, and density gives a more accurate account of the built environment–behavior relationship than traditional approaches allow.

The policy implications follow from this. Improving pedestrian infrastructure and land-use diversity helps, but it is not sufficient on its own. Interventions also need to address perceived barriers, build positive attitudes toward walking, and account for who is and is not walking in the first place. Walkable environments are only useful if they work for diverse populations, including those facing socio-economic or attitudinal barriers.

Walking for transport can be understood as a moving target, shaped by the interaction of physical environments, individual psychology, and everyday life circumstances. The quantitative, multi-dimensional approach used here offers a template for future research that takes both structure and agency seriously.

7. REFERENCES

Adams, E. J., Bull, F. C., & Foster, C. E. (2016). Are perceptions of the environment in the workplace “neighbourhood” associated with commuter walking? *Journal of Transport & Health*, *3*(4), 479–484. https://doi.org/10.1016/j.jth.2016.01.001

Agrawal, A. W., & Schimek, P. (2007). Extent and correlates of walking in the USA. *Transportation Research Part D: Transport and Environment*, *12*(8), 548–563. https://doi.org/10.1016/J.TRD.2007.07.005

Agrawal, A. W., Schlossberg, M., & Irvin, K. (2008). How Far, by Which Route and Why? A Spatial Analysis of Pedestrian Preference. *Journal of Urban Design*, *13*(1), 81–98. https://doi.org/10.1080/13574800701804074

Ajzen, I. (1991). The theory of planned behavior. *Organizational Behavior and Human Decision Processes*, *50*(2), 179–211. https://doi.org/10.1016/0749-5978(91)90020-T

Alfonzo, M. A. (2005). To Walk or Not to Walk? The Hierarchy of Walking Needs. *Environment and Behavior*, *37*(6), 808–836. https://doi.org/10.1177/0013916504274016

Almagor, J., Omer, I., Omer, N., & Birenboim, A. (2024). How far will you go? From empirical findings to formalization of walking route distances. *Computers, Environment and Urban Systems*, *110*, 102117. https://doi.org/10.1016/J.COMPENVURBSYS.2024.102117

Baker, G., Pillinger, R., Kelly, P., & Whyte, B. (2021). Quantifying the health and economic benefits of active commuting in Scotland. *Journal of Transport & Health*, *22*. https://doi.org/10.1016/j.jth.2021.101111

Balarezo, M. L. G., Trépanier, M., Jalbert, J., & Boisjoly, G. (2024). Going the distance: Gender differences in travel in Montréal, Canada. *Journal of Transport Geography*, *118*. https://doi.org/10.1016/j.jtrangeo.2024.103935

Ball, K., Bauman, A., Leslie, E., & Owen, N. (2001). Perceived Environmental Aesthetics and Convenience and Company Are Associated with Walking for Exercise among Australian Adults. *Preventive Medicine*, *33*(5), 434–440. https://doi.org/10.1006/PMED.2001.0912

Bamberg, S., Ajzen, I., & Schmidt, P. (2003). Choice of Travel Mode in the Theory of Planned Behavior: The Roles of Past Behavior, Habit, and Reasoned Action. *Basic & Applied Social Psychology*, *25*(3), 175. https://doi.org/10.1207/S15324834BASP2503_01

Bamberg, S., & Möser, G. (2007). Twenty years after Hines, Hungerford, and Tomera: A new meta-analysis of psycho-social determinants of pro-environmental behaviour. *Journal of Environmental Psychology*, *27*(1), 14–25. https://doi.org/10.1016/j.jenvp.2006.12.002

Bandara, T. N., Higgs, C., Turrell, G., De Livera, A., Gunn, L., & Zapata-Diomedi, B. (2025). Longitudinal effects of the built environment on transportation and recreational walking and differences by age and sex: A systematic review. *Social Science and Medicine*, *368*. https://doi.org/10.1016/j.socscimed.2025.117811

Banister, D. (2005). Unsustainable transport: City transport in the new century. *Unsustainable Transport: City Transport in the New Century*, 1–292. https://doi.org/10.4324/9780203003886/UNSUSTAINABLE-TRANSPORT-DAVID-BANISTER/RIGHTS-AND-PERMISSIONS

Banister, D. (2008). The sustainable mobility paradigm. *Transport Policy*, *15*(2), 73–80. https://doi.org/10.1016/J.TRANPOL.2007.10.005

Barnett, D. W., Barnett, A., Nathan, A., Cerin E., & Van Cauwenberg J. (2017). Built environmental correlates of older adults’ total physical activity and walking: A systematic review and meta-analysis. *International Journal of Behavioral Nutrition and Physical Activity*, *14*(1). https://doi.org/10.1186/s12966-017-0558-z

Basu, N., Haque, M. M., King, M., Kamruzzaman, M., & Oviedo-Trespalacios, O. (2022). A systematic review of the factors associated with pedestrian route choice. *Transport Reviews*, *42*(5), 672–694. https://doi.org/10.1080/01441647.2021.2000064/SUPPL_FILE/TTRV_A_2000064_SM1342.DOCX

Basu, N., Oviedo-Trespalacios, O., King, M., Kamruzzaman, M., & Haque, M. M. (2023). What do pedestrians consider when choosing a route? The role of safety, security, and attractiveness perceptions and the built environment during day and night walking. *Cities*, *143*, 104551. https://doi.org/10.1016/J.CITIES.2023.104551

Basu, R., & Sevtsuk, A. (2022). How do street attributes affect willingness-to-walk? City-wide pedestrian route choice analysis using big data from Boston and San Francisco. *Transportation Research Part A: Policy and Practice*, *163*, 1–19. https://doi.org/10.1016/J.TRA.2022.06.007

Beenackers, M. A., Kamphuis, C. B. M., Giskes, K., Brug, J., Kunst, A. E., Burdorf, A., & van Lenthe, F. J. (2012). Socioeconomic inequalities in occupational, leisure-time, and transport related physical activity among European adults: A systematic review. *International Journal of Behavioral Nutrition and Physical Activity*, *9*(1), 116–116. https://doi.org/10.1186/1479-5868-9-116

Beenackers, M. A., Kamphuis, C. B. M., Mackenbach, J. P., Burdorf, A., & van Lenthe, F. J. (2013). Why some walk and others don't: exploring interactions of perceived safety and social neighborhood factors with psychosocial cognitions. *Health Education Research*, *28*(2), 220–233. https://doi.org/10.1093/her/cyt002

Befolkningsprognos: Umeå kommun 2022 – 2033. (2022). In *Övergripande planering, Umeå kommun*. https://www.umea.se/download/18.72e1ee67180a748ab0b2290/1653310580612/Befolkningsprognos_2022-2033.pdf

Bennett, G. G., McNeill, L. H., Wolin, K. Y., Duncan, D. T., Puleo, E., & Emmons, K. M. (2007). Safe To Walk? Neighborhood Safety and Physical Activity Among Public Housing Residents. *PLoS Medicine*, *4*(10), e306-1607. https://doi.org/10.1371/JOURNAL.PMED.0040306

Bhaskar, Roy. (1997). A realist theory of science. In *[New ed.]*. Verso.

Bird, E. L., Panter, J., Baker, G., Jones, T., & Ogilvie, D. (2018). Predicting walking and cycling behaviour change using an extended Theory of Planned Behaviour. *Journal of Transport and Health*, *10*, 11–27. https://doi.org/10.1016/J.JTH.2018.05.014

Boarnet, M. G., Forsyth, A., Day, K., & Oakes, M. J. (2011). The Street Level Built Environment and Physical Activity and Walking: Results of a Predictive Validity Study for the Irvine Minnesota Inventory. *Environment and Behavior*, *43*, 735–775.

Bollen, K. A. (1989). Structural Equation Models with Observed Variables. In *Structural Equations with Latent Variables* (pp. 80–150). https://doi.org/https://doi.org/10.1002/9781118619179.ch4

Bondemark, A. (2023). Walk this way: How do individuals with different preferences for active travel modes respond to walkability? *Transportation Research Part A: Policy and Practice*, *175*, 103760. https://doi.org/10.1016/J.TRA.2023.103760

Borst, H. C., de Vries, S. I., Graham, J. M. A., van Dongen, J. E. F., Bakker, I., & Miedema, H. M. E. (2009). Influence of environmental street characteristics on walking route choice of elderly people. *Journal of Environmental Psychology*, *29*(4), 477–484. https://doi.org/10.1016/J.JENVP.2009.08.002

Bricka, S., Zmud, J., Wolf, J., & Freedman, J. (2009). Household Travel Surveys with GPS: An Experiment. *Transportation Research Record*, (2105), 51–56.

Broberg, A., & Sarjala, S. (2015). School travel mode choice and the characteristics of the urban built environment: The case of Helsinki, Finland. *Transport Policy*, *37*, 1–10. https://doi.org/10.1016/J.TRANPOL.2014.10.011

Brown, B. B., Werner, C. M., Amburgey, J. W., & Szalay, C. (2007). Walkable Route Perceptions and Physical Features: Converging Evidence for En Route Walking Experiences. *Environment and Behavior*, *39*(1), 34–61. https://doi.org/10.1177/0013916506295569

Buehler, R. ;, Pucher, J., Ribeiro, P., Conticelli, E., Fonseca, F., Papageorgiou, G. N., Buehler, R., & Pucher, J. (2023). Overview of Walking Rates, Walking Safety, and Government Policies to Encourage More and Safer Walking in Europe and North America. *Sustainability*, *15*(7), 5719. https://doi.org/10.3390/SU15075719

Bumbee Labs, ,. (2022). *Bumbee Labs: Intelligent footfall solutions*. https://bumbeelabs.com/

Carlson, C., Aytur, S., Gardner, K., & Rogers, S. (2012). Complexity in Built Environment, Health, and Destination Walking: A Neighborhood-Scale Analysis. *Journal of Urban Health : Bulletin of the New York Academy of Medicine*, *89*(2), 270. https://doi.org/10.1007/S11524-011-9652-8

Carlson, J. A., Sallis, J. F., Conway, T. L., Saelens, B. E., Frank, L. D., Kerr, J., Cain, K. L., & King, A. C. (2012). Interactions between psychosocial and built environment factors in explaining older adults' physical activity. *Preventive Medicine*, *54*(1), 68–73. https://doi.org/10.1016/j.ypmed.2011.10.004

Cerin, E., Leslie, E., Toit, L. du, Owen, N., & Frank, L. D. (2007). Destinations that matter: Associations with walking for transport. *Health and Place*, *13*(3), 713–724. https://doi.org/10.1016/J.HEALTHPLACE.2006.11.002

Cerin, E., Mellecker, R., Macfarlane, D. J., Barnett, A., Cheung, M. C., Sit, C. H. P., & Chan, W. M. (2013). Socioeconomic Status, Neighborhood Characteristics, and Walking Within the Neighborhood Among Older Hong Kong Chinese. *Journal of Aging and Health*, *25*(8), 1425–1444. https://doi.org/10.1177/0898264313510034

Cerin, E., Nathan, A., van Cauwenberg, J., Barnett, D. W., & Barnett, A. (2017). The neighbourhood physical environment and active travel in older adults: A systematic review and meta-analysis. *International Journal of Behavioral Nutrition and Physical Activity*, *14*(1), 1–23. https://doi.org/10.1186/S12966-017-0471-5/METRICS

Cervero, R., & Duncan, M. (2003). Walking, Bicycling, and Urban Landscapes: Evidence from the San Francisco Bay Area. *American Journal of Public Health*, *93*(9), 1478–1483. https://doi.org/10.2105/ajph.93.9.1478

Cervero, R., & Kockelman, K. (1997). Travel demand and the 3Ds: Density, diversity, and design. *Transportation Research Part D: Transport and Environment*, *2*(3), 199–219. https://doi.org/10.1016/S1361-9209(97)00009-6

Chamseddine, Z., & Ait Boubkr, A. (2021). Understanding Gender, Income and Travel Behavior in Casablanca City – Morocco. *Open Transportation Journal*, *15*(1), 272–279. https://doi.org/10.2174/1874447802115010272

Chan, E. T. H., Schwanen, T., & Banister, D. (2021). The role of perceived environment, neighbourhood characteristics, and attitudes in walking behaviour: evidence from a rapidly developing city in China. *Transportation*, *48*(1), 431–454. https://doi.org/10.1007/S11116-019-10062-2/FIGURES/5

Chan, H. Y., Cheng, D., & Chen, A. (2024). Routes with roots: Pedestrian route choices and sense of place of an urban university community. *Journal of Transport Geography*, *118*, 103943. https://doi.org/10.1016/J.JTRANGEO.2024.103943

Chapman, D., Nilsson, K. L., Rizzo, A., & Larsson, A. (2019). Winter City Urbanism: Enabling All Year Connectivity for Soft Mobility. *International Journal of Environmental Research and Public Health*, *16*(10). https://doi.org/10.3390/IJERPH16101820

Chapman, D., Nilsson, K., Larsson, A., & Rizzo, A. (2017). Climatic barriers to soft-mobility in winter: Luleå, Sweden as case study. *Sustainable Cities and Society*, *35*, 574–580. https://doi.org/10.1016/J.SCS.2017.09.003

Chen, C., Cao, Y., Xu, G., Zhong, Q., & Chen, B. (2024). How do urban block built environments affect older adults' walking activities and health effects: a case study in Nanjing, China. *Frontiers in Public Health*, *12*, 1479305. https://doi.org/10.3389/fpubh.2024.1479305

Cho, G.-H., & Rodriguez, D. A. (2015). Neighborhood design, neighborhood location, and three types of walking: results from the Washington DC area. *Environment and Planning B-Planning & Design*, *42*(3), 526–540. https://doi.org/10.1068/b130222p

Christie, C. D., Friedenreich, C. M., Vena, J. E., Turley, L., & McCormack, G. R. (2022). Cross-sectional and longitudinal associations between the built environment and walking: effect modification by socioeconomic status. *BMC Public Health 2022 22:1*, *22*(1), 1233-. https://doi.org/10.1186/s12889-022-13611-0

Cottrill, C. D., Pereira, F. C., Zhao, F., Dias, I. F., Lim, H. B., Ben-Akiva, M. E., & Zegras, P. C. (2013). Future Mobility Survey: Experience in Developing a Smartphone-Based Travel Survey in Singapore. *Transportation Research Record*, (2354), 59–67.

Crone, D., Smith, A., & Gough, B. (2005). "I feel totally at one, totally alive and totally happy": a psycho-social explanation of the physical activity and mental health relationship. *Health Education Research*, *20*(5), 600–611.

Dalton, A. M., Jones, A. P., Panter, J. R., & Ogilvie, D. (2013). Neighbourhood, Route and Workplace-Related Environmental Characteristics Predict Adults' Mode of Travel to Work. *PLoS ONE*, *8*(6). https://doi.org/10.1371/journal.pone.0067575

de Bruijn, G. J., Kremers, S. P. J., Singh, A., van den Putte, B., & van Mechelen, W. (2009). Adult Active Transportation. Adding Habit Strength to the Theory of Planned Behavior. *American Journal of Preventive Medicine*, *36*(3), 189–194. https://doi.org/10.1016/j.amepre.2008.10.019

Department for Transport, ,. (2023). *Transport Statistics Great Britain 2023. London: Department for Transport*. https://www.gov.uk/government/statistics/transport-statistics-great-britain-2024

Duncan, M. J., Winkler, E., Sugiyama, T., Cerin, E., duToit, L., Leslie, E., & Owen, N. (2010). Relationships of Land Use Mix with Walking for Transport: Do Land Uses and Geographical Scale Matter? *JOURNAL OF URBAN HEALTH*, *87*(5), 782–795.

Eng, J., & McCormack, G. R. (2025). Place attachment and walkability and their associations with walking in urban neighbourhoods. *Scientific Reports 2025 15:1*, *15*(1), 35474-. https://doi.org/10.1038/s41598-025-19319-6

Eurostat. (2021). *Population by educational attainment level*.

Evenson, K. R., Sarmiento, O. L., Macon, M. L., Tawney, K. W., & Ammerman, A. S. (2002). Environmental, policy, and cultural factors related to physical activity among Latina immigrants. *Women and Health*, *36*(2), 43–56. https://doi.org/10.1300/J013V36N02_04;PAGE:STRING:ARTICLE/CHAPTER

Ewing, R., & Cervero, R. (2001). Travel and the Built Environment: A Synthesis. *Transportation Research Record*. https://doi.org/10.3141/1780-10

Ewing, R., & Cervero, R. (2010). Travel and the Built Environment. *Journal of the American Planning Association*, *76*(3), 265–294. https://doi.org/10.1080/01944361003766766

Ewing, R., & Hamidi, S. (2015). Compactness versus Sprawl: A Review of Recent Evidence from the United States. *Journal of Planning Literature*, *30*(4), 413–432. https://doi.org/10.1177/0885412215595439/FORMAT/EPUB

Ewing, R., & Handy, S. (2009). Measuring the unmeasurable: Urban design qualities related to walkability. *Journal of Urban Design*, *14*(1), 65–84. https://doi.org/10.1080/13574800802451155

Faludi, A. (1983). Critical Rationalism and Planning Methodology. *Urban Studies*, *20*(3), 265–278. https://doi.org/10.1080/00420988320080521

Feuillet, T., Salze, P., Charreire, H., Menai, M., Enaux, C., Perchoux, C., Hess, F., Kesse-Guyot, E., Hercberg, S., Simon, C., Weber, C., & Oppert, J. M. (2016). Built environment in local relation with walking: Why here and not there? *Journal of Transport & Health*, *3*(4), 500–512. https://doi.org/10.1016/j.jth.2015.12.004

Field, A. P. (2018). *Discovering statistics using IBM SPSS statistics* (5th ed.). Sage Publications.

Forsyth, A. (2015). What is a walkable place? The walkability debate in urban design. *Urban Design International*, *20*(4), 274–292. https://doi.org/10.1057/UDI.2015.22/FULLTEXT.HTML,HTTPS://LINK.SPRINGER.COM/ARTICLE/10.1057

Foster, C., Hillsdon, M., & Thorogood, M. (2004). Environmental Perceptions and Walking in English Adults. *Journal of Epidemiology and Community Health (1979-)*, *58*(11), 924–928. https://doi.org/10.1136/jech.2003.014068

Foster, S., & Giles-Corti, B. (2008). The built environment, neighborhood crime and constrained physical activity: An exploration of inconsistent findings. *Preventive Medicine*, *47*(3), 241–251. https://doi.org/10.1016/J.YPMED.2008.03.017

Frank, L. D., & Engelke, P. O. (2001). The built environment and human activity patterns: Exploring the impacts of urban form on public health. *Journal of Planning Literature*, *16*(2), 202–218. https://doi.org/10.1177/08854120122093339

Friederichs, S. A. H., Kremers, S. P. J., Lechner, L., & De Vries, N. K. (2013). Neighborhood Walkability and Walking Behavior: The Moderating Role of Action Orientation. *Journal of Physical Activity & Health*, *10*(4), 515–522. https://doi.org/10.1123/JPAH.10.4.515

Gao, J., Wang, D., Ettema, D., & Helbich, M. (2023). Weather conditions as cross-sectional moderators of the associations between the physical environment and walking behavior in the Netherlands. *International Journal of Sustainable Transportation*, *17*(10), 1129–1138.

Gardner, B., & Abraham, C. (2008). Psychological correlates of car use: A meta-analysis. *Transportation Research Part F: Psychology and Behaviour*, *11*(4), 300–311. https://doi.org/10.1016/j.trf.2008.01.004

Gardner, B., Bruijn, G. J., & Lally, P. (2011). A Systematic Review and Meta-analysis of Applications of the Self-Report Habit Index to Nutrition and Physical Activity Behaviours. *ANNALS OF BEHAVIORAL MEDICINE*, *42*(2), 174–187.

Ge, Y., He, Z., & Shang, K. (2023). Influence of the Built Environment on Pedestrians' Route Choice in Leisure Walking. *ISPRS International Journal of Geo-Information 2023, Vol. 12, 12*(9). https://doi.org/10.3390/IJGI12090384

Gehl, J. (2010). *Cities for People [Elektronisk resurs]*. Island Press.

Gehl, J. (2011). *Life between buildings: using public space* (J. Koch, Tran.; 6th ed.). Island Press.

Gehrke, S. R., & Wang, L. (2020). Operationalizing the neighborhood effects of the built environment on travel behavior. *Journal of Transport Geography*, *82*. https://doi.org/10.1016/J.JTRANGEO.2019.102561

Giles-Corti, B., Broomhall, M. H., Knuiman, M., Collins, C., Douglas, K., Ng, K., Lange, A., & Donovan, R. J. (2005). Increasing walking: How important is distance to, attractiveness, and size of public open space? *American Journal of Preventive Medicine*, *28*(2), 169–176. https://doi.org/10.1016/J.AMEPRE.2004.10.018

Göteborgs Stad. (2026). *Trafik- och resandeutveckling 2025*. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://goteborg.se/wps/wcm/connect/8b14ee13-e214-444b-ae68-c44cc7af038b/TRU_slutgiltlig+version_tillg%C3%A4nglighetsanpassad.pdf?MOD=AJPERES

Guinn, J. M., & Stangl, P. (2014). Pedestrian and bicyclist motivation: an assessment of influences on pedestrians' and bicyclists' mode choice in Mt. Pleasant, Vancouver. *Urban, Planning and Transport Research*, *2*(1), 105–125. https://doi.org/10.1080/21650020.2014.906907

Guo, Z., & Loo, B. P. Y. (2013). Pedestrian environment and route choice: evidence from New York City and Hong Kong. *Journal of Transport Geography*, *28*, 124–136. https://doi.org/10.1016/J.JTRANGEO.2012.11.013

Hahm, Y., Yoon, H., Jung, D., & Kwon, H. (2017). Do built environments affect pedestrians' choices of walking routes in retail districts? A study with GPS experiments in Hongdae retail district in Seoul, South Korea. *Habitat International*, *70*, 50–60. https://doi.org/10.1016/J.HABITATINT.2017.10.002

Hajrasouliha, A., & Yin, L. (2015). The impact of street network connectivity on pedestrian volume. *Urban Studies*, *52*(13), 2483–2497.

Handy, S., Cao, X., & Mokhtarian, P. (2005). Correlation or causality between the built environment and travel behavior? Evidence from Northern California. *Transportation Research Part D: Transport and Environment*, *10*(6), 427–444. https://doi.org/10.1016/j.trd.2005.05.002

Handy, S. L. (1996). Urban form and pedestrian choices: study of Austin neighborhoods. *Transportation Research Record*, (1552), 135–144. https://doi.org/10.3141/1552-19

Heinen, E., Maat, K., & Van Wee, B. (2011). The role of attitudes toward characteristics of bicycle commuting on the choice to cycle to work over various distances.

Transportation Research Part D, *16*(2), 102–109. https://doi.org/10.1016/J.TRD.2010.08.010

Heinen, E., Panter, J., Mackett, R., & Ogilvie, D. (2015). Changes in mode of travel to work: A natural experimental study of new transport infrastructure. *International Journal of Behavioral Nutrition and Physical Activity*, *12*(1). https://doi.org/10.1186/s12966-015-0239-8

Heinen, E., van Wee, B., & Maat, K. (2010). Commuting by bicycle: An overview of the literature. *Transport Reviews*, *30*(1), 59–96. https://doi.org/10.1080/01441640903187001

Helbing, D., Molnár, P., Farkas, I. J., & Bolay, K. (2001). Self-organizing pedestrian movement. *Environment and Planning B: Planning and Design*, *28*(3), 361–383. https://doi.org/10.1068/B2697

Hersperger, A. M., Oliveira, E., Pagliarin, S., Palka, G., Verburg, P., Bolliger, J., & Grădinaru, S. (2018). Urban land-use change: The role of strategic spatial planning. *Global Environmental Change*, *51*, 32–42. https://doi.org/10.1016/J.GLOENVCHA.2018.05.001

Hirsch, J. A., Moore, K. A., Clarke, P. J., Rodriguez, D. A., Evenson, K. R., Brines, S. J., Zagorski, M. A., & Roux, A. V. D. (2014). Changes in the Built Environment and Changes in the Amount of Walking Over Time: Longitudinal Results From the Multi-Ethnic Study of Atherosclerosis. *American Journal of Epidemiology*, *180*(8), 799–809. https://doi.org/10.1093/aje/kwu218

Hong, J., & Chen, C. (2014). The role of the built environment on perceived safety from crime and walking: examining direct and indirect impacts. *Transportation -Amsterdam-*, *41*(6), 1171–1185. https://doi.org/10.1007/s11116-014-9535-4

Hood, J., Sall, E., & Charlton, B. (2011). A GPS-based bicycle route choice model for San Francisco, California. *Transportation Letters*, *3*(1), 63–75. https://doi.org/10.3328/TL.2011.03.01.63-75

Hoogendoorn, S. P., & Bovy, P. H. L. (2004). Pedestrian route-choice and activity scheduling theory and models. *Transportation Research Part B*, *38*(2), 169–190. https://doi.org/10.1016/S0191-2615(03)00007-9

Hsu, M.-Y., Lee, S.-H., Yang, H.-J., & Chao, H.-J. (2021). Is Brisk Walking an Effective Physical Activity for promoting Taiwanese Adolescents' Mental Health? *Journal of Pediatric Nursing*, *60*, 60–67. https://doi.org/10.1016/j.pedn.2021.03.012

Hu, Y., Tanaka, T., & Wang, L. (2022). Pedestrian Cognition of Street Structure and Route Choices When Strolling: Comparative Study Based on Two Experimental Methods.

Journal of Urban Planning and Development, *148*(2), 05022015. https://doi.org/10.1061/(ASCE)UP.1943-5444.0000778

Huang, R. Z., Moudon, A. V, Zhou, C., & Saelens, B. E. (2019). Higher residential and employment densities are associated with more objectively measured walking in the home neighborhood. *Journal of Transport & Health*, *12*, 142–151. https://doi.org/10.1016/j.jth.2018.12.002

Huo, Y., Wang, C., & Liu, J. (2025). Understanding the Walk Intention of Older Adults in China with the Theory of Planned Behaviour and the Prototype Willingness Model. *Promet (Zagreb)*, *37*(2), 379–391. https://doi.org/10.7307/ptt.v37i2.642

Indebetou, L., & Ahlmer, A.-K. (2023). *Resvanor Umeå 2022* . chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.umea.se/download/18.7812482218690c08728819a0/1679067909860/Resvanor%20i%20Ume%C3%A5,%20s%C3%A5%20reste%20vi%20i%20kommunen%20h%C3%B6sten%202022.pdf

Jack, E., & McCormack, G. R. (2014). The associations between objectively-determined and self-reported urban form characteristics and neighborhood-based walking in adults. *International Journal of Behavioral Nutrition and Physical Activity 2014 11:1*, *11*(1), 71-. https://doi.org/10.1186/1479-5868-11-71

Jacobs, J. (1961). *The death and life of great American cities*. Random House.

Jin, C. J., Li, J., Wu, C., Xiu, X., & Li, D. (2025). Findings in pedestrian route choice experiments: Tradeoff and hypothetical bias. *Travel Behaviour and Society*, *40*, 101000. https://doi.org/10.1016/J.TBS.2025.101000

Jin, C. J., Li, N., Wu, C., Li, D., & Lin, Y. (2025). The Integrated Choice and Latent Variable Model for Exploring the Mechanisms of Pedestrian Route Choice. *ISPRS International Journal of Geo-Information 2024, Vol. 13, 14*(9), 341. https://doi.org/10.3390/IJGI14090341

Jin, C. J., Luo, Y., Wu, C., Song, Y., & Li, D. (2024). Exploring the Pedestrian Route Choice Behaviors by Machine Learning Models. *ISPRS International Journal of Geo-Information 2024, Vol. 13, 13*(5). https://doi.org/10.3390/IJGI13050146

Jin, L., Lu, W., & Sun, P. (2022a). Effect of the Street Environment on Walking Behavior: A Case Study Using the Route Choice Model in the Chunliu Community of Dalian. *Frontiers in Public Health*, *10*, 874788. https://doi.org/10.3389/FPUBH.2022.874788/BIBTEX

Jin, L., Lu, W., & Sun, P. (2022b). Preference for Street Environment Based on Route Choice Behavior While Walking. *Frontiers in Public Health*, *10*, 2267. https://doi.org/10.3389/FPUBH.2022.880251/BIBTEX

Kamruzzaman, M., Washington, S., Baker, D., Brown, W., Giles-Corti, B., & Turrell, G. (2016). Built environment impacts on walking for transport in Brisbane, Australia. *Transportation*, *43*(1), 53–77. https://doi.org/10.1007/s11116-014-9563-0

Kerr, J., Emond, J. A., Badland, H., Reis, R., Sarmiento, O., Carlson, J., Sallis, J. F., Cerin, E., Cain, K., Conway, T., Schofield, G., Macfarlane, D. J., Christiansen, L. B., Van Dyck, D., Davey, R., Aguinaga-Ontoso, I., Salvo, D., Sugiyama, T., Mitáš, J., … Natarajan, L. (2016). Perceived Neighborhood Environmental Attributes Associated with Walking and Cycling for Transport among Adult Residents of 17 Cities in 12 Countries: The IPEN Study. *Environmental Health Perspectives*, *124*(3), 290–298. https://doi.org/10.1289/EHP.1409466

KiM. (2020). *Kerncijfers Mobiliteit*. https://www.kimnet.nl/documenten/2020/10/28/kerncijfers-mobiliteit-2020

Kline, R. B. (2016). Principles and Practice of Structural Equation Modeling. In *Methodology in the Social Sciences* (Fourth edition). The Guilford Press.

Koohsari, M. J., Oka, K., Nakaya, T., & McCormack, G. R. (2023). Urban Form Metrics for Promoting Walking: Street Layouts and Destinations. *Journal of Urban Health*, *100*(5), 1024–1031. https://doi.org/10.1007/S11524-023-00775-2

Koohsari, M. J., Owen, N., Cerin, E., Giles-Corti, B., & Sugiyama, T. (2016). Walkability and walking for transport: Characterizing the built environment using space syntax. *International Journal of Behavioral Nutrition and Physical Activity*, *13*(1), 1–9. https://doi.org/10.1186/S12966-016-0448-9/TABLES/3

Koszowski, C., Wittwer, R., Hubrich, S., & Gerike, R. (2024). Perceived importance of context-specific built-environment factors of walking: A new perspective for prioritizing policy measures for promoting walking. *International Journal of Sustainable Transportation*, *18*(3), 275–290. https://doi.org/10.1080/15568318.2023.2301372

Krenn, P. J., Oja, P., & Titze, S. (2014). Route choices of transport bicyclists: A comparison of actually used and shortest routes. *International Journal of Behavioral Nutrition and Physical Activity*, *11*(1). https://doi.org/10.1186/1479-5868-11-31

Larrañaga, A. M., Rizzi, L. I., Arellana, J., Strambi, O., & Cybis, H. B. B. (2016). The influence of built environment and travel attitudes on walking: A case study of Porto Alegre, Brazil. *International Journal of Sustainable Transportation*, *10*(4), 332–342. https://research.ebsco.com/linkprocessor/plink?id=3def77aa-2c09-3980-9256-c0fd6cf12dd5

Lee, H. S. (2016). Examining neighborhood influences on leisure-time walking in older Korean adults using an extended theory of planned behavior. *Landscape and Urban Planning*, *148*, 51–60. https://doi.org/10.1016/J.LANDURBPLAN.2015.12.011

Lee, H.-S., & Shepley, M. M. (2012). Perceived Neighborhood Environments and Leisure-Time Walking Among Korean Adults: An Application of the Theory of Planned Behavior. *Health Environments Research & Design Journal (HERD) (Vendome Group LLC)*, *5*(2), 99–110.

Lee, I. M., & Buchner, D. M. (2008). The importance of walking to public health. *Medicine and Science in Sports and Exercise*, *40*(7 SUPPL.1). https://doi.org/10.1249/MSS.0B013E31817C65D0

Lee, J. (2016). Impact of neighborhood walkability on trip generation and trip chaining: Case of Los Angeles. *Journal of Urban Planning and Development*, *142*(3). https://doi.org/10.1061/(ASCE)UP.1943-5444.0000312

Lee, S., & Lee, M. H. (2021). Impact of Neighborhood Environment on Pedestrian Route Selection among Elementary Schoolchildren in Korea. *International Journal of Environmental Research and Public Health 2021, Vol. 18, Page 7049*, *18*(13), 7049. https://doi.org/10.3390/IJERPH18137049

Lemieux, M., & Godin, G. (2009). How well do cognitive and environmental variables predict active commuting? *International Journal of Behavioral Nutrition and Physical Activity*, *6*(1), 12. https://doi.org/10.1186/1479-5868-6-12

Leslie, E., Saelens, B., Frank, L., Owen, N., Bauman, A., Coffee, N., & Hugo, G. (2005). Residents' perceptions of walkability attributes in objectively different neighbourhoods: a pilot study. *Health & Place*, *11*(3), 227–236. https://doi.org/10.1016/J.HEALTHPLACE.2004.05.005

Leung, K. M., & Chung, P. K. (2020). Associations Between Social and Physical Environments and Older Adults' Walking for Transportation and Recreation. *Journal of Aging & Physical Activity*, *28*(1), 24–33. https://doi.org/10.1123/japa.2018-0144

Li, J., Auchincloss, A. H., Yang, Y., Rodriguez, D. A., & Sánchez, B. N. (2020). Neighborhood characteristics and transport walking: Exploring multiple pathways of influence using a structural equation modeling approach. *Journal of Transport Geography*, *85*. https://doi.org/10.1016/J.JTRANGEO.2020.102703

Lieu, S. J., & Guhathakurta, S. (2025). Exploring pedestrian route choice preferences by demographic groups: Analysis of street attributes in Chicago. *Transportation Research Part A: Policy and Practice*, *195*, 104437. https://doi.org/10.1016/J.TRA.2025.104437

Lindelöw, D., Svensson, Å., Brundell-Freij, K., & Hiselius, L. W. (2017). Satisfaction or compensation? The interaction between walking preferences and neighbourhood design. *Transportation Research Part D: Transport and Environment*, *50*, 520–532. https://doi.org/10.1016/j.trd.2016.11.021

Litman, T. (2013). Transportation and public health. *Annual Review of Public Health*, *34*(Volume 34, 2013), 217–233. https://doi.org/10.1146/ANNUREV-PUBLHEALTH-031912-114502/CITE/REFWORKS

Liu, J., Liu, L., & Pei, M. (2022). Analysis of older people's walking behavioral intention with the extended theory of planned behavior. *Journal of Transport and Health*, *26*. https://doi.org/10.1016/J.JTH.2022.101462

Liu, J. X., Zhou, J. P., & Xiao, L. Z. (2021). Built environment correlates of walking for transportation: Differences between commuting and non-commuting trips. *Journal of Transport and Land Use*, *14*(1), 1129–1148. https://doi.org/10.5198/jtlu.2021.1933

Liu, Y., Yang, D., de Vries, B., & J.P. Timmermans, H. (2020). Analysis of Built Environment Influence on Pedestrian route choice behavior in Dutch Design Week using GPS Data. *Collective Dynamics*, *5*. https://doi.org/10.17815/CD.2020.59

Liu, Z. Y., Kemperman, A., & Timmermans, H. (2020). Correlates of older adults' walking trip duration. *Journal of Transport & Health*, *18*. https://doi.org/10.1016/j.jth.2020.100889

Löfven, S., & Skog, K. (2018). *Strategi för Levande städer – politik för en hållbar stadsutveckling*. https://www.regeringen.se/4971fa/contentassets/b5640fd317d04929990610e1a20a5383/171823000webb.pdf

López-Lambas, M. E., Sánchez, J. M., & Alonso, A. (2021). The walking health: A route choice model to analyze the street factors enhancing active mobility. *Journal of Transport & Health*, *22*. https://doi.org/10.1016/J.JTH.2021.101133

Loukaitou-Sideris, A. (2014). Fear and safety in transit environments from the women's perspective. *Security Journal*, *27*(2), 242–256. https://doi.org/10.1057/SJ.2014.9

Lovasi, G. S., Moudon, A. V., Pearson, A. L., Hurvitz, P. M., Larson, E. B., Siscovick, D. S., Berke, E. M., Lumley, T., & Psaty, B. M. (2008). Using built environment characteristics to predict walking for exercise. *International Journal of Health Geographics*, *7*, 1–13. https://doi.org/10.1186/1476-072X-7-10

Lue, G., & Miller, E. J. (2019). Estimating a Toronto pedestrian route choice model using smartphone GPS data. *Travel Behaviour and Society*, *14*, 34–42. https://doi.org/10.1016/J.TBS.2018.09.008

Malmö stad. (2024). *Trafik- och mobilitetsplan för ett mer tillgängligt och hållbart malmö : mål och riktlinjer till 2040*. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://motenmedborgarportal.malmo.se/welcome-sv/namnder-styrelser/fritidsnamnden/mote-2024-10-24/agenda/trafik-och-mobilitetsplan-for-ett-mer-tillgangligt-och-hallbart-malmo-pdf-62362?downloadMode=open

McCormack, G. r., Friedenreich, C. m., Giles-Corti, B., Doyle-Baker, P. k., & Shiell, A. (2013). Do Motivation-Related Cognitions Explain the Relationship Between Perceptions of Urban Form and Neighborhood Walking? *Journal of Physical Activity and Health*, *10*, 961–973.

McGuckin, N., & Fucci, A. (2018). *Summary of Travel Trends: 2017 National Household Travel Survey. Report No.: FHWA-PL-18-019*.

McMillan, T. E. (2007). The relative influence of urban form on a child's travel mode to school. *Transportation Research Part A*, *41*(1), 69–79. https://doi.org/10.1016/J.TRA.2006.05.011

Meijers, E., Waterhout, B., & Zonneveld, W. (2007). Closing the Gap: Territorial Cohesion through Polycentric Development. *European Journal of Spatial Development*, *5*(2), 1–24. https://doi.org/10.5281/ZENODO.5137089

Mokhtarian, P. l. (1), & Cao, X. (2). (2008). Examining the impacts of residential self-selection on travel behavior: A focus on methodologies. *Transportation Research Part B: Methodological*, *42*(3), 204–228. https://doi.org/10.1016/j.trb.2007.07.006

Molina-García, J., Castillo, I., & Sallis, J. F. (2010). Psychosocial and environmental correlates of active commuting for university students. *Preventive Medicine*, *51*(2), 136–138. https://doi.org/10.1016/J.YPMED.2010.05.009

Moran, M. R., Rodríguez, D. A., & Corburn, J. (2018). Examining the role of trip destination and neighborhood attributes in shaping environmental influences on children's route choice. *Transportation Research Part D: Transport and Environment*, *65*, 63–81. https://doi.org/10.1016/J.TRD.2018.08.001

Morris, J. N., & Hardman, A. E. (1997). Walking to health. *Sports Medicine (Auckland, N.Z.)*, *23*(5), 306–332. https://doi.org/10.2165/00007256-199723050-00004

Moudon, A. V., & Lee, C. (2003). Walking and bicycling: An evaluation of environmental audit instruments. *American Journal of Health Promotion*, *18*(1), 21–37. https://doi.org/10.4278/0890-1171-18.1.21,

Neto, I. L., Matsunaga, L. H., Machado, C. C., Günther, H., Hillesheim, D., Pimentel, C. E., Vargas, J. C., & D'Orsi, E. (2020). Psychological determinants of walking in a Brazilian sample: An application of the Theory of Planned Behavior. *Transportation Research Part F: Traffic Psychology and Behaviour*, *73*, 391–398. https://doi.org/10.1016/J.TRF.2020.07.002

Newman, P., & Kenworthy, J. (1999). Sustainability and cities : overcoming automobile dependence. In *Sustainability and Cities: Overcoming Automobile Dependence*.

Nguyen, L. M., & Mertens, L. (2021). Psychosocial and Social Environmental Factors as Moderators in the Relation between the Objective Environment and Older Adults' Active Transport. *International Journal of Environmental Research and Public Health*, *18*(5), 1–17. https://doi.org/10.3390/IJERPH18052647

Nobis, C., Kuhnimhof, T., Follmer, R., & Bäumer, M. (2019). *Mobilität in Deutschland − MiD: Zeitreihenbericht 2002 − 2008 − 2017*. http://www.mobilitaet-in-deutschland.de/pdf/MiD2017_Zeitreihenbericht_2002_2008_2017.pdf

Orrego-Oñate, J., & Marquet, O. (2025). The role of perceived and objective accessibility in shaping walking behavior: Insights from mid-sized Spanish cities. *Transportation Research Part A: Policy and Practice*, *192*, 104340. https://doi.org/10.1016/J.TRA.2024.104340

Owen, N., Cerin, E., Leslie, E., duToit, L., Coffee, N., Frank, L. D., Bauman, A. E., Hugo, G., Saelens, B. E., & Sallis, J. F. (2007). Neighborhood Walkability and the Walking Behavior of Australian Adults. *American Journal of Preventive Medicine*, *33*(5), 387–395. https://doi.org/10.1016/j.amepre.2007.07.025

Owen, N., Humpel, N., Leslie, E., Bauman, A., & Sallis, J. (2004). Understanding environmental influences on walking - Review and research agenda. *American Journal of Preventive Medicine*, *27*(1), 67–76. https://doi.org/10.1016/j.amepre.2004.03.006

Ozbil, A., Argin, G., & Yesiltepe, D. (2016). Pedestrian route choice by elementary school students: The role of street network configuration and pedestrian quality attributes in walking to school. *International Journal of Design Creativity and Innovation*, *4*(2), 67–84.

Pallant, J. (2016). *SPSS survival manual: a step by step guide to data analysis using IBM SPSS* (6th ed.).

Panter, J., Griffin, S., Dalton, A. M., & Ogilvie, D. (2013). Patterns and predictors of changes in active commuting over 12 months. *Preventive Medicine*, *57*(6), 776. https://doi.org/10.1016/J.YPMED.2013.07.020

Panter, J., Griffin, S., Jones, A., Mackett, R., & Ogilvie, D. (2011). Correlates of time spent walking and cycling to and from work: Baseline results from the commuting and health in Cambridge study. *International Journal of Behavioral Nutrition and Physical Activity*, *8:124*. https://doi.org/10.1186/1479-5868-8-124

Panter, J., Griffin, S., & Ogilvie, D. (2014). Active commuting and perceptions of the route environment: A longitudinal analysis. *Preventive Medicine*, *67*, 134–140. https://doi.org/10.1016/j.ypmed.2014.06.033

Panter, J., Jones, A. P., Van Sluijs, E. M. F., Griffin, S. J., & Wareham, N. J. (2011). Environmental and psychological correlates of older adult's active commuting. *Medicine and Science in Sports and Exercise*, *43*(7), 1235–1243. https://doi.org/10.1249/MSS.0B013E3182078532

Panter, J. R., & Jones, A. (2010). Attitudes and the environment as determinants of active travel in adults: What do and don't we know? *Journal of Physical Activity and Health*, *7*(4), 551–561. https://doi.org/10.1123/JPAH.7.4.551

Panter, J. R., Jones, A. P., & van Sluijs, E. M. F. (2008). Environmental determinants of active travel in youth: A review and framework for future research. *International Journal of Behavioral Nutrition and Physical Activity*, *5*(1), 34–34. https://doi.org/10.1186/1479-5868-5-34

Panter, J. R., Jones, A. P., Van Sluijs, E. M. F., & Griffin, S. J. (2010). Neighborhood, Route, and School Environments and Children's Active Commuting. *American Journal of Preventive Medicine*, *38*(3), 268–278. https://doi.org/10.1016/J.AMEPRE.2009.10.040

Phillips, D. C., & Burbules, N. C. (2000). Postpositivism and Educational Research. In *International Journal of Educational Management* (Vol. 14, Number 5). Bloomsbury Academic.

Pojani, D., & Stead, D. (2015). Sustainable urban transport in the developing world: Beyond megacities. *Sustainability (Switzerland)*, *7*(6), 7784–7805. https://doi.org/10.3390/SU7067784

Pont, K., Ziviani, J., Wadley, D., Bennett, S., & Abbott, R. (2009). Environmental correlates of children's active transportation: A systematic literature review. *Health and Place*, *15*(3), 849–862. https://doi.org/10.1016/J.HEALTHPLACE.2009.02.002

Prato, C. G., Bekhor, S., & Pronello, C. (2011). Latent variables and route choice behavior. *Transportation 2011 39:2*, *39*(2), 299–319. https://doi.org/10.1007/S11116-011-9344-Y

Prins, R. G., Pierik, F., Etman, A., Sterkenburg, R. P., Kamphuis, C. B. M., & van Lenthe, F. J. (2014). How many walking and cycling trips made by elderly are beyond commonly used buffer sizes: Results from a GPS study. *Health and Place*, *27*, 127–133. https://doi.org/10.1016/j.healthplace.2014.01.012

Pucher, J., & Buehler, R. (2008). Making Cycling Irresistible: Lessons from The Netherlands, Denmark and Germany. *Transport Reviews*, *28*(4), 495–528. https://doi.org/10.1080/01441640701806612

Pucher, J., Dill, J., & Handy, S. (2010). Infrastructure, programs, and policies to increase bicycling: An international review. *Preventive Medicine*, *50*(SUPPL.), S106–S125. https://doi.org/10.1016/J.YPMED.2009.07.028

Pucher, J., Peng, Z. R., Mittal, N., Zhu, Y., & Korattyswaroopam, N. (2007). Urban Transport Trends and Policies in China and India: Impacts of Rapid Economic Growth. *Transport Reviews*, *27*(4), 379–410. https://doi.org/10.1080/01441640601089988

Pucher, J., & Renne, J. L. (2003). Socioeconomics of Urban Travel: Evidence from the 2001 NHTS. *Transportation Quarterly*, *57*(3), 49–77. https://openurl-ebsco-com.proxy.lib.ltu.se/contentitem/buh:10341515?sid=ebsco:plink:crawler&id=ebsco:buh:10341515&crl=c

Pyddoke, R. (2023). *Comparison of policies for increasing sustainable transport mode shares in Swedish cities* (2023:9; VTI Working Paper).

Reichert, F. F., Barros, A. J. D., Domingues, M. R., & Hallal, P. C. (2007). The Role of Perceived Personal Barriers to Engagement in Leisure-Time Physical Activity. *AMERICAN JOURNAL OF PUBLIC HEALTH*, *97*(3), 515–519.

Rhodes, R. E., Brown, S. G., & McIntyre, C. A. (2006). Integrating the Perceived Neighborhood Environment and the Theory of Planned Behavior When Predicting Walking in a Canadian Adult Sample. *American Journal of Health Promotion*, *21*(2), 110–118. https://doi.org/10.4278/0890-1171-21.2.110

Rhodes, R. E., Janssen, I., Bredin, S. S. D., Warburton, D. E. R., & Bauman, A. (2017). Physical activity: Health impact, prevalence, correlates and interventions. *Psychology & Health*, *32*(8), 942–975. https://doi.org/10.1080/08870446.2017.1325486

Rietveld, P., & Daniel, V. (2004). Determinants of bicycle use: do municipal policies matter? *Transportation Research Part A: Policy and Practice*, *38*(7), 531–550. https://doi.org/10.1016/J.TRA.2004.05.003

Riggs, W. (2014). Steps toward validity in active living research: Research design that limits accusations of physical determinism. *Health and Place*, *26*, 7–13. https://doi.org/10.1016/j.healthplace.2013.11.003

Risser, R., & Šucha, M. (2021). *Psychological perspectives on walking : interventions for achieving change*. Routledge.

Rodrigue, L., El-Geneidy, A., & Manaugh, K. (2024). Sociodemographic matters: Analyzing interactions of individuals' characteristics with walkability when modelling walking behavior. *Journal of Transport Geography*, *114*, 103788. https://doi.org/10.1016/J.JTRANGEO.2023.103788

Rodríguez, D. A., & Joo, J. (2004). The relationship between non-motorized mode choice and the local physical environment. *Transportation Research Part D: Transport and Environment*, *9*(2), 151–173. https://doi.org/10.1016/J.TRD.2003.11.001

Rodríguez, D. A., Merlin, L., Prato, C. G., Conway, T. L., Cohen, D., Elder, J. P., Evenson, K. R., McKenzie, T. L., Pickrel, J. L., & Veblen-Mortenson, S. (2015). Influence of the Built Environment on Pedestrian Route Choices of Adolescent Girls. *Environment and Behavior*, *47*(4), 359–394. https://doi.org/10.1177/0013916513520004/ASSET/IMAGES/LARGE/10.1177_0013916513520004-FIG2.JPEG

Roe, J., & Aspinall, P. (2011). The restorative benefits of walking in urban and rural settings in adults with good and poor mental health. *Health & Place*, *17*(1), 103–113. https://doi.org/10.1016/J.HEALTHPLACE.2010.09.003

Saelens, B. E., & Handy, S. L. (2008). Built environment correlates of walking: A review. *Medicine and Science in Sports and Exercise*, *40*(7), S550–S566. https://doi.org/10.1249/MSS.0b013e31817e67a4

Saelens, B. E., Sallis, J. F., & Frank, L. D. (2003). Environmental correlates of walking and cycling: Findings from the transportation, urban design, and planning literatures. *Annals of Behavioral Medicine*, *25*(2), 80–91. https://doi.org/10.1207/S15324796ABM2502_03

Sahlqvist, S., Goodman, A., Cooper, A. R., & Ogilvie, D. (2013). Change in active travel and changes in recreational and total physical activity in adults: Longitudinal findings from the iConnect study. *The International Journal of Behavioral Nutrition and Physical Activity*, *10*. https://doi.org/10.1186/1479-5868-10-28

Sallis, J. F., Cerin, E., Conway, T. L., Adams, M. A., Frank, L. D., Pratt, M., Salvo, D., Schipperijn, J., Smith, G., Cain, K. L., Davey, R., Kerr, J., Lai, P. C., Mitáš, J., Reis, R., Sarmiento, O. L., Schofield, G., Troelsen, J., Van Dyck, D., … Owen, N. (2016). Physical activity in relation to urban environments in 14 cities worldwide: A cross-sectional study. *The Lancet*, *387*(10034), 2207–2217. https://doi.org/10.1016/S0140-6736(15)01284-2

Sarjala, S. (2019). Built environment determinants of pedestrians' and bicyclists' route choices on commute trips: Applying a new grid-based method for measuring the built environment along the route. *Journal of Transport Geography*, *78*, 56–69. https://doi.org/10.1016/J.JTRANGEO.2019.05.004

Sarkar, C., Webster, C., Pryor, M., Tang, D., Melbourne, S., Zhang, X., & Jianzheng, L. (2015). Exploring associations between urban green, street design and walking: Results from the Greater London boroughs. *Landscape and Urban Planning*, *143*, 112–125. https://doi.org/10.1016/j.landurbplan.2015.06.013

Schlossberg, M., Rowell, J., Amos, D., & Sanford, K. (2013). *Rethinking Streets: An Evidence-Based Guide to 25 Complete Street Transformations*. University of Oregon. https://www.rethinkingstreets.com/download.html

Sevtsuk, A., Basu, R., Li, X., & Kalvo, R. (2021). A big data approach to understanding pedestrian route choice preferences: Evidence from San Francisco. *Travel Behaviour and Society*, *25*, 41–51. https://doi.org/10.1016/J.TBS.2021.05.010

Shatu, F., Yigitcanlar, T., & Bunker, J. (2019a). Objective vs. subjective measures of street environments in pedestrian route choice behaviour: Discrepancy and correlates of non-concordance. *Transportation Research Part A: Policy and Practice*, *126*, 1–23. https://doi.org/10.1016/J.TRA.2019.05.011

Shatu, F., Yigitcanlar, T., & Bunker, J. (2019b). Shortest path distance vs. least directional change: Empirical testing of space syntax and geographic theories concerning pedestrian route choice behaviour. *Journal of Transport Geography*, *74*, 37–52. https://doi.org/10.1016/J.JTRANGEO.2018.11.005

Shen, Y., & Ryan, A. (2026). Exploring the intersection of gender with walking, the built environment, and health outcomes via the All of Us dataset. *Journal of Transport Geography*, *130*, 104468. https://doi.org/10.1016/J.JTRANGEO.2025.104468

Shi, Y., Yin, C., Long, Y., Wen, J., & Fan, L. (2025). Residential preferences and purpose-specific walking behaviors: Mediation effects of built environments. *Transportation Research Part D: Transport and Environment*, *149*, 105067. https://doi.org/10.1016/j.trd.2025.105067

Sloboda, B. W., & Yao, V. W. (2005). An analysis of gender differences in vehicles miles traveled (VMT) using nonparametric methods. *46th Annual Transportation Research Forum 2005*.

Southworth, M. (2005). Designing the Walkable City. *Journal of Urban Planning & Development*, *131*(4), 246–257. https://doi.org/10.1061/(ASCE)0733-9488(2005)131:4(246)

Statistical database. (n.d.). *Passenger cars in use by region and type of ownership. Year 2002 - 2025. PxWeb*. Retrieved April 1, 2026, from https://www.statistikdatabasen.scb.se/pxweb/en/ssd/START__TK__TK1001__TK1001A/PersBilarA/

Statistical database. (2020). *Population and household statistics*.

Statistical database. (2021a). *Labour force surveys*.

Statistical database. (2021b). *Population statistics by municipality*. https://www.scb.se

Stefánsdóttir, H., Mouratidis, K., Rynning, M. K., & Meyer, S. F. (2024). Perceived walkability and daily walking behaviour in a "small city context" – The case of Norway. *Journal of Transport Geography*, *121*(4), 104014. https://doi.org/10.1016/j.jtrangeo.2024.104014

Stevenson, M., Thompson, J., de Sá, T. H., Ewing, R., Mohan, D., McClure, R., Roberts, I., Tiwari, G., Giles-Corti, B., Sun, X., Wallace, M., & Woodcock, J. (2016). Land use, transport, and population health: estimating the health benefits of compact cities. *Lancet*, *388*(10062), 2925–2935.

Stewart, O. T., Vernez Moudon, A., Saelens, B. E., Lee, C., Kang, B., & Doescher, M. P. (2016). Comparing associations between the built environment and walking in rural small towns and a large metropolitan area. *Environment and Behavior*, *48*(1), 13–36. https://doi.org/10.1177/0013916515612253

Sugiyama, T., Francis, J., Middleton, N. J., Owen, N., & Giles-Corti, B. (2010). Associations Between Recreational Walking and Attractiveness, Size, and Proximity of Neighborhood Open Spaces. *AMERICAN JOURNAL OF PUBLIC HEALTH*, *100*(9), 1752–1757. https://openurl-ebsco-com.proxy.lib.ltu.se/contentitem/edsbl:RN277573750?sid=ebsco:plink:crawler&id=ebsco:edsbl:RN277573750&crl=c

Sun, F., Norman, I. J., & While, A. E. (2013). Physical activity in older people: A systematic review. *BMC Public Health*, *13*(1), 1–17. https://doi.org/10.1186/1471-2458-13-449/FIGURES/2

Sun, G., Acheampong, R. A., Lin, H., & Pun, V. C. (2015). Understanding Walking Behavior among University Students Using Theory of Planned Behavior. *International Journal of Environmental Research and Public Health*, *12*(11), 13794–13806. https://doi.org/10.3390/ijerph121113794

Sundquist, K., Eriksson, U., Kawakami, N., Skog, L., Ohlsson, H., & Arvidsson, D. (2011). Neighborhood walkability, physical activity, and walking behavior: The Swedish Neighborhood and Physical Activity (SNAP) study. *Social Science and Medicine*, *72*(8), 1266–1273. https://doi.org/10.1016/j.socscimed.2011.03.004

Swedish Transport Administration, ,. (2023, July 5). *Lastkajen – Sveriges väg- och järnvägsdata*. Https://Www.Trafikverket.Se/e-Tjanster/Lastkajen--Sveriges-Vag--Och-Jarnvagsdata/.

Swedish University of Agricultural Sciences. (2023). *Herkules: Sveriges LantbruksUniversitets geodatabas*. https://herkules.slu.se/get/?drop=

Technische Universität Dresden, ,. (2020). *TravelVu and TravelViewer New Ways of Collecting and Evaluating Travel Survey Data: A Site Report from Dresden, Germany* . https://tu-dresden.de/in-bewegung

Teixeira, P. J., Carraça, E. V., Markland, D., Silva, M. N., & Ryan, R. M. (2012). Exercise, physical activity, and self-determination theory: A systematic review. *The International*

Journal of Behavioral Nutrition and Physical Activity, *9*. https://doi.org/10.1186/1479-5868-9-78

Tian, J., Tang, M., & Wang, J. (2022). The effect of path environment on pedestrians' route selection: A case study of University of Cincinnati. *Proceedings of the International Conference on Computer-Aided Architectural Design Research in Asia*, 575–584. https://doi.org/10.52842/conf.caadria.2022.1.575

Tight, M., Timms, P., Banister, D., Bowmaker, J., Copas, J., Day, A., Drinkwater, D., Givoni, M., Gühnemann, A., Lawler, M., Macmillen, J., Miles, A., Moore, N., Newton, R., Ngoduy, D., Ormerod, M., O'Sullivan, M., & Watling, D. (2011). Visions for a walking and cycling focussed urban transport system. *Journal of Transport Geography*, *19*(6), 1580–1589. https://doi.org/10.1016/J.JTRANGEO.2011.03.011

Timpabi, A. P., Adams, C. A., & Osei, K. K. (2023). The role of infrastructure and route type choices for walking and cycling in some cities in Ghana. *Urban, Planning and Transport Research*, *11*(1). https://doi.org/10.1080/21650020.2023.2222838

Ton, D. (2019). *Unravelling Mode and Route Choice Behaviour of Active Mode Users* [Delft University of Technology]. https://research.tudelft.nl/en/publications/unravelling-mode-and-route-choice-behaviour-of-active-mode-users/

Ton, D., Duives, D. C., Cats, O., Hoogendoorn-Lanser, S., & Hoogendoorn, S. P. (2019). Cycling or walking? Determinants of mode choice in the Netherlands. *Transportation Research Part A: Policy and Practice*, *123*, 7–23. https://doi.org/10.1016/J.TRA.2018.08.023

Tong, Y., & Bode, N. W. F. (2022). The principles of pedestrian route choice. *Journal of the Royal Society Interface*, *19*(189). https://doi.org/10.1098/RSIF.2022.0061

Tong, Y., & Bode, N. W. F. (2023). Empirical Investigations on the Role of Psychological Factors in Pedestrian Route Choice. *Modeling and Simulation in Science, Engineering and Technology*, *Part F1951*, 81–101. https://doi.org/10.1007/978-3-031-46359-4_4/SAVE-RESEARCH

Trafikanalys. (2015). *RVU Sverige – Den nationella resvaneundersökningen 2014 [The Swedish National Travel Survey 2014]*. www.trafa.se

Trafikanalys. (2019). *RVU Sverige – Den nationella resvaneundersökningen 2018 [The Swedish National Travel Survey 2018]*.

Trafikanalys. (2023). *RVU Sverige – Den nationella resvaneundersökningen 2022 [The Swedish National Travel Survey 2022]*. www.trafa.se

Trafikanalys. (2025). *RVU Sverige – Den nationella resvaneundersökningen 2024 [The Swedish National Travel Survey 2024]*.

Trafikförvaltningen. (2020). *Fakta om SL och länet 2020 - Region Stockholm*. https://www.regionstockholm.se/dokument/kollektivtrafik/rapport/2021/fakta-om-sl-och-lanet-2020/

Trivector, A. B. (2022). *TravelVu – appen som detekterar resor*. https://www.trivector.se/it-system/programvaror/travelvu/

Troped, P. J., Wilson, J. S., Matthews, C. E., Cromley, E. K., & Melly, S. J. (2010). The Built Environment and Location-Based Physical Activity. *American Journal of Preventive Medicine*, *38*(4), 429–438. https://doi.org/10.1016/J.AMEPRE.2009.12.032

Turrell, G., Hewitt, B., Haynes, M., Nathan, A., & Giles-Corti, B. (2014). Change in walking for transport: a longitudinal study of the influence of neighbourhood disadvantage and individual-level socioeconomic position in mid-aged adults. *International Journal of Behavioral Nutrition and Physical Activity*, *11*, 151. https://doi.org/10.1186/s12966-014-0151-7

Umea | CIVITAS. (n.d.). Retrieved April 1, 2026, from https://civitas.eu/cities/umea

Umeå Municipality (Gator och parker). (2019). *Fotgängarprogram för Umeå*.

United Nations Economic Commission for Europe, ,. (2022, April 29). *Towards a pan-European master plan on walking*. https://unece.org/climate-change/news/towards-pan-european-master-plan-walking

Vale, D. S., & Pereira, M. (2016). Influence on pedestrian commuting behavior of the built environment surrounding destinations: A structural equations modeling approach. *International Journal of Sustainable Transportation*, *10*(8), 730–741.

van Beek, A., Feng, Y., Duives, D. C., & Hoogendoorn, S. P. (2024). Studying the impact of lighting on the pedestrian route choice using Virtual Reality. *Safety Science*, *174*. https://doi.org/10.1016/J.SSCI.2024.106467

Van Cauwenberg, J., Van Holle, V., Simons, D., Deridder, R., Clarys, P., Goubert, L., Nasar, J., Salmon, J., De Bourdeaudhuij, I., & Deforche, B. (2012). Environmental factors influencing older adults' walking for transportation: a study using walk-along interviews. *International Journal of Behavioral Nutrition and Physical Activity*, *9*(1), 85–85. https://doi.org/10.1186/1479-5868-9-85

Van Dyck, D., Cerin, E., Conway, T. L., De Bourdeaudhuij, I., Owen, N., Kerr, J., Cardon, G., Frank, L. D., Saelens, B. E., & Sallis, J. F. (2012). Perceived neighborhood environmental attributes associated with adults' transport-related walking and cycling: Findings from the USA, Australia and Belgium. In *International Journal of Behavioral Nutrition and Physical Activity* (Vol. 9, Number 1). eScholarship, University of California. https://research.ebsco.com/linkprocessor/plink?id=5dd32600-22b1-3cfa-90a3-919b7b0be6dd

Van Dyck, D., Cerin, E., Conway, T. L., De Bourdeaudhuij, I., Owen, N., Kerr, J., Cardon, G., & Sallis, J. F. (2014). Interacting psychosocial and environmental correlates of leisure-time physical activity: A three-country study. *Health Psychology*, *33*(7), 699–709. https://doi.org/10.1037/A0033516

Van Holle, V., Van Cauwenberg, J., Deforche, B., Van de Weghe, N., De Bourdeaudhuij, I., & Van Dyck, D. (2015). Do psychosocial factors moderate the association between objective neighborhood walkability and older adults' physical activity? *Health and Place*, *34*, 118–125. https://doi.org/10.1016/J.HEALTHPLACE.2015.05.004

Wang, J., & Huang, J. (2025). An alternative perspective on the relationship between multiscale built environments and walking behavior: evidence from the government-subsidized resettlement towns in China. *Journal of Asian Architecture and Building Engineering*. https://doi.org/10.1080/13467581.2025.2455016

Wang, Y., Aziz, N. F., Cui, H., Shen, C., & Zhang, Z. (2024). Interaction of perceived Chinese campus walkability and psychosocial factors on college students' walking behavior. *Journal of Infrastructure, Policy and Development*, *8*(11). https://doi.org/10.24294/jipd.v8i11.8968

Watson, K. B., Whitfield, G. P., Thomas, J. V., Berrigan, D., Fulton, J. E., & Carlson, S. A. (2020). Associations between the National Walkability Index and walking among US Adults — National Health Interview Survey, 2015. *Preventive Medicine*, *137*. https://doi.org/10.1016/j.ypmed.2020.106122

Wicramasinghe, V., & Dissanayake, S. (2017). Evaluation of pedestrians' sidewalk behavior in developing countries. *Transportation Research Procedia*, *25*, 4068–4078. https://doi.org/10.1016/J.TRPRO.2017.05.327

Wilcox, S., Bopp, M., Oberrecht, L., Kammermann, S. K., & McElmurray, C. T. (2003). Psychosocial and Perceived Environmental Correlates of Physical Activity in Rural and Older African American and White Women. *The Journals of Gerontology: Series B*, *58*(6), P329–P337. https://doi.org/10.1093/GERONB/58.6.P329

Winters, M., Teschke, K., Grant, M., Setton, E. M., & Brauer, M. (2010). How far out of the way will we travel? Built environment influences on route selection for bicycle and car travel. *Transportation Research Record*, (2190), 1–10. https://doi.org/10.3141/2190-01

Wiśniewski, L. S. (2021). Urban distances. Dimensions of urban units and distribution of functions in the city in context of walking, cycling and public transport distances. *Space&FORM*, *2020*(46), 211–237. https://doi.org/10.21005/PIF.2021.46.C-08

Wozniak, M., Filomena, G., & Wronkowski, A. (2025). What's your type? A taxonomy of pedestrian route choice behaviour in cities. *Transportation Research Part F: Traffic Psychology and Behaviour*, *109*, 1257–1274. https://doi.org/10.1016/J.TRF.2025.01.012

Yang, L., Yang, H., Cui, J., Zhao, Y., & Gao, F. (2024). Non-linear and synergistic effects of built environment factors on older adults' walking behavior: An analysis integrating LightGBM and SHAP. *Transactions in Urban Data, Science & Technology*, *3*(1/2), 46–60. https://doi.org/10.1177/27541231241249866

Yang, Y. (2015). Interactions between psychological and environmental characteristics and their impacts on walking. *Journal of Transport & Health*, *2*(2), 195–198. https://doi.org/10.1016/J.JTH.2014.11.003

Yang, Y., & Diez-Roux, A. V. (2012). Walking Distance by Trip Purpose and Population Subgroups. *American Journal of Preventive Medicine*, *43*(1), 11–19. https://doi.org/10.1016/J.AMEPRE.2012.03.015

Yang, Y., & Diez-Roux, A. V. (2017). Adults' Daily Walking for Travel and Leisure: Interaction between Attitude Toward Walking and the Neighborhood Environment. *American Journal of Health Promotion*, *31*(5), 435–443. https://doi.org/10.1177/0890117116669278

Yu, C. Y. (2024). Factors Shaping Attitudes Toward Walking to the Grocery Store and Their Influence on Behaviors. *Findings*. https://doi.org/10.32866/001C.123352

Yuan, Q., Hu, Y., Steiner, R., Manini, T. M., & Bai, X. (2025). Mindful walks: Understanding the connection between street characteristics and recreational walking routes in older adults with cognitive concerns. *Cities*, *162*, 105969. https://doi.org/10.1016/J.CITIES.2025.105969

Zhang, Z. H., Wang, H. M., Pang, L., Fisher, T., & Yang, S. (2023). Comparisons of Built Environment Correlates of Walking in Urban and Suburban Campuses: A Case Study of Tianjin, China. *Land*, *12*(11). https://doi.org/10.3390/land12111972

Zhao, L., Shen, Z., Zhang, Y., & Ma, Y. (2019). The impact of the community built environment on the walking times of residents in a community in the downtown area of Fuzhou. *Sustainability (Switzerland)*, *11*(3). https://doi.org/10.3390/su11030691

Zhu, D., Song, D., Zhu, B., Zhao, J., Li, Y., Zhang, C., Zhu, D., Yu, C., & Han, T. (2024). Understanding complex interactions between neighborhood environment and personal perception in affecting walking behavior of older adults: A random forest approach combined with human-machine adversarial framework. *Cities*, *146*, 104737. https://doi.org/10.1016/J.CITIES.2023.104737

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