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The role of the neighbourhood environment in rural and urban areas

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The AI tools DeepL and Copilot were used for linguistic review in parts of this thesis.

Summary

Physical activity is widely recognised for its physical, mental, and social health benefits across the lifespan. Adolescence is an important period in life characterised by increasing independence and the development of lifelong health behaviours. Despite this, over 80% of adolescents globally do not meet the World Health Organization's (WHO) recommended levels of physical activity. Active travel, such as walking and cycling, is one of the four domains of active living and has recently gained attention across disciplines including sports science, public health, and urban and transport planning, due to its health benefits, potential for social development and contribution to sustainable transport. Active travel contributes significantly to overall physical activity levels, enables adolescents to travel independently within their neighbourhood and helps to reduce CO_2 emissions and air and noise pollution, therefore contributing to both individual and planetary health.

To promote physical activity and active travel, the WHO launched the Global Action Plan on Physical Activity, which aims to reduce physical inactivity by 15% worldwide by 2030. This global policy framework emphasises the importance of the environment in the context of active travel promotion. This link is also reflected in socioecological models, illustrating how individual, social, and environmental factors interact to influence health behaviours. In active travel frameworks for youth, both objective features of the built environment and perceptions of the environment, by adolescents and their parents, are identified as key influences on active travel behaviour.

International research has found that both people's perceptions of their environment - usually assessed through questionnaires - and the objectively measured built environment - often measured via Geographic Information Systems (GIS) - are associated with active travel, across different regions and age groups. However, findings remain fragmented, especially for adolescents, highlighting the need for a systematic synthesises of existing empirical studies.

In Germany, there is a significant gap in active school travel rates of adolescents across urbanisation levels. While over 50% of adolescents in cities walk or cycle to school, only 11% do so in rural areas. Despite the importance of environmental influences, active travel research in Germany has largely focused on socio-structural correlates such as age, sex, socioeconomic status and urbanisation level. There remains a significant gap in understanding how specific environmental characteristics relate to specific active travel modes such as walking and cycling across different urbanisation levels.

Walkability is a well-established concept that combines different built environment characteristics to measure how conducive a neighbourhood is to walking. In recent years, bikeability has quickly gained public and research interest; however, developed indices are still only tailored towards adults living in urban areas, which do not account for the needs of adolescents and those living in towns or rural areas.

This thesis therefore investigates the relationship between the built environment, perceptions of the environment and active travel in adolescents across urbanisation levels. It comprises three studies: a systematic review on perceived environmental influences on adolescent active travel; an empirical analysis of how perceived environmental characteristics relate to walking and non-motorised vehicle use across urbanisation levels in Germany; and a GIS-based investigation of bikeability characteristics associated with cycling to school in different urban and rural contexts.

The **first paper** (see chapter 2) systematically reviewed and synthesised studies examining the relationship between the perceived environment and active travel in adolescents. Specifically, it investigated how different environmental features relate to active travel and whether adolescents' and parents' perceptions differ in their influence. The review identified 51 studies and synthesised them using an effect direction plot for quantitative analysis and a narrative synthesis to highlight context-dependent findings. The analysis found convincing evidence that shorter distances to destinations are positively associated with active travel. Additional possible associations were found for traffic safety, walking and cycling infrastructure, aesthetics, street connectivity, and overall perceived environment scores. The narrative synthesis indicated that both adolescents' and parents' perceptions were associated with active travel and that safe infrastructure may be more relevant for girls, whereas accessibility may be more relevant for boys. These findings underscore the significance of accessible destinations, safe walking and cycling infrastructure, and the role of both adolescents' parents' perceptions. However, the review also identified important research gaps, such as the limited focus on rural areas, the lack of differentiation between travel modes (e.g. walking vs. cycling), and a predominant emphasis on school commutes. These gaps informed the development of the second paper.

The **second paper** (see chapter 3) assessed which perceived environment characteristics relate to walking and non-motorised vehicle use across urbanicity levels in a German-wide sample of adolescents. It utilised pooled data from waves 2 and 3 of the MoMo Study, a study that assesses motor performance, physical activity, health, and their determinants in children and adolescents aged 4-17 years in Germany. Twelve different environment perceptions were related to walking and non-motorised vehicle use in cumulative link mixed models nested within rural areas, small towns, medium-sized towns and cities. The results indicate that not only the environment perceptions

differ between urbanity levels, but also their relationship with active travel is context-dependent - both in terms of urbanity as well as in terms of the active travel mode. For instance, in rural areas and small towns, a pleasant neighbourhood and access to shops were linked to non-motorised vehicle use, while in more urban areas, the presence of cars was negatively associated with such travel. Notably, only the presence of public sports facilities was consistently associated with active travel across all contexts, suggesting their importance as accessible and important destinations for adolescents. These findings highlight the need to consider walking, cycling, and other non-motorised vehicle use as distinct behaviours influenced by different environmental factors, and to tailor active travel promotion strategies to specific urban and rural contexts.

The **third paper** (see chapter 4) focused on built environment characteristics and cycling in different urbanisation contexts. In particular, its aims were to identify and operationalise bikeability characteristics relevant to adolescents using open GIS data and assess their relationship with cycling to school with regard to different travel distances in cities, towns and rural areas in Germany. Three types of street infrastructure, five accessibility measures, and hilliness were derived from the literature as relevant bikeability characteristics. Linking these indicators to cycling-to-school data from the MoMo Study revealed distinct patterns across urbanisation levels. In both cities and towns, the presence of safe residential streets was positively associated with cycling, whereas separated cycling infrastructure was particularly important in towns. Access to destinations such as outdoor sports facilities, shops, and schools within a 4-16-minute cycling radius was linked to higher cycling rates, especially in towns. These findings underscore the need for safe cycling infrastructure and accessible places, which may require different solutions in cities, towns and rural areas. The study also showcases how open GIS data and machine learning approaches for data analysis can reveal patterns that built the foundation for the development of a bikeability index for adolescents.

This thesis contributes to the state of science in multiple ways: *First*, it provides a comprehensive synthesis of existing evidence on the relationship between different characteristics of the perceived environment and active travel in adolescents and identifies key research gaps. *Second*, it addresses these research gaps, namely the distinction between active travel modes, the inclusion of data across different urbanisation levels and the inclusion of active travel data beyond school commutes in a large German-wide sample. It demonstrates the context-dependency of environmental characteristics for different active travel modes and urbanisation levels. *Third*, it explores the concept of bikeability in an adolescent population by linking open GIS data with cycling data from the MoMo Study. A machine learning data analysis approach provided novel insights into how different cycling infrastructure and accessibility characteristics relate to cycling in cities, towns and rural areas, laying the groundwork for future research in this area.

This thesis is grounded on established frameworks in the physical activity and active travel context and uses large data sets to generate generalisable findings on the relationship between perceived and built environment and active travel across urban and rural contexts. Future research should build on these findings by examining the psychological mechanisms, such as attitudes and habits, that mediate the relationship between environmental factors and active travel behaviour. To enhance the impact of active travel research across disciplines such as urban and transport planning, researchers should more explicitly target and advocate for specific travel modes like walking and cycling, and emphasise their health benefits in the education of professionals outside the public health domain. Additionally, emerging societal and technological developments are changing the active travel and its research landscape. The influence of new means of transport, such as e-bikes and e-scooters, should be closely monitored in order to identify opportunities and threats for active travel promotion. Advances in methodology, such as machine learning approaches to process information from street view imagery and the growing availability of open GIS data sets, may help to further understand the role of the environment for active travel.

Zusammenfassung

Körperliche Aktivität ist für ihre umfassenden positiven Auswirkungen auf die physische, psychische und soziale Gesundheit über die gesamte Lebensspanne hinweg bekannt. Die Adoleszenz ist eine wichtige Lebensphase, die durch zunehmende Unabhängigkeit und die Entwicklung lebenslanger Gesundheitsverhalten gekennzeichnet ist. Dennoch erreichen weltweit über 80% der Jugendlichen den von der Weltgesundheitsorganisation (WHO) empfohlenen Umfang für körperliche Aktivität nicht. Die aktive Mobilität, wie z. B. zu Fuß gehen und Rad fahren kann zu einem aktiven Lebensstil beitragen und wird in den letzten Jahren aufgrund der gesundheitlichen Vorteile, des Potenzials für die soziale Entwicklung und des Beitrags zu nachhaltiger Mobilität in verschiedenen Disziplinen wie der Sportwissenschaft, Public Health sowie Stadt- und Verkehrsplanung zunehmend thematisiert. Aktive Mobilität trägt signifikant zum allgemeinen Bewegungsniveau bei, ermöglicht Jugendlichen, sich frei und unabhängig in ihrer Nachbarschaft zu bewegen und kann CO_2-Emissionen, Luftverschmutzung und Lärmbelastung reduzieren, wodurch sowohl die individuelle als auch die planetare Gesundheit gefördert wird.

Um die körperliche Aktivität und aktive Mobilität zu fördern, hat die WHO den „Global Action Plan on Physical Activity“ ins Leben gerufen, dessen Ziel es ist, die körperliche Inaktivität bis 2030 weltweit um 15% zu reduzieren. Dieses globale Strategiepapier betont die Bedeutung der Bewegungsumwelt für die Förderung von aktiver Mobilität. Dieser Zusammenhang spiegelt sich auch in sozioökologischen Modellen wider, die veranschaulichen, wie individuelle, soziale und umweltbezogene Faktoren zusammenwirken und so das Aktivitätsverhalten beeinflussen. In Modellen, die die aktive Mobilität von Kindern und Jugendlichen erklären, werden sowohl die bauliche Umwelt als auch subjektive Wahrnehmung derselben durch Jugendliche und deren Eltern als wichtige Einflussfaktoren für das aktive Mobilitätsverhalten identifiziert.

Internationale Forschungsergebnisse zeigen Zusammenhänge zwischen verschiedenen Merkmalen der wahrgenommenen und gebauten Umwelt und aktiver Mobilität in unterschiedlichen regionalen Kontexten und über die gesamte Lebensspanne. Dabei wird die wahrgenommene Umwelt in der Regel durch standartisierte Fragebögen und die gebaute Umwelt mithilfe von geografischen Informationssystemen (GIS) erfasst. Die Ergebnisse für Jugendliche sind jedoch uneinheitlich, weshalb eine systematischen Synthese bestehender empirischer Studien benötigt wird, um den Forschungsstand adäquat darzustellen.

In Deutschland zeigen sich deutliche Unterschiede im aktiven Mobilitätsverhalten von Jugendlichen, je nachdem, ob sie in städtischen oder ländlichen Gebieten wohnen. Das zeigt sich besonders beim Schulweg: Während über 50% der Jugendlichen in Städten zu Fuß oder mit dem Fahrrad zur Schule kommen, sind es in ländlichen Regionen lediglich 11%. Trotz der Bedeutung umweltbezogener Einflussfaktoren konzentriert sich die Forschung zu aktiver Mobilität in Deutschland bislang überwiegend auf soziostrukturelle Merkmale wie Alter, Geschlecht, sozioökonomischen Status und Urbanisierungsgrad. Allerdings fehlen wichtige Informationen darüber, wie die Wahrnehmung bestimmter Umweltmerkmale mit unterschiedlichen Formen aktiver Mobilität zusammenhängt und ob diese Zusammenhänge sowohl in ländlichen als auch in städtischen Gebieten gleichermaßen bestehen.

Walkability ist ein etabliertes Konzept, das verschiedene Merkmale der gebauten Umwelt kombiniert, um zu bewerten, wie fußgängerfreundlich ein Wohnumfeld ist. In den letzten Jahren hat auch das Konzept der Bikeability, das analaog zur Walkability die Fahrradfreundlichkeit abbilden soll, zunehmend an gesellschaftlicher und wissenschaftlicher Relevanz gewonnen. Bestehende Indizes sind bisher nur für Großstädte entwickelt worden und berücksichtigen weder die Bedürfnisse von Jugendlichen noch die Besonderheiten mittel- und kleinstädtischer oder ländlicher Räume.

Diese Dissertation untersucht daher den Zusammenhang zwischen der gebauten sowie wahrgenommenen Umwelt und aktiver Mobilität von Jugendlichen in städtischen und ländlichen Gebieten. Sie umfasst drei Studien: eine systematische Übersichtsarbeit zu wahrgenommenen Umweltfaktoren und aktiver Mobilität bei Jugendlichen; eine empirische Analyse des Zusammenhangs zwischen Umweltwahrnehmungen und dem Gehen bzw. der Nutzung nicht-motorisierter Fortbewegungsmittel in städtischen und ländlichen Gebieten in Deutschland; sowie eine GIS-basierte Untersuchung von Bikeability-Merkmalen und deren Zusammenhang mit dem Schulweg per Rad in unterschiedlichen urbanen und ländlichen Kontexten.

Die **erste Studie** (siehe Kapitel 2) fasst den Forschungsstand zu Zusammenhängen zwischen der wahrgenommenen Umwelt und aktiver Mobilität bei Jugendlichen systematisch zusammen. Untersucht wurde insbesondere, wie verschiedene Umweltmerkmale mit aktiver Mobilität zusammenhängen und ob sich die Wahrnehmungen von Jugendlichen und Eltern unterschiedlich auswirken. Insgesamt wurden 51 Studien identifiziert und mithilfe eines Effect Direction Plots quantitativ sowie durch eine narrative Synthese qualitativ mit Kontextbezug ausgewertet. Die Analyse zeigte, dass kürzere Distanzen durchweg positiv mit aktiver Mobilität assoziiert sind. Weitere mögliche Zusammenhänge zeigten sich für Verkehrssicherheit, Geh- und Radinfrastruktur, Ästhetik, Straßenvernetzung und allgemeine Umweltindizes. Ergebnisse der narrativen Synthese deuteten darauf hin, dass sowohl die Wahrnehmungen der Jugendlichen selbst als auch die der Eltern mit der aktiven Mobilität von Jugendlichen zusammenhängen. Dabei scheinen sichere Infrastruktur insbesondere für Mädchen und eine gute Erreichbarkeit verschiedener Orte eher für

Jungen relevant zu sein. Die Ergebnisse unterstreichen die Bedeutung erreichbarer Orte, sicherer Geh- und Radinfrastruktur sowie die Rolle Umweltwahrnehmungen sowohl von den Jugendlichen als auch von den Eltern. Gleichzeitig wurden Forschungslücken identifiziert, etwa die geringe Betrachtung ländlicher Räume, die fehlende Differenzierung zwischen aktiven Mobilitätsformen (z.B. Gehen vs. Radfahren) und die mangelnde Berücksichtigung von Wegen abseits der Schulmobilität. Diese Forschungslücken wurden in der zweiten Studie aufgegriffen.

Die **zweite Studie** (siehe Kapitel 3) untersucht, welche wahrgenommenen Umweltmerkmale mit dem Gehen und der Nutzung nicht-motorisierter Fortbewegungsmittel in städtischen und ländlichen Gebieten zusammenhängen. Als Datengrundlage dienten gepoolte Daten der Wellen 2 und 3 der MoMo-Studie, einer deutschlandweiten Studie, die die motorische Leistungsfähigkeit, körperliche Aktivität, Gesundheit und deren Einflussfaktoren bei Kindern und Jugendlichen im Alter von 4 bis 17 Jahren erhebt. Zwölf wahrgenommene Umweltmerkmale wurden mithilfe von Cummulative Link Mixed Models analysiert, die separat für ländliche Regionen, Kleinstädte, Mittelstädte und Großstädte berechnet wurden. Die Ergebnisse zeigten, dass sich nicht nur die wahrgenommene Umwelt zwischen den Urbanisierungsgraden unterscheidet, sondern auch deren Zusammenhang mit aktiver Mobilität kontextabhängig ist – sowohl in Bezug auf den Urbanisierungsgrad als auch auf die jeweilige Mobilitätsform. So waren in ländlichen Regionen und Kleinstädten ein angenehmes Wohnumfeld und die Erreichbarkeit von Geschäften mit der Nutzung nicht-motorisierter Fortbewegungsmittel assoziiert, während in urbaneren Gebieten die Präsenz von Autos negativ mit dieser Mobilitätsform zusammenhing. Auffällig war, dass lediglich das Vorhandensein öffentlicher Sportstätten in allen Kontexten positiv mit aktiver Mobilität assoziiert war, was ihre besondere Bedeutung für Jugendliche unterstreicht. Die Ergebnisse verdeutlichen die Notwendigkeit, Gehen, Radfahren und andere Formen nicht-motorisierter Mobilität als separate Mobilitätsformen zu betrachten, für die auch in Abhängigkeit vom Urbanisierungsgrad unterschiedliche Umweltwahrnehmungen von Relevanz sind. Entsprechende Ansätze zur Förderung aktiver Mobilität müssen also immer auf den Kontext angepasst werden.

Die **dritte Studie** (siehe Kapitel 4) untersucht Bikeability-Merkmale der gebauten Umwelt und den Zusammenhang dieser Merkmale mit dem Radfahren in städtischen und ländlichen Gebieten. Ziel war es, relevante Umweltmerkmale für eine fahrradfreundliche Umgebung für Jugendliche in der aktuellen Forschungsliteratur zu identifizieren, diese mithilfe frei verfügbarer GIS-Daten zu operationalisieren und ihren Zusammenhang mit dem Radfahren zur Schule in Großstädten, Mittel- und Kleinstädten sowie ländlichen Regionen zu analysieren. Drei Arten von Straßeninfrastruktur, fünf unterschiedliche Orte (z.B. Schulen, Geschäfte, Parks) sowie die Topografie wurden aus der Literatur als relevante Bikeability-Merkmale für Jugendliche abgeleitet. Die Verknüpfung dieser Merkmale mit Radfahrdaten aus der MoMo-Studie zeigte, dass unterschiedliche Merkmale mit dem Radfahren in Groß-, Mittel- und Kleinstädten zusammenhängen. In Großstädten sowie Mittel- und Kleinstädten war das Vorhandensein sicherer Wohnstraßen positiv mit dem

Radfahren assoziiert, während getrennte Radinfrastruktur insbesondere in Mittel- und Kleinstädten eine wichtige Rolle spielte. Die Erreichbarkeit von bspw. Sportstätten, Geschäften und Schulen innerhalb eines 4- bis 16-minütigen Radfahr-Radius war mit einem Schulweg per Rad assoziiert, besonders in Klein- und Mittelstädten. Die Ergebnisse unterstreichen die Bedeutung sicherer Radinfrastruktur und die Erreichbarkeit relevanter Orte, die je nach Urbanisierungsgrad unterschiedlich ausgeprägt ist. Zudem zeigt die Studie, wie frei verfügbare GIS-Daten und maschinelles Lernen genutzt werden können, um Muster zu identifizieren, die zur Entwicklung eines Bikeability-Index für Jugendliche genutzt werden können.

Diese Dissertation trägt auf mehreren Ebenen zum wissenschaftlichen Fortschritt beim Thema aktive Mobilität bei. *Erstens* bietet sie eine umfassende Synthese bestehender Evidenz zu Zusammenhängen zwischen verschiedenen Merkmalen der wahrgenommenen Umwelt und aktiver Mobilität bei Jugendlichen und identifiziert zentrale Forschungslücken. *Zweitens* adressiert sie diese Lücken – insbesondere die Differenzierung zwischen Gehen und anderen nicht-motorisierten Fortbewegungsmitteln, die Berücksichtigung städtischer und ländlicher Gebiete sowie die Einbeziehung des Mobilitätsverhaltens jenseits des Schulwegs – anhand einer großen deutschlandweiten Stichprobe. Sie zeigt die Kontextabhängigkeit umweltbezogener Einflussfaktoren auf verschiedene Formen aktiver Mobilität unter Berücksichtigung der Urbanisierungsgrade auf. *Drittens* wird das Konzept der Bikeability erstmals auf eine jugendliche Population angewendet, indem frei verfügbare GIS-Daten mit Radfahrdaten aus der MoMo-Studie verknüpft werden. Ein maschinelles Lernverfahren ermöglichte neue Einblicke in die Bedeutung verschiedener Infrastruktur- und Erreichbarkeitsmerkmale für das Radfahren in urbanen und ländlichen Kontexten und bildet die Grundlage für weiterführende Forschung in diesem noch jungen Forschungsbereich.

Diese Dissertation bedient sich etablierter theoretischer Modelle, die die körperliche Aktivität und das aktive Mobilitätsverhalten erklären, und nutzt umfassende Datensätze, um generalisierbare Erkenntnisse über den Zusammenhang zwischen wahrgenommener und gebauter Umwelt sowie aktiver Mobilität in urbanen und ländlichen Kontexten zu gewinnen. Zukünftige Forschung sollte auf diesen Ergebnissen aufbauen, indem sie zusätzlich psychologische Mechanismen wie Einstellungen und Gewohnheiten untersucht, die den Zusammenhang zwischen Umweltfaktoren und aktivem Mobilitätsverhalten moderieren. Um die Sichtbarkeit der Forschung zu aktiver Mobilität auch in Disziplinen abseits der Sportwissenschaft und Public Health, also z.B. in der Stadt- und Verkehrsplanung zu erhöhen, sollten Forschende gezielter spezifische Mobilitätsformen wie Gehen und Radfahren untersuchen. In diesem Kontext sollen auch deren gesundheitliche Vorteile in der Ausbildung von Fachkräften außerhalb des Public-Health-Bereichs stärker thematisiert werden. Darüber hinaus verändern gesellschaftliche und technologische Entwicklungen die Mobilitätslandschaft und die zu ihrer Untersuchung herangezogenen Forschungsmethoden. Der Einfluss neuer Verkehrsmittel, wie E-Bikes und E-Scooter, sollte von der Wissenschaft beobachtet werden, um zukünftige Chancen und Risiken zur Förderung aktiver Mobilität zu identifizieren. Die Weiterentwicklung von Methoden, etwa der Einsatz von Machine-Learning-Verfahren zur Auswertung von Bilddaten auf Straßenebene und die zunehmende Verwendung frei verfügbarer GIS-Datensätze, kann dazu beitragen, die Rolle der Umwelt für das aktive Mobilitätsverhalten noch besser zu verstehen.

Preface

Parts of this thesis have been published in peer-reviewed journals. The following chapters can be read independently from each other:

Chapter 2:
Klos, L., Eberhardt, T., Nigg, C., Niessner, C., Wäsche, H., & Woll, A. (2023). Perceived physical environment and active transport in adolescents: A systematic review. *Journal of Transport & Health, 33*, 101689. https://doi.org/10.1016/j.jth.2023.101689

Chapter 3:
Klos, L., Fiedler, J., Nigg, C., Niessner, C., Wäsche, H., & Woll, A. (2024). Walking and non-motorized vehicle use in adolescents: The role of neighborhood environment perceptions across urbanization levels. *German Journal of Exercise and Sport Research, 54*(1), 145–155. https://doi.org/10.1007/s12662-023-00931-5

Chapter 4:
Klos, L., Lazarides, C., Pedrick-Case, R., Fry, R., Wäsche, H., Niessner, C., & Woll, A. (under review). Groundwork for adolescent bikeability assessment in Germany: An open GIS and regularised regression approach across cities, towns and rural areas. Submitted to *Transportation Research Interdisciplinary Perspectives*.

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1 Introduction

The introduction is divided into three parts: The relevance of active travel and the role of the environment is first presented empirically, anchored theoretically and further elaborated in the German context. The second part presents the current state of research on this topic and, in particular, the measurement methods of active travel and the perceived and built environment, as well as the concepts of walkability and bikeability. This is followed by the resulting research gaps and the corresponding research questions of this thesis. The final section briefly outlines the methods of the individual studies included.

1.1 Relevance

Active travel, such as walking and cycling, has attracted growing attention in research and among professionals in public health, urban planning, and transport planning as a way to promote healthier and more sustainable mobility. In several European cities (e.g. Copenhagen, Paris, Barcelona), extensive urban transformations take place to create safer and more appealing environments that encourage active travel. This thesis contributes to this emergent research topic, investigating the relationship between the built environment, its perception and active travel in adolescents living in urban and rural areas.

The following sections first address adolescents' physical (in)activity and how active travel may contribute to healthier physical activity levels. Next, different theoretical models and frameworks are presented that aim to explain the relationship between the built environment, its perceptions and active travel behaviour. The last paragraph introduces findings of active travel studies on adolescents in Germany.

1.1.1 Physical activity and health: Adolescents' inactive lifestyles as an invisible health threat

Sufficient physical activity is important for healthy development across the lifespan. Its benefits on physical, mental and social health are well-documented (Bouchard et al., 2012). Although adolescence is in general considered a period of low immediate health risks, it is an important developmental phase during which lifelong health behaviours are established (van Sluijs et al., 2021). Yet, over 80% of adolescents worldwide do not meet the recommended physical activity levels, placing them at increased risk for preventable, non-communicable diseases such as obesity and type II diabetes (Guthold et al., 2020).

Historically, physical activity promotion focused on structured exercise and sports during leisure time. However, since the early 2000s, researchers became more and more interested in physical activity and inactivity across all living domains, namely recreational activities (e.g. exercise), household and occupational activities, as well as active travel (Sallis et al., 2006). This shift was not only motivated by trying to reach the people in their living environments to remove barriers to exercise but also by research that suggests that any amount of physical activity, regardless of intensity, provides substantial health benefits. Conversely, prolonged sedentary behaviour is associated with significant health risks (Ekelund et al., 2019). These findings are now also reflected in the World Health Organisation's (WHO) guidelines on physical activity and sedentary behaviour. The WHO recommends that adolescents engage in at least an average of 60 minutes of moderate-to-vigorous physical activity per day. In addition, they should do vigorous activities or those that strengthen muscles and bones at least three days a week and limit the amount of sedentary time (Bull et al., 2020).

1.1.2 Active travel: Health-enhancing physical activity "to go"

Active travel is one of the four living domains defined by Sallis et al. (2006), and especially children's and adolescents' active travel gained growing interest in both scientific and public health communities in recent years (Cook et al., 2022; Ji et al., 2022; Larouche, 2018). In this thesis, *active travel* refers to "travel in which the sustained physical exertion of the traveller directly contributes to their motion" (Cook et al., 2022, p. 154). Other terms such as *active transport* and *active mobility* are used interchangeably in the literature [1]. While this definition includes a wide

[1] The different chapters of this thesis may either use the terms active travel or active transport. The same applies to urbanicity and urbanisation levels as well as built and physical environment that can be used interchangeably.

range of active travel modes such as e-biking, scootering or skateboarding, most studies referenced throughout solely focus on walking and cycling as the most common active travel modes.

On average, using active travel modes contributes between 5 and 45 minutes of physical activity per day in children and adolescents (Prince et al., 2022). One great opportunity for regular physical activity through active travel for adolescents is the trip to and from school. It is estimated that an active commute to and from school accounts for approximately 48% of the recommended physical activity during school days (Campos-Garzón et al., 2023). A meta-analysis by Martin et al. (2016) found that more than one third of adolescents' moderate-to-vigorous physical activity on school days came from walking to and from school, highlighting the potential of active travel to improve physical activity levels. Active travel, and cycling in particular, is associated with better cardiovascular fitness (Henriques-Neto et al., 2020; Larouche, Saunders, et al., 2014) and protective against psychosomatic symptoms (Kleszczewska et al., 2020). Additionally, active travel to school is inversely associated with obesity (Martin-Moraleda et al., 2022).

On top of these individual health effects, active travel offers broader social, environmental and public health advantages. It encourages independent mobility, offering adolescents new opportunities for exploring their neighbourhood environment without accompanying adults, increasing their autonomy and supporting their personal development (Mitra, 2013). Further, replacing passive travel modes with active ones reduces local air and noise pollution and lowers carbon emissions, factors that contribute to climate change and negatively impact global health. As such, active travel is one of the few forms of physical activity that simultaneously promotes both individual and planetary health (Abu-Omar et al., 2023).

1.1.3 The role of the neighbourhood environment for physical activity and active travel

In the early 2000s, when research on the role of the neighbourhood environment for physical activity just started amidst the popular use of ecological models, it was estimated that this field of research would increase significantly in the next 5-10 years (Giles-Corti et al., 2005). Since then, a substantial body of evidence has emerged linking various neighbourhood characteristics to physical activity across different age groups, including children and adolescents (Ding et al., 2011), adults (McCormack & Shiell, 2011), and older adults (D. W. Barnett et al., 2017).

Guided by this evidence, the WHO launched the Global Action Plan on Physical Activity with the target of a 15% relative reduction in physical inactivity worldwide by 2030 (World Health Organization, 2018). The plan outlines four strategic objectives: *create active societies, create active systems, create active environments*, and *create active people*. It specifically highlights the need for a change in different structures, including the environment, e.g. by improving walking and cycling networks and strengthening road safety. Within the last 20 years, environmental approaches to promote health-enhancing physical activity have become a central focus both in research and practice. Their importance within a larger, interconnected system that includes individual behaviour, environmental factors and policy influences, is widely acknowledged (Bartholomew Eldredge et al., 2016).

1.1.3.1 An ecological perspective on physical activity and the environment

The core principle of ecological models is that behaviour is affected by various interconnected layers, ranging from individual to environmental factors. In the context of physical activity, Sallis et al. (2006) proposed a widely-recognised ecological model of the four domains of active living: active recreation, household activities, occupational activities, and active travel (see figure 1.1). Within this model, the active living domains represent physical activity behaviours that are influenced by individual-level characteristics (e.g. demographics, psychological factors) and the perceived environment (e.g. how convenient and safe it is to be physically active within those domains).

Beyond the individual and perceived environment, the model includes behaviour settings such as the home or school environment or neighbourhood, and their characteristics, including walkability, physical activity equipment, and aesthetics. At an even broader level lie the policy environments (e.g. urban planning regulations, traffic management, school policies). Finally, three overarching environmental dimensions, the information environment, the socio-cultural environment, and the natural environment, cut across all layers of the model.

While this model provides a comprehensive framework for understanding the multiple influences on physical activity, it remains heuristic in nature. It does not specify domain-specific correlates or causal pathways between levels, limiting the usefulness and explanatory power in terms of predictability or the formulation of verifiable hypotheses. In fact, the empirical evidence on the causal influence of specific neighbourhood characteristics on overall physical activity remains sparse (Kärmeniemi et al., 2018; McCormack & Shiell, 2011; Tcymbal et al., 2020).

Therefore, ecological models can serve as a solid overarching theoretical foundation, but more specific and more detailed models are needed to gain a deeper insight into the relation between the environment and physical activity (Giles-Corti et al., 2005; Sallis et al., 2006). Focusing on a single domain, such as active travel and its domain-specific environment characteristics (e.g. walking and cycling infrastructure), has yielded more consistent associations (Giles-Corti et al., 2005; McCormack & Shiell, 2011; Tcymbal et al., 2020).

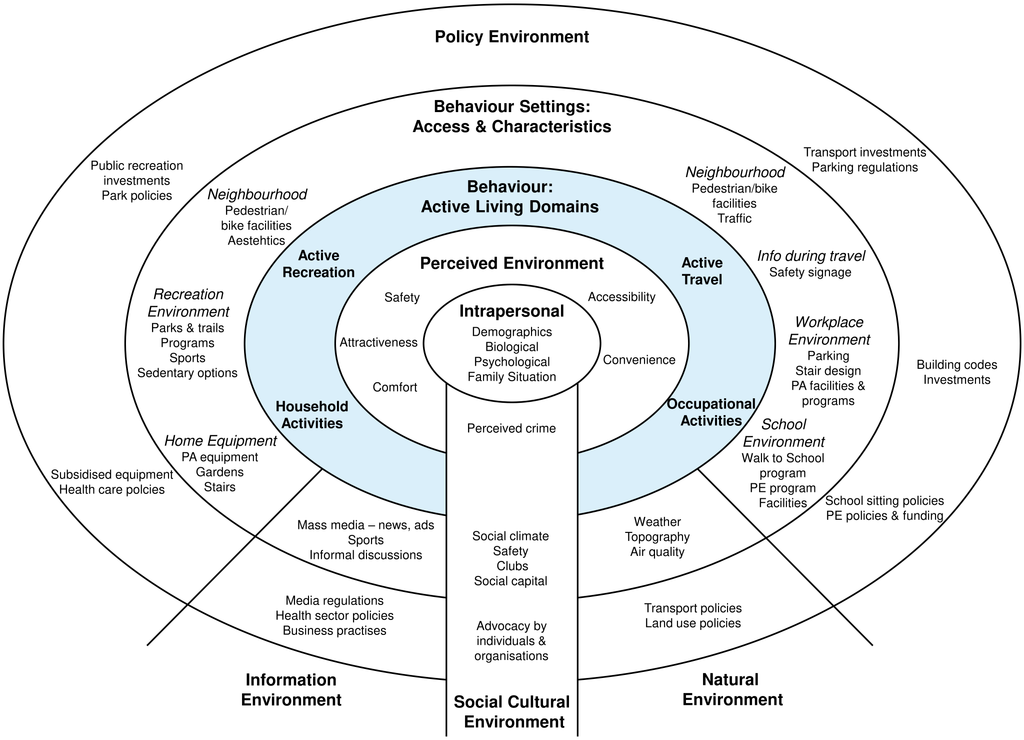

Figure 1.1: Ecological model of four domains of active living (adapted from Sallis et al., 2006)

1.1.3.2 Theoretical frameworks for youth's active travel

A wide range of theoretical models have been developed to explain active travel behaviour that vary in their focus on broader environmental or internal psychological processes, their travel context and target population (Götschi et al., 2017).

Over the last two decades, several models and frameworks were developed to explain children's and adolescents' active travel behaviour (McMillan, 2005; Mitra, 2013; Panter et al., 2008; Pont et al., 2011; M. L. Rahman, Moore, et al., 2020; Sirard & Slater, 2008). While many of these frameworks build on their predecessors, they introduce specific adaptations and extensions. Most focus solely on active travel to school (Mitra, 2013; Sirard & Slater, 2008), with some targeting specific age groups, such as primary school children (McMillan, 2005) and adolescents in secondary school (M. L. Rahman, Moore, et al., 2020), or additionally consider independent mobility as a secondary outcome (Mitra, 2013). Only two frameworks extend their frameworks to consider all active trips (Panter et al., 2008; Pont et al., 2009). Despite differences in focus and terminology, all these frameworks share a common emphasis on the relationship between the built environment, its perception, and active travel behaviour.

One particularly influential model is the Conceptual Framework for Youth's Active Travel by Panter et al. (2008). This framework integrates prior models and empirical findings on correlates of youth travel behaviour. As illustrated in figure 1.2, it consists of three main components: physical environmental factors, individual factors, and behavioural outcomes. It also includes moderators such as age, gender, trip distance, and broader external factors.

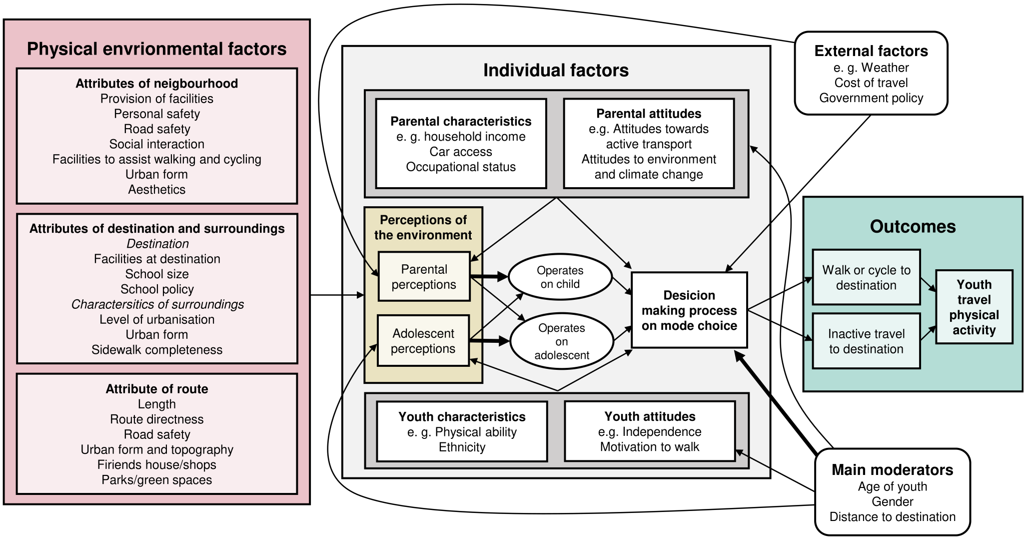

Figure 1.2: Conceptual Framework for Youth's Active Travel by Panter et al. (2008)

The physical environmental factors are divided into attributes of the neighbourhood, destination and route. Adolescents' and parents' individual characteristics and attitudes shape how they perceive these environment attributes. These environment perceptions are then evaluated in the decision-making process to choose the travel mode for the planned trip. Importantly, parents' influence on the decision decreases during adolescence as the adolescents themselves become more independent (Panter et al., 2008). This framework guided the development of research questions and the structure of this thesis.

1.1.3.3 Adolescents' active travel in Germany in the rural-urban context

Germany's population is relatively evenly spread across different levels of urbanisation: around one-third live in large cities with more than 100,000 inhabitants, about one-quarter each in small towns (5,000–19,999 inhabitants) and medium-sized towns (20,000–99,999 inhabitants), and roughly one in seven people live in rural areas with fewer than 5,000 inhabitants (Statistisches Bundesamt, 2024). Between those different urbanisation levels, there are several characteristic differences, such as population density, settlement patterns, traffic infrastructure, and access to different places of daily living, such as supermarkets, shops, and recreational facilities (Assmann, 2023).

These contextual differences shape adolescents' opportunities for active travel. A key example is active travel to and from school. Whereas most primary schools can be reached by foot or bicycle in Germany, secondary schools are often located in more centralised areas. As a result, the transition to secondary school typically leads to a decline in active travel, especially in rural regions (Klos, Burchartz, et al., 2023). For instance, the median walking time to the nearest secondary school is 71–90 minutes in very rural areas, compared to 42 minutes in urban areas. Similarly, the median cycling duration is 23-29 minutes and 14 minutes in very rural and urban areas, respectively (Neumeier, 2018). These urban-rural differences, including the limited access to schools by foot or bike, are also reflected in the school travel behaviour.

According to national data from the COMO-Study, only 11% of adolescents in rural areas walk or cycle to school, compared to over 50% in cities (see figure 1.3; Klos et al., 2025). However, this does not imply that those who do not walk or cycle to school are entirely inactive. A large share of adolescents, especially in more rural areas, use public transport, which often includes short active trips, e.g. walking to the bus stop (Durand et al., 2016; Ermagun & Levinson, 2017; Voss et al., 2015). This active part takes on average 8.5 minutes, while walking and cycling to school take 12.1 and 14.7 minutes, respectively (Klos et al., 2025). Looking at temporal trends, active school travel rates did not change substantially in Germany over the last two decades (Reimers et al., 2021), though descriptive, unweighted data indicate that cycling may have increased in cities (Klos et al., 2025; Reimers et al., 2013).

Beyond school travel, 70% of adolescents in Germany report walking or cycling to other destinations such as visiting friends, shopping, or leisure activities. The urbanisation level is not relevant for active travel to these destinations, except for shopping: Adolescents in rural areas are less likely to walk and more likely to use motorised transport for shopping trips (Marzi et al., 2023).

In summary, while active travel is generally common among German adolescents, urbanisation levels significantly influence travel patterns, particularly for school commutes. Research has primarily focused on demographic and contextual correlates of active school travel, including age,

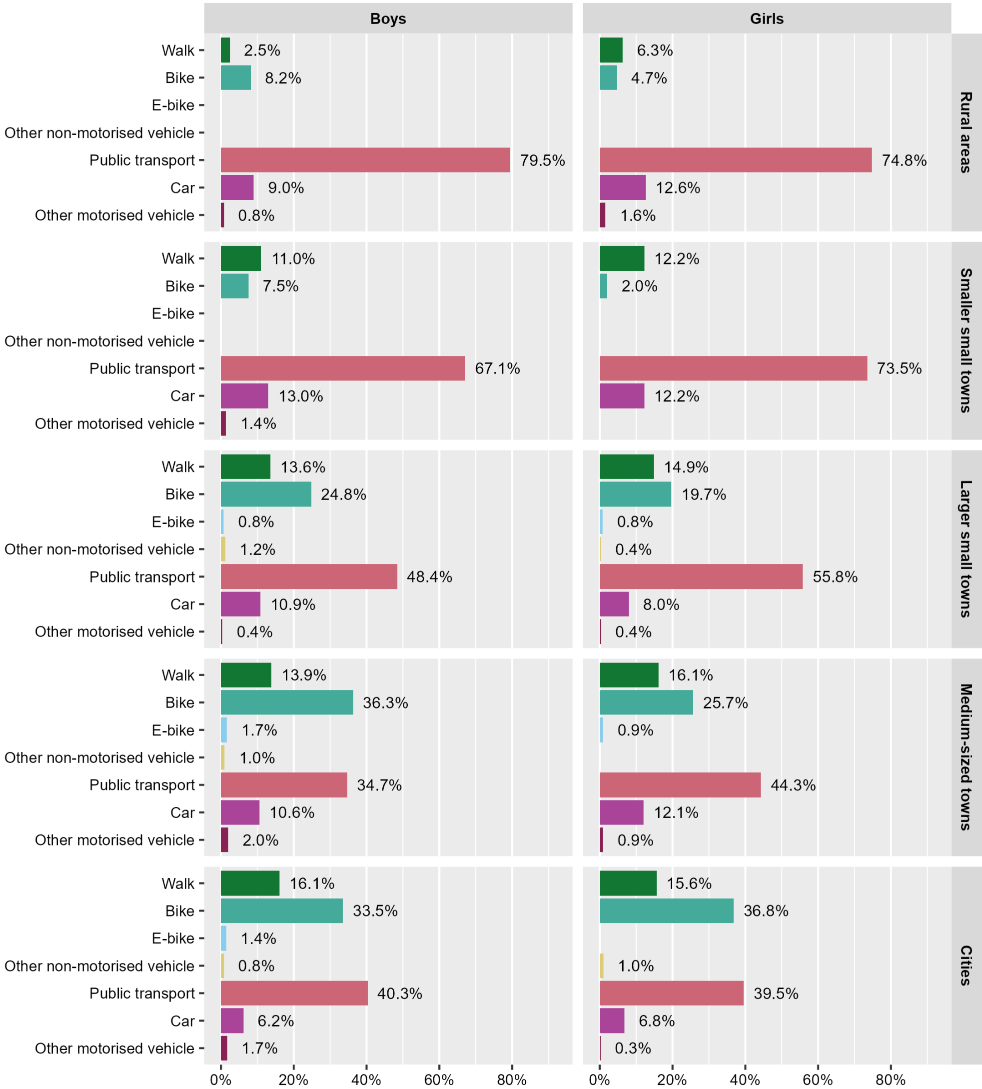

Figure 1.3: School travel mode to secondary school across different urbanisation levels (adapted from Klos et al., 2025)

sex, socioeconomic status, migration background, and urbanisation level (Klos et al., 2025; Klos, Burchartz, et al., 2023; Marzi et al., 2023; Reimers et al., 2013, 2021; Wex et al., 2023). However, there is a significant gap in understanding how specific environmental characteristics influence the choice of active travel modes such as walking and cycling across different urban and rural contexts (Larouche et al., 2015).

1.2 State of research

The first two sections provide an overview of common assessment methods of active travel and the perceived and built environments. It follows a broad summary of the state of research regarding the relationship between the perceived and built environment and active travel, including a brief introduction to the concepts of walkability and bikeability.

1.2.1 Assessing active travel

Active travel can be measured in several ways, depending on the research discipline and objectives. Questionnaires are the most commonly used method, particularly in studies examining individual, social, and environmental correlates of active travel (Evans et al., 2022; Klos, Eberhardt, et al., 2023; Pont et al., 2009). Most instruments for school-aged children and adolescents only focus on the mode of travel to and from school (e.g. walking, cycling, bus, or car). As school travel is a highly routinised behaviour, such measures are generally considered highly valid and reliable (Larouche, Oyeyemi, et al., 2014). Nevertheless, a lot of studies assess school travel without using questionnaires that were assessed for validity and reliability (Herrador-Colmenero et al., 2014). Fewer questionnaires ask for the frequency or duration of school trips, and even fewer include travel to destinations beyond school (Larouche, Oyeyemi, et al., 2014). In addition to self-reports, objective methods such as a combination of accelerometers and Global Positioning Systems (GPS) are used to assess the intensity and energy expenditure of active travel (e.g. Chaix et al., 2014). GPS can also provide additional data on trip origin, destination, and route travelled, enabling more detailed analyses of active travel behaviour. Recently, big data approaches using commercial cycling apps have gained popularity for analysing cycling behaviour (Romanillos et al., 2016). However, these data sources are limited by user bias and a lack of contextual information (e.g. demographic or social characteristics). A more detailed discussion on new technologies to measure active travel can be found in section 5.3.3.

1.2.2 Assessing perceived and built environments

According to the framework of Panter et al. (2008), the environment can be assessed from two perspectives: The perceived environment, meaning the subjective representation of our surroundings, and the built environment, which includes both man-made and natural environments.

The perceived environment is typically assessed through questionnaires. One widely used tool is the Neighbourhood Environment Walkability Scale (NEWS) (Rosenberg et al., 2009), which has been translated and adapted for various populations (Almeida et al., 2021). Another example is the ALPHA environment questionnaire that was developed specifically for the European context (Spittaels et al., 2009). It assesses factors such as land use mix-diversity, traffic and crime safety, neighbourhood aesthetics, walking and cycling facilities, street connectivity, land use mix-access, residential density, and recreational facilities.

The built environment is most commonly measured via Geographic Information Systems (GIS) (Smith et al., 2021). "A GIS is a computer system for capturing, storing, querying, analysing, and displaying geospatial data" (Chang, 2019, p. 1). It is used to describe the location and attributes of built and natural spatial features such as roads, houses, rivers or forests. In the context of active travel research, it can be used to measure the distance to school, population and intersection density, and land use mix and then linked to active school travel data (Ikeda, Stewart, et al., 2018). The availability of geospatial data has increased significantly with the rise of volunteered geographic information and open data platforms like OpenStreetMap (Yan et al., 2020). An alternative to GIS is the use of audit tools, such as the Microscale Audit of Pedestrian Streetscapes (MAPS), which allow detailed, on-site assessments of specific areas (Millstein et al., 2013). While these tools can provide high-quality data, they are resource-intensive, especially when mapping larger areas.

Empirical studies show a low agreement between the perceived and built environment measures (Orstad et al., 2017). Both types of measures are related to physical activity (Orstad et al., 2017) and active travel modes such as cycling (Ma & Dill, 2015). In accordance with the previously introduced frameworks, relationships between the perceived environment and physical activity behaviours are stronger than those with the built environment (Panter et al., 2008). Although theoretically linked, perceived and built environments are distinct constructs and should both be considered to fully understand their influence on active travel (Bailey et al., 2014; Orstad et al., 2017).

1.2.3 From environment correlates of active travel to walkability and bikeability

Active travel occurs in all life stages as is reflected in numerous studies that focus on the relation between perceived and built environment characteristics and active travel in children (D'Haese et al., 2015; Ikeda, Hinckson, et al., 2018), adolescents (Klos, Eberhardt, et al., 2023), young to middle-aged adults (L. Wang & Wen, 2017) and older adults (Cerin et al., 2017). Across the lifespan, associations between various environment characteristics, both perceived and objective, and active travel are found.

Historically, the assessed environment characteristics examined in the context of physical activity and active travel mostly revolved around walkability, which refers to the extent to which the environment is friendly to people who walk (H. Wang & Yang, 2019). Many of the environmental assessment tools used in physical activity and active travel research were therefore originally developed with walkability as their central focus (Frank et al., 2010; Saelens et al., 2003). Among the most common perceived environment measures is the NEWS (Kerr et al., 2016; Klos, Eberhardt, et al., 2023). Intersection density, residential density and land use mix are used to assess walkability objectively in the context of active travel and physical activity research (Fonseca et al., 2022). However, the sole focus on walkability, especially in relation to other outcomes other than walking (e.g. physical activity and cycling), is criticised as being used beyond its original scope (Forsyth, 2015). In response, broader frameworks such as active living environments have emerged. These include natural, built, and social neighbourhood features that support physical activity and equitable access to health-promoting resources (Tobin et al., 2022), thereby expanding the scope beyond walking infrastructure and behaviour.

In recent years, another concept emerged that shifts the scope from walking to cycling (Castanon & Ribeiro, 2021), instead of broadening the scope. In contrast to walkability, bikeability aims to quantify perceived comfort and convenience and access to important destinations of cycleway networks (Lowry et al., 2012). While both walking and cycling are summarised as active travel, they differ significantly in terms of speed, range, infrastructure use, and safety concerns (Forsyth & Krizek, 2011). These different characteristics and requirements may even lead to conflicts between walking and cycling promotion (Forsyth, 2015; Forsyth & Krizek, 2011) as highly walkable and highly bikeable environments may look very different (Muhs & Clifton, 2016). Therefore, bikeability is an important addition to the conceptual landscape of active travel, as it captures the unique infrastructural, perceptual, and behavioural dimensions of cycling that are not adequately addressed by walkability measures.

Although there is no consensus on how to define and measure bikeability yet (Muhs & Clifton, 2016), existing bikeability indices usually include indicators for cycling infrastructure and road safety, accessibility of various locations and other environmental indicators such as the gradient of roads or air and noise pollution (Castanon & Ribeiro, 2021; Kellstedt et al., 2021; Valenzuela et al., 2022). While a fair amount of walkability research has been conducted in children and adolescents (Bruno et al., 2025) and across urban and rural contexts (Molina-García et al., 2020; Patel et al., 2025), there is a lack of bikeability research in children and adolescents (Paulusová & Sharmeen, 2024) and existing bikeability indices are limited to large cities (Kellstedt et al., 2021). Understanding and promoting cycling in those less densely populated areas has great potential, especially when compared to walking due to its greater range and therefore greater potential for accessibility (Forsyth & Krizek, 2011; Kircher et al., 2022).

To advance the field, future research should systematically examine both perceived and built environmental characteristics that influence different modes of active travel. Special attention should be given to adolescents and to diverse geographic contexts, including rural areas and towns, to ensure that active travel promotion strategies are inclusive and effective.

1.3 Research questions

This thesis includes three papers that address the above-mentioned research gaps. Two studies focus on the relationship between the perceived environment and active travel, while the third investigates the relationship between the built environment and cycling (see figure 1.4).

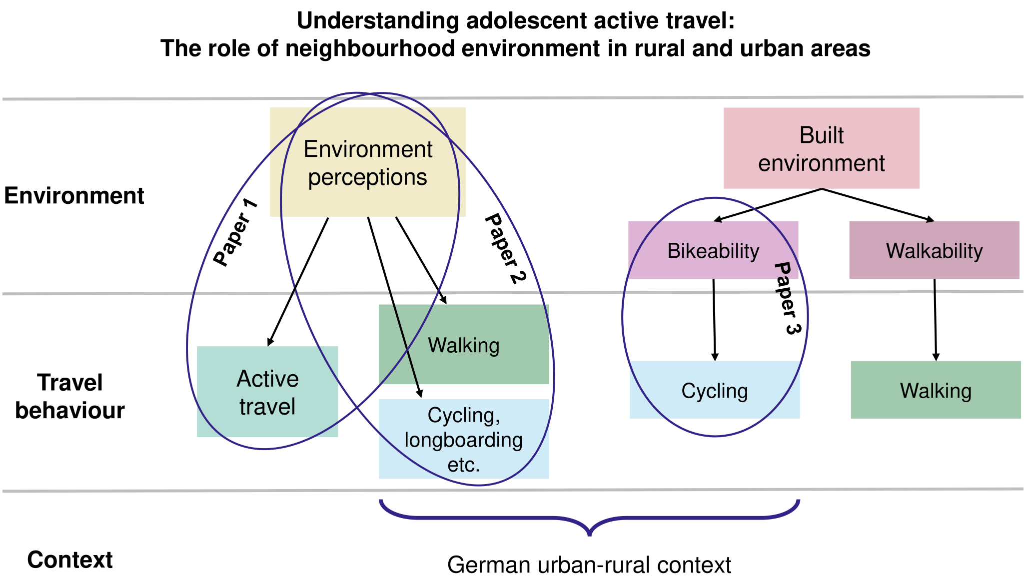

Figure 1.4: Overview of the papers included in this thesis

Although several reviews have examined the relationship between the perceived environment and active travel in primary school children (D'Haese et al., 2015; Ikeda, Hinckson, et al., 2018; Rothman et al., 2018), there is a lack of synthesis for this relationship in adolescents. According to the framework proposed by Panter et al. (2008), adolescents' own perceptions may be more influential in their travel decisions than those of their parents. However, this has only been empirically assessed in a few individual studies (Aranda-Balboa et al., 2021; Esteban-Cornejo et al., 2016; Grow et al., 2008; A. A. d. P. d. Silva et al., 2018). While many studies assessed the perceptions and their associations with active travel, their findings are not yet easily generalisable, particularly regarding specific characteristics of the perceived environment, such as traffic safety or walking and cycling infrastructure.

The first study of this thesis, "*Perceived physical environment and active transport in adolescents: A systematic review*", addresses the following research questions:

1. **Are perceived environment characteristics related to active travel in adolescents?**
2. **Are there differences in associations between adolescents' and parents' environment perceptions and active travel in adolescents?**

In addition to answering these research questions, the review revealed several key research gaps. First, most studies focus exclusively on active travel to school, not considering trips to other destinations, such as visits to friends or relatives, shops, or recreational facilities (Marzi et al., 2023). Second, study samples are mostly drawn from single, predominantly urban locations. Since neighbourhood characteristics, such as population and intersection density and access to destinations, vary significantly across urban and rural areas, perceptions of the environment are likely to differ as well (M. L. Rahman, Pocock, et al., 2020). To better understand how environmental perceptions influence active travel, research must include a range of urbanisation levels, from rural areas to cities. Third, few studies distinguish between active travel modes despite significant differences, e.g. between walking and cycling. Both have different street infrastructure requirements, operate at different travel speeds and are used to cover different distances and therefore need to be analysed separately (Forsyth & Krizek, 2011; van Dyck et al., 2010). Additionally, less common modes such as scootering, longboarding, or inline skating are often excluded, despite their contributions to physical activity and relevance for urban and transport planning (Cook et al., 2022).

The second study of this thesis, "*Walking and non-motorised vehicle use in adolescents: the role of neighbourhood environment perceptions across urbanisation levels*", addresses the following research questions:

1. **Which perceived environment characteristics are related to walking in adolescents in rural areas, small towns, medium-sized towns, and cities?**
2. **Which perceived environment characteristics are related to non-motorised vehicle use, including cycling, longboarding and others, in adolescents in rural areas, small towns, medium-sized towns, and cities?**

While the first two studies focus on the perceptions of the environment, the third study shifts attention to built environmental characteristics and contributes to the growing field of bikeability research. As outlined in section 1.2.3, existing bikeability indices are primarily designed for adults (Paulusová & Sharmeen, 2024) and are often limited to single urban areas (Castanon &

Ribeiro, 2021; Kellstedt et al., 2021; Muhs & Clifton, 2016; Valenzuela et al., 2022). To develop a bikeability index for adolescents, their specific requirements for a safe and convenient cycling environment must be considered. Increasing availability and quality of open GIS data enable new ways to link objective bikeability characteristics to cycling data. This way, a wide range of geographic contexts, from rural areas to cities, can be assessed to account for their specific environmental conditions and infrastructure (Molina-García et al., 2020). To develop a bikeability index tailored towards adolescents, bikeability characteristics need to be identified, operationalised, and examined in terms of their relevance across different geographic contexts. It is essential to first understand whether these characteristics are consistent across cities, towns, and rural areas, and how they relate to actual cycling behaviour within varying cycling distances. Rather than calculating a final index, this study lays the groundwork by exploring these relationships and assessing the feasibility of using open GIS data to capture adolescent-relevant bikeability features.

The third study of this thesis, "*Groundwork for adolescent bikeability assessment in Germany: An open GIS and regularised regression approach across cities, towns and rural areas*" addresses the following research questions:

1. **How can the bikeability characteristics for adolescents be operationalised in Germany using open GIS data?**
2. **How do the bikeability characteristics within different cycling distances relate to cycling to school in adolescents living in cities, towns and rural areas in Germany?**

1.4 Methods

To address the research questions outlined above, this thesis comprises three empirical papers that collectively examine the relationship between perceived and built environmental characteristics and active travel among adolescents. Each paper employs a distinct methodological approach - a systematic literature review, a survey-based analysis, and spatial modelling - which are described in detail in the following sections.

1.4.1 Paper 1: A systematic review on environment perceptions and active travel

The first paper of this thesis is a systematic review that synthesises evidence on the relationship between the perceived environment and active travel among adolescents. The review was pre-registered in PROSPERO (CRD42022307377) and conducted in accordance with PRISMA guidelines (Page et al., 2021) to ensure standardised reporting of methods and results. It includes quantitative studies published between May 2008 and February 2022 that examine associations between perceived environmental characteristics and measures of active travel in samples of adolescents aged 12 to 17 years.

Articles were identified through searches across six databases across various disciplines, including medicine and health (PubMed), transport (TRID), sports science (SPORTDiscus), and pedagogy (ERIC). To enhance efficiency and reduce screening errors, title and abstract screening was conducted using ASReview, an active machine learning tool that ranks titles and abstracts by relevance (van de Schoot et al., 2021). In addition, a snowball search was performed to identify additional relevant studies. The quality of all included articles was assessed using the NIH Quality Assessment Tool (National Institutes of Health, 2021).

The synthesis of results was conducted in two ways. First, a quantitative synthesis based on effect direction (Boon & Thomson, 2021) was carried out for different perceived environmental characteristics (e.g. distance to destinations, traffic safety, walking and cycling infrastructure) to find consistent and possible associations between those characteristics and active travel. Second, a qualitative synthesis explored the context of significant findings, such as differences between parents' and adolescents' perceptions, gender differences, distinctions between walking and cycling, and variations across regional contexts.

1.4.2 Paper 2: Environment perceptions and active travel in Germany in the MoMo Study

The second paper is based on data from the Motorik-Module (MoMo) Study, a nationally representative German study assessing physical fitness, physical activity, and their determinants in children and adolescents aged 4–17 years. Originally, MoMo was a module of the German Health Interview and Examination Survey for Children and Adolescents (KiGGS), led by the Robert Koch Institute, which enabled data linkage between the two studies. The first three cross-sectional cohorts were conducted between 2003 and 2017 (Woll et al., 2021). A longitudinal sample across the cohorts was also obtained from the baseline cohort and supplemented with new participants in wave 1 (Wagner et al., 2014). A final cohort (wave 3) was conducted independently of KiGGS between 2018 and 2022, incorporating core KiGGS health measures. Data collection for this cohort was interrupted by the COVID-19 pandemic, resulting in a split between a pre-pandemic sample with in-person assessments and a pandemic sample participating in an online survey and optional digital motor tests.

This paper uses data from MoMo wave 2 (2014–2017) and the pre-pandemic sample of wave 3 (2018–2021). Pooling these datasets increased statistical power, and due to standardised procedures and identical questionnaires, it removes the need for complex data harmonisation as required in meta-analyses (Deeks et al., 2024). The final sample included 3,976 adolescents aged 11–17 years (51.3% female). Perceptions of the environment were assessed using a validated questionnaire (Reimers et al., 2012), while walking and non-motorised vehicle use (e.g. cycling, longboarding) were measured using two 6-point Likert scales. Urbanicity was classified based on the population of the home municipality (Federal Institute for Research on Building, Urban Affairs and Spatial Development, n.d.). Sex, age, socioeconomic status, sample point, and cohort were included as confounders. A descriptive analysis of the sample and environmental perceptions across urbanicity levels was provided. To examine associations between perceived environment and active travel, four cumulative link mixed models were calculated for walking and four for non-motorised vehicle use, each stratified by urbanicity level (rural areas, small towns, medium-sized towns, and cities). Cumulative link models were used to handle the ordinal dependent variables, as requirements for a linear model approach were not met. Sample points were included as a random factor to account for the variation in active travel between municipalities across Germany.

1.4.3 Paper 3: Linking geographic information system and MoMo data to characterise bikeable neighbourhoods

The third paper aims to identify bikeability characteristics relevant to adolescents by linking open-access GIS data to pre-COVID-19 data from MoMo wave 3, based on participants' home addresses. Relevant bikeability characteristics for the German context were identified and operationalised using open GIS data from OpenStreetMap, the German Census, mapsofeurope and Eurostat (see table 1.1).

A total of 1,131 adolescents aged 11–17 years (49.8% female) provided data on sex, age, socioeconomic status, cycling to school, and home address. To quantify bikeability within neighbourhoods, a publicly available, time-based routing algorithm was used. This algorithm accounts for delays at intersections and speed reductions due to street slopes (Pereira et al., 2021). It was used to measure bikeability characteristics within 4-, 8-, 12-, 16-, and 20-minute cycling radii from home. Cycling to school was analysed in relation to bikeability characteristics across these radii, nested within urban, town, and rural contexts, using an elastic net regression. This machine learning method can handle high-dimensional data with multicollinearity and can reveal specific patterns (Zou & Hastie, 2005). The optimal balance between the elastic net mixing parameter α and the shrinking parameter λ was determined through a 10-fold cross-validation based on the lowest mean squared error. The analysis was controlled for age, sex, socioeconomic status, and municipality.

Table 1.1: Identified bikeability characteristics for adolescents, their operationalisation and data source

Bikeability characteristics	Operationalisation	GIS data source
Traffic safety and infrastructure		
Overall designated cycling infrastructure	Length of any cycling infrastructure that is physically separated or disconnected from car traffic	OpenStreetMap
Main streets safe for cycling	Length of main streets that have a physically separated cycleway	OpenStreetMap
Residential streets safe for cycling	Length of residential streets with a speed limit of $\leqslant$30 km/h	OpenStreetMap
Access to important destinations		
Schools	Number of schools	OpenStreetMap
Shopping facilities	Number of selected shopping and food facilities relevant to adolescents	OpenStreetMap
Parks	Area of parks	OpenStreetMap
Sports facilities	Area of outdoor sports facilities	OpenStreetMap
Relatives and friends	Number of residents	German Census
Surrounding environment		
Hilliness	Slope of streets	European Digital Elevation Model
Context		
Urbanisation	Classification of the home municipality based on the degree of urbanisation	Eurostat

GIS: Geographic Information System

2 First paper: Perceived physical environment and active transport in adolescents: A systematic review

Slightly modified version of the 1^{st} published article.

Klos, L., Eberhardt, T., Nigg, C., Niessner, C., Wäsche, H., & Woll, A. (2023). Perceived physical environment and active transport in adolescents: A systematic review. *Journal of Transport & Health, 33*, 101689. https://doi.org/10.1016/j.jth.2023.101689

2.1 Abstract

Perceptions of the physical environment influence adolescents' active transport. However, it is unclear which characteristics of the environment are most important for adolescents' active transport and whether parents' and adolescents' perceptions influence their active transport behaviour differently. This systematic review synthesises evidence on the relationship between physical environment perceptions and active transport in adolescents.

A systematic search from May 2008 to March 2022 was conducted in seven databases. Titles and abstracts were screened independently by two reviewers using the open-source machine learning software ASReview. An effect direction plot was created to find overall effects between studies and a narrative synthesis was conducted to highlight differential aspects within studies. Study quality was assessed using the NIH Quality Assessment Tool.

Fifty-one articles met the inclusion criteria. Shorter perceived distance was consistently associated with more active transport. Possible associations between active transport and traffic and general safety, walking and cycling infrastructure, aesthetics, street connectivity, and mixed or summary environment scores were found. In studies assessing both parents' and adolescents' perceptions, associations between perceived environment and active transport differed by survey

group (adolescents/parents). Regarding gender differences, accessible destinations may be more important for boys, while safe walking and cycling infrastructure may be more important for girls.

The findings, although limited mostly to cross-sectional studies conducted in single cities or districts, help to understand the relation between the environment and active transport from an adolescent perspective. Short distances, appropriate and safe walking and cycling infrastructure, and aesthetic surroundings are important for adolescents' active transport. When designing active transport-friendly neighbourhoods, different perceptions of adolescents and their parents, boys and girls should be considered.

2.2 Introduction

The benefits of physical activity (PA) for children's and adolescents' physical and mental health have been well established (Poitras et al., 2016; Rodriguez-Ayllon et al., 2019). However, PA levels decline from childhood to adolescence (Farooq et al., 2020), resulting in four of five adolescents not meeting the World Health Organization PA recommendations of 60 min of moderate to vigorous intensity PA per day (Guthold et al., 2020; World Health Organization, 2010). While adolescence is mostly considered a healthy period in life, modifiable risk behaviours formed during this period (e.g. low levels of PA) may be responsible for health problems during adulthood (van Sluijs et al., 2021).

A crucial part of health-enhancing PA in adolescents is active transport (AT). For example, in Denmark, adolescents accumulate almost 20% of their total moderate to vigorous intensity PA through active transport (Klinker et al., 2014). Walking or cycling for transport also increases overall PA (Denstel et al., 2015; Khan et al., 2021; Martin et al., 2016). Interventions to promote AT, e.g. to and from school, only reported trivial to small effects (Chillón et al., 2011; Villa-González et al., 2018). A majority of those interventions only focused on three of the five strategies of the Community Action Model (the five Ps; Bors et al., 2009), namely Preparation, Promotions and Programs, and often excluded Policy and Physical. Therefore, it is important to understand which environmental factors may influence AT behaviours to help future interventions implementing effective policy and environment-related strategies.

According to AT frameworks, the decision-making process on whether to travel actively is strongly influenced by the objective and perceived physical environment (Mitra, 2013; Panter et al., 2008). However, evidence suggests that there is only little overlap between objectively measured characteristics of the physical environment and their perceptions in adolescents (Pocock et al., 2019; Prins et al., 2009). Further, the perceived and objective environment relate differently to PA and AT in adolescents (Pocock et al., 2019; Prins et al., 2009). For example, a study with adolescents including both perceived and objective environment assessments showed that perceived, but not objectively assessed sports facilities were associated with walking and cycling in leisure time and sports activity engagement in the Netherlands (Prins et al., 2009).

When children transition to adolescence, their AT behaviour changes and the environment in which they travel actively may change as well (Panter et al., 2008). This transition often overlaps with a change from primary to secondary school, leading to several simultaneous transitions across domains (e.g. social, educational, physical environmental) and contexts (e.g. home, school) which influence AT (Jindal-Snape et al., 2020). For example, adolescents have a higher level of independent mobility than children (Shaw et al., 2015), allowing them to travel within their neighbourhood without adult supervision, and gaining more control over their own mobility decisions (Mitra, 2013). Further, feasible distances for walking and cycling increase in adolescence (D'Haese et al., 2011; van Dyck et al., 2010), facilitating AT to more distant destinations and expanding their range of independent AT. This might be due to parents of adolescents being less concerned about environmental barriers than parents of children, however, some concerns about distance and traffic safety are still present (Aranda-Balboa et al., 2020). Parental perceptions of the environment differ from those of adolescents and parents may also identify different environmental barriers than adolescents which influence AT (Aranda-Balboa et al., 2021). Therefore, it is necessary to focus on adolescents separately from children in an AT context and to consider differences in parents' and adolescents' perceptions of the environment and their relation with AT.

Several reviews have been conducted to assess the relationship between physical environment and AT in children and adolescents (D'Haese et al., 2015; Ikeda, Hinckson, et al., 2018; Ikeda, Stewart, et al., 2018; Nordbø et al., 2020; Pont et al., 2009; Rothman et al., 2018; Smith et al., 2017; B. Y.-M. Wong et al., 2011). Most found associations for some environmental factors such as traffic safety (Ikeda, Hinckson, et al., 2018; Nordbø et al., 2020), walkability (D'Haese et al., 2015; Ikeda, Hinckson, et al., 2018; Nordbø et al., 2020) or distance to destination (Ikeda, Hinckson, et al., 2018; Ikeda, Stewart, et al., 2018; B. Y.-M. Wong et al., 2011) and AT. However, some reviews focused exclusively on the objectively measured environment (Ikeda, Stewart, et al., 2018; Smith et al., 2017; B. Y.-M. Wong et al., 2011), while others solely focused on children (D'Haese et al., 2015; Ikeda, Hinckson, et al., 2018; Rothman et al., 2018). Those addressing the perceived environment and including adolescents were conducted more than a decade ago (Pont et al., 2009) or neglected potential differences in AT behaviour between children and adolescents (Nordbø et al., 2020). Lastly, few reviews considered AT to other destinations than school (D'Haese et al., 2015; Nordbø et al., 2020). Therefore, the aims of this systematic review were (1) to assess the relationship between the perceived physical environment and AT in adolescents and (2) to evaluate differences between associations of adolescents' and parents' perceptions and AT.

2.3 Methods

This review was conducted following the PRISMA guidelines (Page et al., 2021). The study protocol of this review was pre-registered at the International prospective register of systematic reviews (PROSPERO; CRD42022307377).

2.3.1 Eligibility criteria

Although adolescence starts at the age of ten according to the World Health Organization (2022b), this review only focused on adolescents aged 12–17, as similar reviews covered age ranges up to 12 (D'Haese et al., 2015; Rothman et al., 2018) or 13 years (Ikeda, Hinckson, et al., 2018). Studies with mixed age groups were included when results for this age group were reported separately or over 50% of the participants were within the defined age range. For longitudinal and intervention studies, participants had to meet the age requirement at all measurement points. The last systematic review focusing on AT that included adolescents used studies published before May 2008 (Pont et al., 2009), thus our search was limited to studies published from May 2008 onwards. Studies had to contain adolescents' or parents' perceptions of the physical environment. In the AT context, the physical environment was defined as the natural (e.g. topography) and man-made (e.g. road infrastructure) context in which adolescents live (Pont et al., 2011). Perceptions of the physical environment included perceived design aspects, traffic, distance to and accessibility of venues and destinations, and safety, but also natural features such as weather (D'Haese et al., 2015). Further, studies had to contain a form of measure of AT (e.g. AT as mode choice or AT minutes/week) and include associations between AT (dependent variable) and perceptions of the physical environment (independent variable). Intervention studies were included if they solely focused on changing the physical environment. Multi-component interventions including additional intervention strategies, e.g. information campaigns on school travel, were excluded. Only quantitative studies were included.

2.3.2 Search strategy

The databases Web of Science Core Collection (Web of Science), MEDLINE & PMC (PubMed), TRIS & ITRD (TRID), SPORTDiscus (EBSCOHost), and ERIC were searched on February 24th, 2022 based on titles and abstracts. As there was no way to limit the search to titles and abstracts in TRID, the "keywords" search, which uses all of the indexed fields including titles and abstracts, was used. Date restriction in ERIC was only possible for full years, so the lower date limit was set to January 2008. A grey literature search for dissertation and theses was conducted using the database ProQuest Dissertations and Theses Global. The search strategy consisted of four topics (active transport, adolescents, environment, perceptions) connected by the boolean operator “AND”. The search term was developed based on previous reviews (D’Haese et al., 2015; Ikeda, Hinckson, et al., 2018; Pont et al., 2009) and was adapted to our context of research limited to adolescents and perceptions of the physical environment. The full search strategy can be found in the study protocol uploaded at PROSPERO and in Appendix A of the published article.

2.3.2.1 Selection process

After removing duplicates, titles and abstracts were screened in one step using ASReview (van de Schoot et al., 2021). ASReview uses an active machine learning approach to identify the most relevant records. To set up the model, the term frequency-inverse document frequency (tf-idf) statistic was used for feature extraction and the naïve Bayes classifier was selected to calculate relevant scores. The “max query” strategy was chosen to always show the most relevant reference (van de Schoot et al., 2021). To train the initial model, five records evaluated as relevant and irrelevant were provided by the researcher, respectively (van Haastrecht et al., 2021). Afterwards, records sorted by the model were shown to the researcher for marking as relevant or irrelevant based on the title and abstract. Each decision of the researcher was used to further retrain the model for higher accuracy. Title and abstract screening was stopped once 50 consecutive references were coded as irrelevant (Bleijendaal et al., 2022).

One researcher started screening titles and abstracts using ASReview until the stopping criterion of 50 consecutive irrelevant records was reached. A second researcher then screened all titles and abstracts excluded by the first researcher to ensure no relevant records were missed (Zhu et al., 2022). In the next step, full texts of relevant studies were assessed based on the predefined inclusion and exclusion criteria. Disagreements concerning the inclusion of full texts were resolved by discussion. If no agreement could be reached, a third researcher was contacted. A reverse snowball search was conducted checking the references cited by included articles.

2.3.3 Study risk of bias assessment

Risk of bias was assessed using the NIH Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies (National Institutes of Health, 2021). This tool contains 14 items focusing on the research question, sample characteristics (e.g. study population, participation rate), exposures, outcomes, follow-up, and confounding. For cross-sectional studies, four items only relevant for cohort studies were removed (items 6, 7, 10 & 13). The item “Were the outcome assessors blinded to the exposure status of participants?" was removed completely as it was not relevant for any of the studies. Studies were categorised into good, fair, or poor based on the risk of bias identified by items labelled "yes", "no" or "not reported". Some flaws can influence study quality more than others; therefore, studies were rated individually as good, fair or poor by the reviewers based on the severity of flaws instead of calculating a quality summary score (National Institutes of Health, 2021). For example, no sample size justification may be less serious than not having a clearly defined, valid and reliable measure of the perceived environment. Detailed results for each study can be found in Appendix B of the published article. Two reviewers carried out the quality assessment independently and disagreements were resolved by discussion.

2.3.4 Data extraction and synthesis

Data used in this review was extracted by one reviewer and checked by another to reduce the risk of errors. To describe included studies, author and year of publication, location of data collection, sample size, age and gender distribution, type and destination of AT, perceived environment assessment, and results were extracted. Where possible, the direction of effect, p-values, and effect measures (e.g. odds ratios for logistic regressions) from adjusted results were extracted for each association between aspects of the perceived environment and AT.

Results were classified into the environment categories traffic safety, crime safety, walking and cycling infrastructure, land-use mix diversity, aesthetics, street connectivity, land-use mix access, recreational facilities, and residential density based on the categories of the neighbourhood Environment Walkability Scale (NEWS) for youth (Rosenberg et al., 2009). Further, self-reported distance or time, general safety, weather, and a summary or mixed score category for indices across different categories (e.g. walkability scores) were added retrospectively to complete the range of environmental categories found in included studies. General safety refers to questions or scales that could not be clearly assigned to either traffic or crime safety.

Given the large heterogeneity of studies regarding environmental perceptions and measures and types of AT, a meta-analysis was ruled out and a quantitative synthesis in the form of an effect direction plot was conducted (Boon & Thomson, 2021; Higgins et al., 2022). The effect direction plot uses the direction of effect (positive, negative or conflicting findings) to summarise results for the associations between different environmental categories and AT without relying on statistical significance (Boon & Thomson, 2021). For each study, positive and negative effect estimates were counted within each environment category. In general, a positive effect is considered an effect in the expected direction, e.g. higher traffic safety is expected to be positively associated with AT. If 70% or more outcomes report a similar direction, an upward or downward arrow was drawn for a positive or negative direction of effect, respectively. If less than 70% of outcomes report a similar direction, sideways arrows were assigned to indicate mixed or conflicting results (Boon & Thomson, 2021).

The consistency of results across studies was rated for categories containing at least five studies (Ikeda, Hinckson, et al., 2018). “Consistent associations” were defined by categories including at least ten studies and having the same effect direction in >75% of studies. “Possible associations” were found if either >75% of effects point in the same direction in less than ten studies or 50–75% of associations point in one and less than 25% in the opposite direction in categories with ten or more studies.

While the effect direction plot can visualise the tendency of effects, it only provides little information about the context of the study and does not take effect sizes or statistical significance into account. Therefore, a narrative synthesis was conducted to complement the effect direction plot by highlighting qualitative aspects, such as differences between adolescent- and parent-reported perceived environment, focusing on significant findings. The narrative synthesis also included studies which were not eligible for the effect direction plot (e.g. if the direction of effect is only reported for significant findings).

2.4 Results

A total of 2,388 records were found in the initial search (see figure2.1). After removing 864 duplicates, 1,524 records were screened using ASReview. Of those, 526 titles and abstracts were screened before meeting the stopping criterion. Full-texts were not available for five conference meeting reports which were therefore excluded after abstract screening. After full-text screening and the snowball search identifying three additional records, a total of 51 studies were included.

In total, 22 included studies were conducted in Europe, twelve in North America, seven in South America, four in Asia, four in Oceania, and two in Africa. Forty-nine studies used a cross-sectional and two a longitudinal study design. Adolescents’ perceptions of the environment were included in 34 studies, twelve studies included parents’ perceptions, and five studies included both. AT was assessed by questionnaire in all studies. Forty studies assessed AT rates or frequencies, and eight studies assessed AT duration (e.g. minutes per week; De Meester et al., 2013; Deforche et al., 2010; Hermosillo-Gallardo et al., 2020; Mendonça et al., 2018; Mitáš et al., 2018; Oyeyemi et al., 2014; Prins et al., 2009; van Dyck et al., 2013). Two studies assessed both AT rates or frequencies and duration (A. Barnett, Sit, et al., 2019; Verhoeven et al., 2016). Nine studies limited their study sample to participants living within a walkable or bikeable distance (ranging from 1.6 to 8 km) to school (Carlson et al., 2014; Martins et al., 2017; Nelson & Woods, 2010; Ozbil et al., 2021; Pocock et al., 2019; M. L. Rahman, Pocock, et al., 2020; van Dyck et al., 2010;

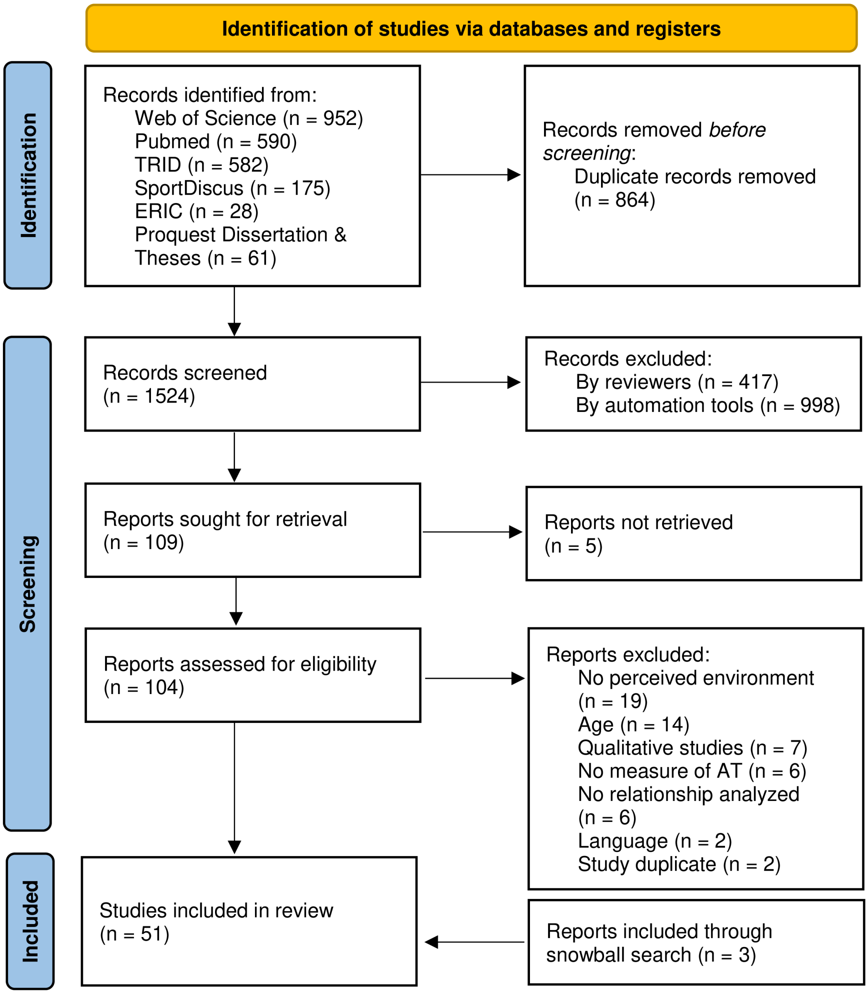

Figure 2.1: Flow diagram of the screening process (adapted from Page et al., 2021)

Verhoeven et al., 2016; Voorhees et al., 2010). The full data extraction table can be found in the supplement of this thesis (Supplement A.1).

Based on the quality assessment, 22 studies were rated good, 13 fair and 16 poor quality. Most quality concerns were missing sample size justification or power description (n = 40), not reporting or having a participation rate lower than 50% (n = 28), and non-reliable and non-valid measures for AT (n = 25) or perceptions of the environment (n = 19). Full results of the quality assessment can be found in Appendix B of the published article. Forty-one of 51 studies were included in the effect direction plot (see figure2.2). Data used to create the plot is found in Appendix C of the published article.

In the following paragraphs, we initially present the general outcomes from the effect direction plot. Subsequently, we discuss individual studies that have identified significant findings and provide a context for interpreting the collective results from the plot.

2.4.1 Traffic safety

Out of 30 studies included in the effect direction plot, 18 reported a positive, seven an inconclusive and five a negative effect direction. Nine studies were of good, eleven of fair, and ten of poor quality. Overall, there is evidence for a possible association between traffic safety and AT; this association remains when excluding poor-quality studies.

There was a relationship between adolescents' perceptions of traffic safety and AT in several studies across multiple regions and continents (Christiansen et al., 2014; De Meester et al., 2013; Kamargianni & Polydoropoulou, 2014; Leung & Le, 2019; Pocock et al., 2019; M. L. Rahman, Pocock, et al., 2020; K. S. Silva et al., 2011; Voorhees et al., 2010). Relevant aspects of traffic safety included places being unsafe to walk (Pizarro et al., 2012; Pocock et al., 2019; M. L. Rahman, Pocock, et al., 2020; Voorhees et al., 2010) or cycle (M. L. Rahman, Pocock, et al., 2020), too much traffic, speeding and reckless traffic, and dangerous crossings (Christiansen et al., 2014; Leung & Le, 2019; M. L. Rahman, Pocock, et al., 2020). Safety to walk or jog and having well-lit streets were only associated with AT in girls (Pizarro et al., 2012). Further, Kamargianni and Polydoropoulou (2014) reported that traffic lights were only associated with AT in urban but not in rural areas.

Parental perceptions of road traffic conditions and dangerous intersections (Y. Gao et al., 2018; Huertas-Delgado et al., 2018), pedestrian safety (Carlson et al., 2014), and the absence of policemen at crosswalks (Huertas-Delgado et al., 2017) were associated with AT. Longitudinal evidence suggests that adolescents were more likely to increase the frequency of active school trips over time if parents were satisfied with pedestrian crossings and had fewer concerns about missing traffic lights or pedestrian crossings (Hume et al., 2009).

Studies surveying both adolescents and their parents found similar relations between traffic safety (Grow et al., 2008) or too much traffic and dangerous intersections and using an active transport mode (Aranda-Balboa et al., 2021). However, Esteban-Cornejo et al. (2016) reported that only parental traffic safety perceptions were associated with more active trips. For adolescents with low socioeconomic status, seeing pedestrians and cyclists around their home influenced their

Author & Year	Country	Traffic safety	Crime safety	Safety general	Infra-structure	Distance & time	Land-use mix access	Land-use mix diver-sity	Aes-thetics	Street connec-tivity	Recre-ational facilities	Wea-ther	Resi-dential density	Sum scores
Self-report studies														
Berger et al., 2019	UK	◀▶	▲					▼		▲				
Dias et al., 2020	Brazil	◀▶	▼		◀▶		◀▶	◀▶	▲	◀▶	▲			
Dias et al., 2021	Brazil	▼	▲		▲		▲	▲	▲	▲	▲			
Hermosillo-Gallardo et al., 2020	Mexico	◀▶	◀▶											
Mäki-Opas et al., 2014	Netherlands													▲
Mendonça et al., 2018	Brazil	▼	▲	▲	◀▶		▲		▲		▼			
Molina-García et al., 2018	Spain													▲
Nelson et al., 2010	Ireland	▲	◀▶		▲		▲	▲	▼	▲	▲			
Oyeyemi et al., 2014	Nigeria			◀▶	◀▶		◀▶		◀▶	◀▶			◀▶	
van Dyck et al., 2010	Belgium	▲	▲		◀▶									▲
Voorhees et al., 2010	US	▲	▲		◀▶		▲		▲		▼			
Christiansen et al., 2014	Denmark	◀▶								▲				
Emond et al., 2012 [a]	US	▲			▼	▲				▲				
Kamargianni et al., 2014	Greece	▲		▲	▲				▲			◀▶		
Mandic et al, 2015 [a]	New Zealand			▲		▲			▼					
Martins et al., 2017	Portugal	◀▶	▼		▲	▲	▼		▲					
Mitáš et al., 2018	Czech Republic, Poland			◀▶										
Pocock et al., 2019	New Zealand	▲			▲									
Prins et al., 2009	Netherlands				▲						▲			
Rahman et al., 2020	New Zealand	▲			◀▶									
Silva et al., 2011	Brazil	▲	▲			▲						▼		
Agyeman et al., 2022	Ghana					◀▶	◀▶							
Fitch et al., 2019	US	▼				▲	▼							
García-Cervantes et al., 2014	Spain													▲
Leung et al., 2019	Vietnam	▲	▲		▲	▲		▲	▲		▲	▲		
Loucaides et al., 2010 [a]	Cyprus	◀▶		▲	▲	▲								
Loureiro et al., 2014	Portugal		▲	▲		▲	▲		▲		▼			
Parent-report studies														
Carlson et al., 2014	US	▲	◀▶		◀▶		◀▶	▲	◀▶	▲				
Ozbil et al., 2021	Turkey				◀▶				◀▶	▼				
Babey et al., 2009	US			▲										
DeWeese et al., 2013	US	▲	▼		▼									
Gao et al., 2018	China	▲	▲		▲		▼							
Huertas-Delgado et al., 2017	Spain	▲	▼		▲	▲						▼		
Huertas-Delgado et al., 2018	Ecuador	▼	▼		▲	◀▶						▼		
Palma et al., 2020	Chile	◀▶	▼		▲	▲						▼		
Pojani et al., 2014	Albania	▲		▲		▲								
Woldeamanuel, 2016	US	▲	▼			▲						▲		
Self- & parent-report studies														
Aranda-Balboa et al., 2021	Spain	▲	◀▶			▲						▲		▲
Da Silva et al., 2018	Brazil	▼	◀▶											
Esteban-Cornejo et al., 2016	US	▲	▲											
Grow et al., 2008	US	▲	▲		▲			◀▶	◀▶	▲	▲			

Figure 2.2: Effect direction plot of included studies (adapted from Boon and Thomson, 2021)

Effect direction: ▲ ⩾70% positive effect; ▼ ⩾70% negative effect; ◀▶ mixed effects/ conflicting findings; Sample size: Large arrow >1200; medium arrow 400–1200; small arrow <400; Study quality: denoted by row colour: green = high study quality; amber = fair study quality; red = poor study quality; [a] Unadjusted results of these studies were used as the direction of effect was not available for all comparisons in their adjusted analyses.

travel mode choice, whereas for parents being able to cross the street safely was an important factor for AT (A. A. d. P. d. Silva et al., 2018).

2.4.2 Crime safety

Out of 23 studies included in the effect direction plot, eleven reported positive, five inconclusive, and seven negative effects. Nine studies of good, six of fair, and eight of poor quality were included. Overall, there is an inconclusive association between crime safety and AT. However, when excluding poor-quality studies, of which five report negative effect directions, criteria for a possible positive association are met.

Adolescent perceived crime danger (K. S. Silva et al., 2011), warnings about strangers (Leung & Le, 2019), and neighbourhood violence and theft (Loureiro & Gaspar de Matos, 2014; Mendonça et al., 2018) were negatively associated with AT. Within studies, the relation between adolescents' perceptions of crime safety and AT was more pronounced for AT to other destinations than school (Berger et al., 2019; Verhoeven et al., 2016) and for girls more than for boys (Nelson & Woods, 2010). In boys with low socioeconomic status, higher crime safety was associated with less leisure walking (Dias et al., 2020).

Nelson and Woods (2010) found parents' perceptions of crime safety to be negatively associated with AT, indicating a significant relationship in the unexpected direction. Two studies focusing on both adolescents' and parents' perceptions of crime safety found that only adolescents' perceptions relate to AT (Aranda-Balboa et al., 2021; Grow et al., 2008). Two studies found that only parents' perceptions of crime and stranger danger safety were associated with AT in families of high socioeconomic status (A. A. d. P. d. Silva et al., 2018) and AT frequency (Esteban-Cornejo et al., 2016), respectively.

2.4.3 General safety

Out of nine studies included in the effect direction plot, seven reported positive and two inconclusive effect directions. Two studies were rated as good, three as fair, and four as poor quality. Overall, there is a possible association between general safety and AT. When excluding poor-quality studies, no association is found.

Adolescent-perceived safety was significantly associated with AT regardless of urbanisation level (Kamargianni & Polydoropoulou, 2014; Loucaides et al., 2010). However, a very high level of safety was only associated with energy expenditure during AT in girls, but not in boys (Mitáš et al., 2018). Further, parents' safety perceptions were associated with walking to school and leisure time AT (Mandic et al., 2015; Pojani & Boussauw, 2014).

2.4.4 Walking and cycling infrastructure

Out of 23 studies included in the effect direction plot, 13 reported positive, eight inconclusive and two negative effects. Nine studies were of good, eight of fair, and seven of poor quality. Overall, there is a possible association between walking and cycling infrastructure and AT. No association is found based on good and fair-quality studies only.

De Meester et al. (2013) reported walking infrastructure to be related to active school transport, but not to walking or cycling to other destinations. For girls, but not for boys, separate paths from car traffic were associated with AT (Nelson & Woods, 2010). In Mediterranean urban and rural areas, wide sidewalks relate to AT, whereas in rural areas, the network condition of sidewalks was important (Kamargianni and Polydoropoulou, 2014). In a Vietnamese study, obstacle-free roads increased the odds of using AT (Leung & Le, 2019).

Parental perceptions of walking and cycling infrastructure and sidewalk conditions were associated with AT and walking to school, respectively (Y. Gao et al., 2018; Ozbil et al., 2021). In studies comparing adolescents' and parents' perceptions of walking and cycling infrastructure, only adolescents' perceptions showed positive associations with AT (Aranda-Balboa et al., 2021; Grow et al., 2008).

2.4.5 Distance and time to destination

Out of 15 studies included in the effect direction plot, 13 studies showed positive and two inconclusive effects. However, only fair (n = 5) and poor-quality studies (n = 10) were included. Nevertheless, there is a consistent association between distance and time to destination and AT across studies. Excluding poor studies, a possible association remains.

Greater self-reported distance or travel time to school was consistently negatively associated with cycling to school (Emond and Handy, 2012; Fitch et al., 2019) and general school-related AT (De Meester et al., 2013; Loucaides et al., 2010; Loureiro & Gaspar de Matos, 2014; Mandic et al., 2015; Martins et al., 2017; K. S. Silva et al., 2011). Even when living within 2 miles of school, the school being too far away was a perceived barrier for adolescents influencing active school transport mode choice (Martins et al., 2017). Adolescents were more likely to use AT if they (Leung & Le, 2019; Mandic et al., 2015) or their parents (A. Barnett, Sit, et al., 2019) perceived the distances or travel times to be short. In all but one study (Palma et al., 2020), parental perceptions of longer school distance were negatively related to AT to and from school (A. Barnett, Sit, et al., 2019; Huertas-Delgado et al., 2017, 2018; Pojani & Boussauw, 2014; Woldeamanuel, 2016). All studies including both adolescent- and parent-reported distance to school reported negative associations with AT to and from school for both adolescents' and parents' perceptions (Aranda-Balboa et al., 2021; A. Barnett, Akram, et al., 2019).

2.4.6 Land-use mix access

Out of 12 studies included in the effect direction plot, five reported positive, four inconclusive, and three negative effects. Seven studies were of good, one of fair, and four of poor quality. There is no convincing evidence for an overall association between land-use mix access and AT. No association was found when excluding poor studies.

Still, some meaningful relationships were reported. For example, adolescents' perceptions on access to services were associated with AT (Dias et al., 2021; Loureiro & Gaspar de Matos, 2014) and specifically with walking to school (A. Barnett, Akram, et al., 2019; Voorhees et al., 2010, 2011). Access to destinations was the only environmental predictor of AT duration in boys but not in girls (Oyeyemi et al., 2014). In contrast, Dias et al. (2020) only reported a relation between land-use mix access and walking to other destinations only in girls of low socioeconomic status. Adolescents living close to school were four times more likely to use AT to and from school if shops were within walking distance (Nelson & Woods, 2010). Living close to shops or having shops on the way to school was also related to cycling to school (Mäki-Opas et al., 2014) and more active trips overall (Leung & Le, 2019). School bus access was positively associated with walking to school, whereas public transport access increased the odds of cycling compared to walking (Agyeman et al., 2022). Living close to a bus stop was not related to general AT, while trajectory analyses showed bus stops being related to decreased odds over time for walking to other destinations than school (Berger et al., 2019). Parents' perceptions on access to services were associated with active school trip frequency but not with AT to other destinations in one good-quality study (A. Barnett, Sit, et al., 2019).

2.4.7 Land-use mix diversity

Out of seven studies included in the effect direction plot, four showed positive, two inconclusive, and one negative effect direction. Seven studies were of good, one of fair, and one of poor quality. There is no overall association between land-use mix diversity and AT.

Land-use mix diversity, as perceived by adolescents, was consistently associated with AT only in a few studies (Deforche et al., 2010; Dias et al., 2021). Only boys or boys of high socioeconomic status chose active school transport modes or walked to other destinations more often if they lived in proximity to different destinations (Dias et al., 2020; Nelson & Woods, 2010). De Meester et al. (2013) reported that land-use mix diversity was only associated with AT to and from school, but not with walking or cycling to other destinations. Lastly, parent-perceived access to services was related to a higher frequency of active trips (A. Barnett, Sit, et al., 2019).

2.4.8 Aesthetics

Out of 14 studies, eight reported positive, four inconclusive, and two negative effect directions between aesthetics and AT. Most studies were of good (n = 8) or fair (n = 4) quality. Overall, there is a possible association between aesthetics and AT. Looking at good and fair quality studies only, no association was found.

General neighbourhood aesthetics perceived by adolescents were associated with AT (Deforche et al., 2010; Dias et al., 2021; Loureiro & Gaspar de Matos, 2014). Adolescents who perceived their neighbourhood to be more aesthetic were more likely to take a school bus instead of using a bike, car or taxi (A. Barnett, Akram, et al., 2019). Most other studies focusing on specific aesthetic elements in the neighbourhood found natural elements such as trees, green spaces, and a nice scenery to be related to AT (Kamargianni & Polydoropoulou, 2014; Leung & Le, 2019; Mandic et al., 2015; Ozbil et al., 2021).

2.4.9 Street connectivity

Out of ten studies included in the effect direction plot, seven reported positive, one inconclusive, and two negative effect directions. All studies were of good (n = 7) or fair (n = 3) quality. Overall, there is a possible association between street connectivity and AT which is also found when excluding poor-quality studies.

Adolescent perceived street connectivity was associated with AT in several Belgian and Danish studies (Christiansen et al., 2014; De Meester et al., 2013; Deforche et al., 2010). Parental perceptions of street connectivity were significantly associated with occasional but not with regular active trips to and from school in the US (Carlson et al., 2014).

2.4.10 Proximity of recreational facilities

Out of nine studies included in the effect direction plot, six showed positive and three negative associations with AT. Five studies were of good, two of fair, and two of poor quality. Overall, there is no association between the proximity of recreational facilities and AT.

Adolescent-reported accessibility to recreational facilities was positively associated with AT mode and frequency (Dias et al., 2020, 2021; S. C. Duncan et al., 2016; Leung & Le, 2019; Mendonça et al., 2018; Nelson & Woods, 2010; Prins et al., 2009) and AT duration (Deforche et al., 2010). Studies taking gender into account found associations between AT and the presence of public parks for boys only (Nelson & Woods, 2010). Also, neighbourhood recreation facilities were associated with walking in boys of medium or high socioeconomic status but not in girls, regardless of socioeconomic status (Dias et al., 2021). In contrast, A. Barnett, Akram, et al. (2019) reported the proximity of recreational facilities to be negatively associated with walking to school compared to using public transport. Assessing the relation between both adolescents' and parents' perceptions and proximity of recreation facilities, Grow et al. (2008) found positive associations between both adolescents' and parents' perceptions and proximity of recreation facilities and AT.

2.4.11 Weather

Out of seven studies included in the effect direction plot, three reported positive, one inconsistent, and three negative effects. Three studies of fair and four of poor quality were included. Overall, there is no evidence for an association between weather and AT.

Associations between weather and AT were context-specific. For example, bad weather during winter was associated with less AT in Greek urban and rural insular areas, but not in rural mainland areas (Kamargianni & Polydoropoulou, 2014). Further, bad weather may influence AT negatively especially in the morning school commute but not on the way home in the afternoon (Woldeamanuel, 2016). Depending on the climate, not only cold or rainy weather may inhibit AT, as in a Vietnamese study, feeling uncomfortable to walk or cycle because it is too hot was a substantial barrier for AT (Leung & Le, 2019).

2.4.12 Residential density

Five studies assessed the relationship between residential density and AT (A. Barnett, Akram, et al., 2019; De Meester et al., 2013; Oyeyemi et al., 2014; van Dyck et al., 2013; Verhoeven et al., 2016) and only one was included in the effect direction plot (Oyeyemi et al., 2014). Residential density was positively related to walking and negatively to cycling to other places than school; However, no relation was found between residential density and walking or cycling to school in that same study (Verhoeven et al., 2016).

2.4.13 Summary scores of the perceived physical environment

All five studies included in the effect direction plot for mixed and summary scores reported findings in a positive direction. Three studies of good, one of fair, and one of poor quality were included. Overall, there is a possible relationship between summary scores and AT.

One study used the Assessing Levels of Physical Activity (ALPHA) environment questionnaire (García-Cervantes et al., 2014), two calculated a walkability score from residential density, street connectivity and land-use mix (van Dyck et al., 2010, 2013), two others assessed adolescents' environmental barriers to AT (S. C. Duncan et al., 2016; Molina-García et al., 2018), and the final two used walking and cycling environment scores (Aranda-Balboa et al., 2021; Mäki-Opas et al., 2014).

The ALPHA total score correlated with leisure AT trips in girls but not in boys (García-Cervantes et al., 2014). Walkability and environmental barriers were associated with AT in one of two studies each (Molina-García et al., 2018; van Dyck et al., 2010). Finally, only adolescents' perceptions of the built environment for walking and cycling but not their parents' were associated with using AT modes (Aranda-Balboa et al., 2021).

2.5 Discussion

This systematic review examined the relationship between adolescents' and parents' perceptions of the physical environment and AT. Consistent associations were observed for AT and distance or time to destination, possible associations for traffic and general safety, walking and cycling infrastructure, aesthetics, street connectivity and mixed or summary environment scores, and inconclusive associations for crime safety, land-use mix access, land-use mix diversity, recreational facilities, weather, and residential density.

In concordance with our results, both measured and self-reported distance and time were associated with AT in numerous other reviews on children and adolescents (Aranda-Balboa et al., 2020; Ikeda, Hinckson, et al., 2018; Ikeda, Stewart, et al., 2018; Nordbø et al., 2020; Pont et al., 2009; Rothman et al., 2018; B. Y.-M. Wong et al., 2011). However, most studies only assessed AT mode or frequency (e.g. Aranda-Balboa et al., 2021). While shorter distances increase AT rates and frequencies, duration and PA-related health benefits may decrease (S. Duncan et al., 2016; Panter et al., 2011). Therefore, distance might negatively influence transport mode choice or trip frequency, but positively influence PA duration during those active trips (Verhoeven et al., 2016). However, this postulated mechanism could not be assessed based on the studies included in this review.

There was a possible association between AT and traffic or general safety, but not between crime safety. Similar results were found for children (D'Haese et al., 2015; Ikeda, Hinckson, et al., 2018). Traffic safety is one of the major concerns among parents (Aranda-Balboa et al., 2020) and concerns often revolve around dangers from car traffic. According to the PA global status report by the World Health Organization (2022a), 80% of countries have a national road safety strategy. However, less than half of them have standards for separated walking and cycling infrastructure, safe crossings, and safe speeds, and only 18% of countries have a fully funded safety campaign (World Health Organization, 2022a). Traffic safety is thus a well-known concern, but especially the effects of the implementation of safety measures on AT is still lacking. Although being included in over half of the studies, there is no convincing evidence that crime safety is associated with AT and few significant associations were found. The relationship between crime safety and AT may only be a positive one in high-income countries where AT is a desirable activity, and children and adolescents choose to travel actively. In lower-income countries, AT may be a necessity as there are no other transport options despite crime safety concerns (González et al., 2020).

This review found possible associations between AT infrastructure and street connectivity with AT. Previous reviews on children found mixed results and the strength of the relationship might depend on other factors, e.g. transport mode or socioeconomic status (D'Haese et al., 2015; Ikeda, Hinckson, et al., 2018). Intervention studies suggest that improvements in AT infrastructure, such as separating pedestrians and cyclists from car traffic, are important to improve accessibility and connectivity and reduce conflicts between street users (Panter et al., 2019). By improving walking and cycling infrastructure, perceptions about safety, connectivity, and access might also improve. Especially cycling can benefit from better infrastructure (Mölenberg et al., 2019), as adolescents and their parents perceive cycling as less safe than walking (Mandic, Hopkins, García Bengoechea, Flaherty, et al., 2017). However, few studies in this review have distinguished between walking and cycling, not allowing for a separate analysis of walking and cycling.

Aesthetics showed a possible association with AT. Several previous reviews mostly focusing on children report no relation (D'Haese et al., 2015; Ikeda, Hinckson, et al., 2018; Nordbø et al., 2020). Most studies finding significant associations in this review included some form of green space or landscape. In urban areas, green space along the route can improve satisfaction with active trips (Ta et al., 2021), and large-scale open spaces and street trees have shown to increase walking time in adults (Vich et al., 2019). However, in children and adolescents, associations between green space and AT have been mixed, with most studies not finding significant associations (Nordbø et al., 2020). Given the heterogeneous results, more studies are needed to explore the relationship between aesthetics and AT in adolescents.

Environmental summary scores across multiple categories were possibly associated with AT. The conceptual consideration behind these scores is that the physical environment comprises several components which are perceived together and thus influence AT behaviour. This is in line with the results of the International Physical Activity and Environment (IPEN) study, showing that multi-variable indices of the built environment, both self-reported and objectively assessed, were more strongly related to AT than single indicators (Sallis et al., 2020). While summary scores cannot distinguish between the relevance of individual factors, they indicate that perceptions of the physical environment are important for adolescents.

There was no sufficient evidence for a relation between AT and land-use mix access, land-use mix diversity, recreational facilities, weather, and residential density. Except for crime safety and land-use mix access, less than ten studies were included in the effect direction plot. In this review, there is a large difference in the amount of research on the different environment perceptions. For example, safety aspects were included in most studies, whereas e.g. residential density and street connectivity were included in few studies. Nevertheless, significant positive relations were found within each category. Future studies should cover multiple aspects of the built environment to help understand the relation between environmental perceptions and AT.

Only five studies assessed both adolescents' and parents' environment perceptions and those found different characteristics related to AT depending on who was surveyed. This indicates that the perceptions of parents and adolescents both influence AT behaviour, but they might do so in different ways. Some categories (e.g. walking and cycling infrastructure) show more significant results for adolescents' perceptions than parents', indicating that adolescent perceptions are more important for AT decision-making. Parents have a strong influence on their child's PA and AT behaviour. However, this influence subsides in adolescence allowing adolescents to become more independent and let them make their own AT decisions (Edwardson & Gorely, 2010; Panter et al., 2008; Pont et al., 2011). This shows the need to carefully consider whose perceptions should be assessed based on their research question.

The relation between perceptions and AT differs between girls and boys. Perceptions of traffic and general safety as well as good walking and cycling infrastructure were more important for girls while land-use mix access, land-use mix diversity and recreational facilities were more often associated with AT in boys. Thus, for girls, environment characteristics of the trip may play a stronger role whereas for boys, destinations in their neighbourhood such as shops and parks might be more important for AT than safety aspects (Mitra & Nash, 2019). Despite the limited evidence about gender-specific aspects of AT in youth (Marzi et al., 2020), gender-sensitive analyses of the built environment are important and should be considered in future research (Tcymbal et al., 2020).

2.5.1 Limitations of individual studies

Most studies had a cross-sectional and only two had a longitudinal design, limiting the review to observational evidence. No experimental studies fit the inclusion criteria. Most included studies focus on small regions or single cities or districts within one country, limiting comparability. For example, road infrastructure can differ between countries, between urban and rural areas, and even within similar-sized cities of the same country. More representative, large-scale international studies including adolescents across rural and urban areas are needed to compare environments and policies on AT between countries.

Over half of the studies had several weaknesses, increasing the risk of bias. Most notably, several studies did not use valid and reliable questionnaires to assess the physical environment, sometimes relying on a single or few items (e.g. Babey et al., 2009; Fitch et al., 2019). This may result in underestimated associations. Still, 25 studies used established questionnaires, such as NEWS or ALPHA.

Regardless of the questionnaire type, there is potential confounding, e.g. between perceptions of traffic safety and walking and cycling infrastructure or walkability of the neighbourhood. Further, recent research suggests that both adolescents and parents perceive their school route environment to be less safe and report more barriers the longer the home-school distance (Mandic et al., 2020, 2022). Thus, environment perceptions may change based on the distance to certain destinations. Only nine studies in this review limited their sample to a certain distance to school to account for those differences. The lack of adjustments in other studies warrants caution when interpreting the results. Further research should consider the distance to destination(s) of interest (e.g. school if the study focuses on school travel) and limit the study sample to those who live within walking or cycling distance to such destinations.

Multiple studies used single questions to measure AT which were not tested for validity and reliability. Especially for school transport, many analyses were conducted using a single dichotomous “active vs. passive” variable. Instead, in the case of school transport, trips to and from school should be assessed (Herrador-Colmenero et al., 2019) and analysed for walking and cycling separately (Ikeda, Stewart, et al., 2018). When combining car transport and public transport into a single “passive” category, it is not considered that getting to bus stops and train stations contributes to substantial amounts of PA (Durand et al., 2016). Further, some studies dichotomised continuous data (e.g. AT duration; Mendonça et al., 2018; Prins et al., 2009, leading to a significant loss of power (Dawson & Weiss, 2012; Fedorov et al., 2009).

2.5.2 Implications for practitioners

This review provides guidance for policy-makers and practitioners. First, places of relevance for adolescents (e.g. schools, shops, parks) should be within a walkable or bikeable distance. For example, enrolling in the closest school may help to increase active school transport rates (Mandic, Sandretto, et al., 2017). Second, it is important to address adolescents' and parents' traffic safety concerns by providing both infrastructure which is objectively safe, but also makes the pedestrian or cyclist feel safe (e.g. Gössling and McRae, 2022). This applies especially to cycling, as cycling feels less safe than walking for adolescents and their parents (Mandic, Hopkins, García Bengoechea, Flaherty, et al., 2017). Our work further suggests that boys' and girls' AT is influenced by different aspects of the environment. Despite the limited evidence about gender-specific aspects of AT in youth (Marzi et al., 2020), it might be worthwhile considering gender-specific needs in AT promotion (Tcymbal et al., 2020). Third, adolescents are more likely to use AT in aesthetically pleasing neighbourhoods. This emphasises the importance of well-maintained, visible public spaces (e.g. free from litter) and aspects of nature such as trees, parks, and blue spaces for AT. For example, re-routing foot and cycling paths close to green spaces and separated from traffic could improve the AT experience (Ta et al., 2021). Finally, the relation between the physical environment and AT should be considered an important aspect with regard to transformative processes of sustainable development in neighbourhoods and urban areas (Wäsche et al., 2021).

2.5.3 Strengths and limitations of this review

This is the first systematic review on active transport and the relationship with the perceived physical environment focusing on the important age group of adolescents aged 12–17 years. The review also provides an important evidence synthesis regarding different environmental perceptions of adolescents and their parents.

Using ASReview as a screening tool, several references were not screened by the reviewers, which may lead to references being missed. However, simulation studies have shown that after screening 8–33% of the studies sorted by relevance in ASReview, 95% of eligible studies are found. Until we reached our stopping criterion of 50 consecutive irrelevant records, we had screened 34.5% of all records, hence screening the maximum range that is necessary to identify most relevant studies (van de Schoot et al., 2021). In addition, even when screening all results manually, human error rates result in 10% misclassified abstracts (Z. Wang et al., 2020).

A synthesis based on the direction of effect has several limitations. First, this synthesis does not consider the effect size or statistical significance. Second, within studies, the effect direction plot always presents a positive or negative association for single results, whereas multiple comparisons may show inconclusive results. Nevertheless, using effect directions allowed most studies to be included in the synthesis and for a more concise narrative synthesis being able to focus on the context of significant findings.

2.6 Conclusion

This systematic review revealed consistent associations between AT and distance or time as well as possible associations between AT and general and traffic safety, walking and cycling infrastructure, aesthetics, street connectivity, and summary environment scores. Causal relationships could not be explored as most studies only reported cross-sectional results. The applicability and comparability of results are limited as most studies were conducted in single regions, cities, or districts. More longitudinal, international studies on adolescents' AT with representative samples across rural and urban areas are needed. Due to a small number of studies assessing both adolescents' and parents' environmental perceptions there is some, but limited evidence that adolescents' and parents' perceptions influence AT behaviour differently. Future research should account for those differences while also considering the different demands and needs of boys and girls. Finally, practitioners, such as urban planners and public health advocates, should focus on creating neighbourhoods where destinations of interest for adolescents are in direct proximity to encourage AT while also providing appropriate walking and cycling infrastructure so adolescents feel comfortable and safe walking and cycling in their neighbourhood.

3 Second paper: Walking and non-motorised vehicle use in adolescents: the role of neighbourhood environment perceptions across urbanisation levels

Slightly modified version of the 2^{nd} published article.

Klos, L., Fiedler, J., Nigg, C., Niessner, C., Wäsche, H., & Woll, A. (2024). Walking and non-motorised vehicle use in adolescents: The role of neighborhood environment perceptions across urbanization levels. *German Journal of Exercise and Sport Research, 54*(1), 145–155. https://doi.org/10.1007/s12662-023-00931-5

3.1 Abstract

Promoting active travel is key to achieving the sustainable development goals of sustainable communities, climate action, and health and well-being. Walking and non-motorised vehicle use (e.g. cycling, longboarding) are influenced by the perceptions of the neighbourhood environment. However, most evidence is limited to studies conducted in urban areas. This study aims to assess the relationship between perceived environment and walking as well as non-motorised vehicle use stratified across different levels of urbanicity in adolescents in Germany. Cross-sectional data of 3,976 adolescents aged 11–17 (51% female) from the nationwide Motorik-Modul Longitudinal Study in Germany were used. Age, sex, socioeconomic status, neighbourhood environment perceptions, duration of walking, and non-motorised vehicle use were assessed via questionnaire. Separate cumulative link mixed models were calculated to analyse the relationships between environment perceptions and walking as well as non-motorised vehicle use across rural areas, small towns, medium-sized towns, and cities. The presence of public sports facilities was related

to both walking and non-motorised vehicle use across urbanicity levels. Relationships with other aspects of the perceived environment, such as traffic safety concerns and walking or cycling infrastructure, were more context-specific meaning that associations differed based on active travel mode and urbanicity level. Additionally, non-motorised vehicle use differed considerably across sample points. To conclude, when creating active and sustainable environments for active travel, it is crucial to target specific travel modes and take the urbanicity and regional context into account.

3.2 Introduction

Physical activity is important for children's and adolescents' physical health and mental well-being (Chaput et al., 2020; Poitras et al., 2016; Rodriguez-Ayllon et al., 2019). The World Health Organization recommends that children and adolescents should engage in at least an average of 60 min of moderate-to-vigorous-intensity physical activity per day (Bull et al., 2020). Insufficient physical activity levels are especially prevalent in adolescents (Guthold et al., 2020), which may carry into adulthood (van Sluijs et al., 2021).

Active travel (AT) is an important behaviour that contributes to overall physical activity (Martin et al., 2016) and is a key objective for targeting several United Nations sustainable development goals (United Nations, n.d.). It has been reported that AT may be responsible for almost 20% of moderate-to-vigorous physical activity in adolescents (Klinker et al., 2014). This makes AT an important contributor to the sustainable development goal *Good Health and Well-Being*. Furthermore, AT is beneficial for preventing greenhouse gas emissions when chosen over motorised travel modes (Abu-Omar et al., 2023). It is estimated that 41% of short car trips could be substituted by walking or cycling. This would save nearly 5% of CO_2 emissions of car travel (Neves & Brand, 2019), contributing to the sustainable development goal *Climate Action*. A change toward AT can offer large benefits to society through creating social capital and better safety in neighbourhoods, reducing fossil fuel dependency, and creating economic benefit - and all with little to no negative effects (Giles-Corti et al., 2010), contributing to the sustainable development goal *Sustainable Cities and Communities*.

When children become adolescents, they grow more independent of their parents and become more involved in the decision-making process for AT (Mitra, 2013; Panter et al., 2008), can travel longer distances by foot or bike (van Dyck et al., 2010), and can reach more places of interest (e.g. school, recreational facilities, shops) physically active and without parental supervision.

The WHO emphasises in its "Global Action Plan on Physical Activity" that creating active environments across urban and rural areas is a key pillar for physical activity promotion (World

Health Organization, 2018). Hence, perceptions of the physical environment are important in the decision-making process of whether to engage in AT (Panter et al., 2008). A recent review found that several perceptions of the environment such as short travel distances, traffic safety, walking and cycling infrastructure, aesthetics, and street connectivity are associated with AT (Klos, Eberhardt, et al., 2023). However, most studies included in this review were limited to single cities or districts and only focused on school transport modes. Thus, there is limited evidence on whether environmental perceptions are associated with AT beyond active school commutes.

To date, few studies have assessed adolescents' AT behaviour in rural and urban areas. This is especially important since physical activity shows detrimental trends in children and adolescents in rural areas (C. Nigg et al., 2022). From a socioecological perspective (Sallis et al., 2006), neighbourhood environment characteristics are crucial for AT, such as walkability, infrastructure, and connectivity (Giles-Corti et al., 2022). These characteristics are usually more common in urban areas, making them, in general, more conducive to AT than rural areas. The few studies investigating AT across urban and rural areas found that urban adolescents are more likely to engage in AT than their rural counterparts (Christiana et al., 2021; Hermosillo-Gallardo et al., 2018; Marzi et al., 2023). However, commuting actively (Johansson et al., 2012) and especially cycling to school (Reimers et al., 2013, 2021) is more common in medium-sized towns compared to cities, suggesting a non-linear relationship between urbanicity level and AT. Regarding neighbourhood environment characteristics, more urban areas are characterised by a higher population and intersection density as well as a higher overall walkability than rural areas (M. L. Rahman, Pocock, et al., 2020). Conversely, urban areas are perceived to be less safe to walk or cycle than rural areas (M. L. Rahman, Pocock, et al., 2020). Therefore, environmental perceptions and their influence on AT may differ across urbanicity levels. For example, Kamargianni and Polydoropoulou (2014) found that the network condition of the sidewalks was only relevant in rural areas whereas traffic lights were only associated with AT in urban areas.

Regarding AT modes, a distinction should be made between walking and using non-motorised vehicles (NMV) such as cycling or longboarding. As NMVs are usually faster than walking, feasible distances for walking are significantly shorter than, e.g. cycling (van Dyck et al., 2010) and are used for different trips. Further, walking is perceived as less dangerous and relies on different road and safety infrastructure than NMVs (Cook et al., 2022; Mandic, Hopkins, García Bengoechea, Flaherty, et al., 2017). The Netherlands and Denmark are renowned for their walking- and cycling-friendly cities. By contrast, Germany remains a car-centric country even though increasing efforts are made to promote walking and cycling, especially in bigger cities (Buehler & Pucher, 2017). Helping to understand what is important for adolescents' active travel decision-making across Germany, this study may guide policymakers to promote sustainable travel for the next young generation.

Therefore, this study aimed to assess the relationship between perceived environment and walking as well as NMV use stratified across urban and rural areas in adolescents living in Germany.

3.3 Methods

3.3.1 Sample

Cross-sectional data from two cohorts of the Motorik-Modul Longitudinal Study (MoMo) were used. MoMo is a part of the German Health Interview and Examination Survey for Children and Adolescents (KiGGS) conducted by the Robert Koch Institute. MoMo collected data on physical fitness, physical activity, and social and environmental determinants of children and adolescents across 167 sample points in four measurement waves between 2003 and 2021. Each wave consists of a representative cross-sectional sample including children and adolescents aged 4–17 years and a longitudinal sample. Further information on MoMo can be found elsewhere (Wagner et al., 2014; Woll et al., 2021).

For this study, cross-sectional data from participants aged 11–17 years from MoMo wave 2 (2014–2017) and MoMo wave 3 (2018–2020) were used. As the MoMo assessments were interrupted at the start of the COVID-19 pandemic, only data collected before the first lockdown in Germany in March 2020 were included since physical activity engagement in rural and urban areas cannot be generalised in pandemic and non-pandemic times (C. Nigg et al., 2021, 2022).

MoMo was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Karlsruhe Institute of Technology Ethics Committee (wave 2 and 3, 2014–2017 and 2018–2021, respectively). MoMo was also approved by the Federal Commissioner for Data Protection and Freedom of Information. All participants were informed in detail about the study, gave written consent, and participated voluntarily. The presence and consent of a legal guardian were mandatory for participants younger than 15 years of age.

3.3.2 Variables

Age, sex, socioeconomic status, environment perceptions, walking, and NMV use were assessed via a questionnaire (Schmidt et al., 2016). The 167 sample points were drawn to be representative of Germany, accounting, e.g. for region and urbanicity (Woll et al., 2021). Multiple points were drawn in Hamburg and Berlin since they are large cities. Participants of these cities were allowed to take part in any of the scheduled assessments to allow for a reduced travel time for participants to the test locations. Thus, the sample points were summarised for Hamburg and Berlin, respectively, resulting in 162 instead of 167 sample points in the analyses.

3.3.2.1 Outcomes: walking and non-motorised vehicle use

Walking was assessed by asking, "How long is the distance you walk per day?" Possible answer categories were, "I almost never walk"; "I walk less than 1km per day"; "I walk between 1 and 2km per day (15–30min per day)"; "I walk 3–5km per day (30–60min per day)"; "I walk 6–10km per day (1–2h per day)"; and "I walk 10km and more per day (more than 2h per day)". NMV use was assessed by asking, "How long is the distance that you go by bike (only transport, not cycling for exercise/sport) and other non-motorised transportation (e.g. longboard)?" Possible answers were, "I almost never go by bike/longboard or the like"; "less than 1km per day"; "1–5km per day (5–10min per day)"; "6–10km per day (10–30min per day)"; "11–20km per day (30–60min per day)"; and "more than 20km per day (more than 60min per day)".

3.3.2.2 Neighbourhood environment perceptions

Adolescents' perceptions of the physical environment were assessed by 12 items concerning the accessibility of public recreation facilities (public sports facilities and playgrounds), private sports providers (sports clubs and commercial sports providers). Safety and infrastructure (safe pedestrian infrastructure, safe cycling infrastructure, presence of cars, youth playing outside, safety from crime, pleasant neighbourhood for walking and cycling), and accessibility (access to shops, access to public transport). All items were assessed using a 4-point Likert scale with higher values indicating a more AT-friendly environment except for one item assessing the presence of cars with an inverse order. The scale showed moderate test–retest reliability (Reimers et al., 2012). Single items were used instead of the factor structure from Reimers et al. (2012) as some items showed opposing relationships with walking or NMV use within factors.

3.3.2.3 Urbanicity

Urbanicity is based on the number of residents in the participants' home towns. Participants were categorised into four urbanisation levels: Rural areas (<5000 residents), small towns (5000–19,999 residents), medium-sized towns (20,000–99,999 residents), and cities ($\leqslant$100,000 residents) based on the categorisation of the Federal Institute for Research on Building, Urban Affairs and Spatial Development (n.d.).

3.3.2.4 Socioeconomic status

Education, occupation, and disposable household equivalent income were assessed for both parents. Answers were categorised and given a score between 1 and 7 for each category. The highest score between parents was used to calculate the socioeconomic (SES) sum score ranging between 3 (lowest) and 21 (highest) points. If participants had only one parent, the score of this parent was used (Lampert et al., 2018). This index is an established instrument used in health-monitoring studies in Germany (Lampert et al., 2013).

3.3.3 Statistical analysis

All analyses were conducted using R (R Core Team, 2023)and RStudio (Posit team, 2023). Descriptive statistics (i.e., means and standard deviations for continuous variables and counts and frequencies for categorical variables) of the samples were calculated stratified by urbanicity level.

To analyse relationships between environmental perceptions and walking and NMV use, cumulative link mixed models were calculated stratified by urbanicity level using the ordinal package (Christensen, 2022). The central assumption for cumulative link mixed models is the proportional odds assumption meaning that the relationship between any pair of the ordered categorical outcome variable is the same. To test the assumption, a series of cumulative logit mixed models were calculated where the ordinal variable is collapsed into two categories and for each combination, a binary logistic regression was run (Williams, 2016). Plotting the coefficients across the different logistic regressions, the parallel odds assumption was met across the large majority of models. The outcomes are reported as odds ratio (OR), which represents the change in the odds of being in a higher category of the dependent variable associated with a one-unit increase in the predictor.

Intraclass correlation coefficients (ICCs) of the null models indicated that sample points should be included as a random factor for the NMV use models (ICC=0.10–0.15) and may be included in the walking models (ICC=0.01–0.05). For all but two models (walking in rural areas and small towns), model fit improved significantly (decrease in the Akaike information criterion >5) when adding random intercepts for the sample points. Differences in fixed effect estimates for those two models with and without random factors were negligible, and thus sample points were included in all models to maintain comparability between models. The predictors of interest were the 12 perceived environment variables as fixed factors. Since physical activity has shown associations with socio-demographic characteristics, the final models also included age, sex (n_{boys}=1,935; n_{girls}=2,041), and SES. A dummy-coded measurement-wave variable was added to account for potential cohort effects (n_{wave2}=2,894; n_{wave3}=1,082). Sample points were included as a random factor, allowing for different intercepts for walking and NMV use scores for each sample point.

Logit models with standard unstructured thresholds were selected for all models based on model fit. Model summaries were created using the sjPlot package (Lüdecke, 2023). All cases with complete data were considered for the analysis.

3.4 Results

In wave 2, 3,219 adolescents aged 11–17 participated, of whom 2,894 had complete data (10.0% removed due to missing data). In wave 3, 1,261 adolescents aged 11–17 participated, of whom 1,082 had complete data (14.2% removed due to missing data). Reasons for exclusion were missing data on SES (n=77), walking (n=205), NMV use (n=119), and/or in one or more environment variables (n=278; for details see figure 3.1). Excluded participants from wave 2 were not different to those included. In wave 3, participants excluded due to missing data were more likely to have a low SES (30% vs. 20%).

The sample was on average 14.5±2.0 years old, 51% were girls, and most participants lived in small (n=1,323) and medium-sized towns (n=1,136). While walking was distributed similarly across urbanicity levels, NMV use for 10 or more minutes per day was highest in medium-sized towns (see table 3.1). Cities had the highest rate of adolescents who (almost) never use NMV (36%). Participants from MoMo wave 2 were slightly older (14.6±2.0 vs. 14.3±2.0 years) and had a lower SES score (14.0±3.8 vs. 15.2±3.3) than participants from MoMo wave 3 (see Supplementary Table 1 in the published article for details).

3.4.1 Environment perceptions across urbanicity levels

As presented in figure 3.2, perceptions of the neighbourhood environment differed between urbanicity levels. Perceptions of the presence of sports and recreational facilities, walking and cycling infrastructure presence, and access to shops and bus stops by foot were higher in more urban areas. However, rural adolescents perceived their neighbourhood to have fewer cars and a higher crime safety and to be more pleasant for walking and cycling. Some perceptions, such as the presence of sports clubs and commercial sports facilities as well as cycling paths, were rated highest in medium-sized towns, showing a non-linear pattern across urbanicity levels.

Table 3.1: Description of the sample stratified by urbanicity level

	Rural, n = 800	Small town, n = 1,323	Medium-sized town, n = 1,136	City, n = 717	Overall, n = 3,976
Measurement wave					
MoMo wave 2	580 (73%)	1,004 (76%)	836 (74%)	474 (66%)	2,894 (73%)
MoMo wave 3	220 (28%)	319 (24%)	300 (26%)	243 (34%)	1,082 (27%)
Age[1]	14.5 (2.0)	14.5 (2.0)	14.5 (2.0)	14.5 (2.0)	14.5 (2.0)
Sex					
Male	408 (51%)	630 (48%)	551 (49%)	346 (48%)	1,935 (49%)
Female	392 (49%)	693 (52%)	585 (51%)	371 (52%)	2,041 (51%)
Socioeconomic status[1,2]	13.4 (3.5)	13.9 (3.5)	14.7 (3.7)	15.5 (3.8)	14.3 (3.7)
Walking					
Almost never	15 (1.9%)	42 (3.2%)	61 (5.4%)	21 (2.9%)	139 (3.5%)
Less than 1 km (<15 min) per day	121 (15%)	205 (15%)	196 (17%)	82 (11%)	604 (15%)
1-2 km (15-30 min) per day	358 (45%)	515 (39%)	459 (40%)	289 (40%)	1,621 (41%)
3-5 km (30-60 min) per day	242 (30%)	443 (33%)	328 (29%)	257 (36%)	1,270 (32%)
6-10 km (1-2 h) per day	56 (7.0%)	96 (7.3%)	82 (7.2%)	60 (8.4%)	294 (7.4%)
More than 10 km (>2 h) per day	8 (1.0%)	22 (1.7%)	10 (0.9%)	8 (1.1%)	48 (1.2%)
Non-motorised vehicle use					
(Almost) No cycling, longboarding, etc.	233 (29%)	334 (25%)	270 (24%)	256 (36%)	1,093 (27%)
Less than 1km per day	194 (24%)	249 (19%)	132 (12%)	116 (16%)	691 (17%)
1-5km (<10 min) per day	235 (29%)	414 (31%)	348 (31%)	157 (22%)	1,154 (29%)
6-10km (10-30min) per day	107 (13%)	252 (19%)	299 (26%)	144 (20%)	802 (20%)
11-20km (30-60 min) per day	26 (3.3%)	62 (4.7%)	80 (7.0%)	35 (4.9%)	203 (5.1%)
More than 20km (>60min) per day	5 (0.6%)	12 (0.9%)	7 (0.6%)	9 (1.3%)	33 (0.8%)

All measures are in format n (%) unless specified otherwise,
[1]Mean (standard deviation),
[2]Socioeconomic status is measured on a scale from 3 to 21, with higher values indicating a higher status

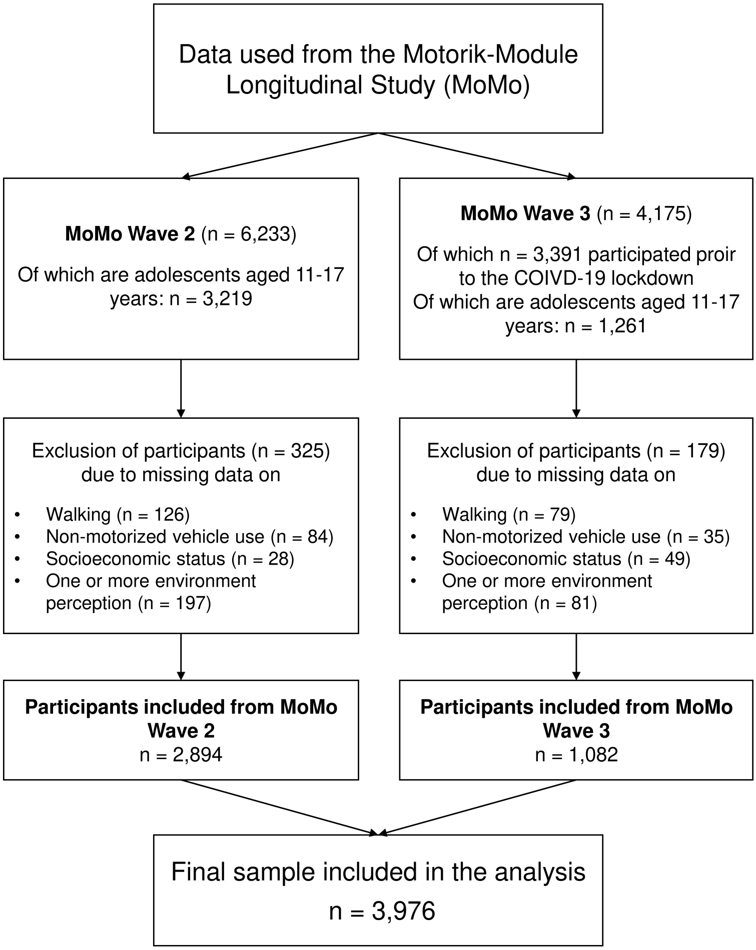

Figure 3.1: Flowchart of the participants included in the analyses

3.4.2 Relationship between perceived environment and walking

In rural areas, the perceived presence of public sports facilities (OR=1.29, p=0.025), cycling paths (OR=1.30, p<0.001), and cars (OR=0.81, p=0.026) was associated with walking (see table 3.2). In medium-sized towns, the presence of public sports facilities (OR=1.32, p=0.002) and playgrounds (OR=1.28, p=0.006) was linked to more walking. In cities, access to shops by foot (OR=1.26, p=0.029) was associated with walking. No associations were observed in small towns. Overall, walking increased with age (OR=1.11–1.19, all p<0.004). Higher SES was related to

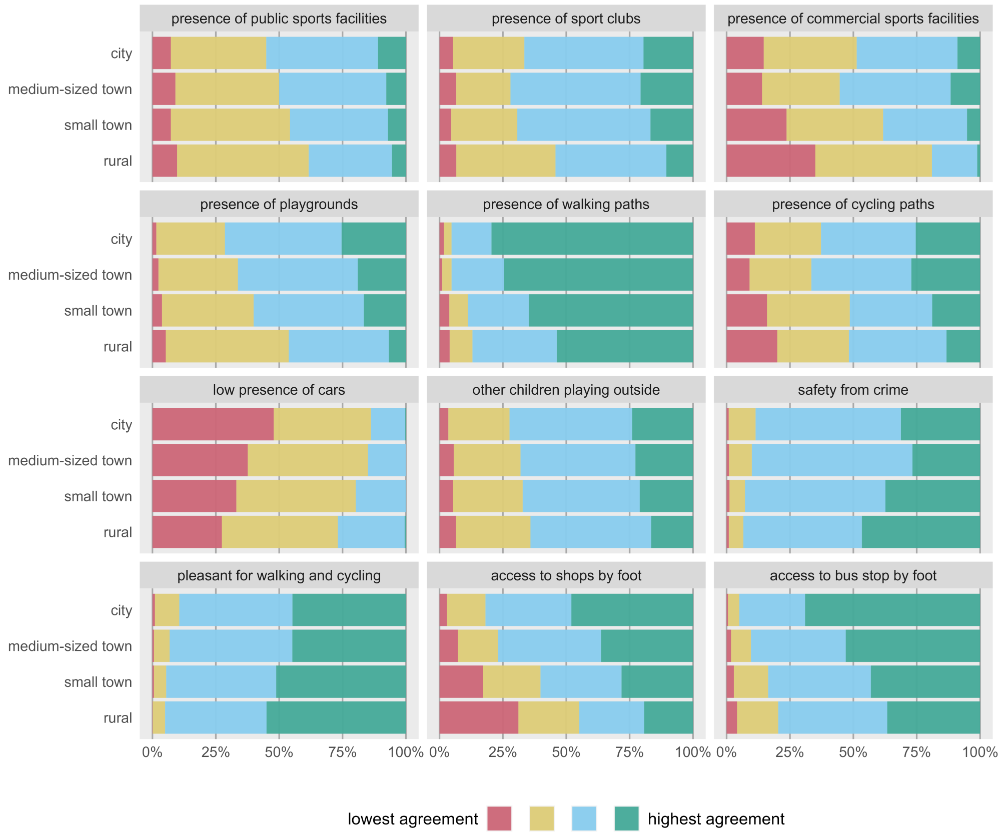

Figure 3.2: Distribution of environment perceptions across urbanicity levels

The item *presence of cars* was reverse-coded for this plot to keep the colour scheme consistent (*red* = less PA-friendly neighbourhood, *green* = more PA-friendly neighbourhood). Data used for this plot can be found in Supplementary Table 2 of the published article.

more walking in rural areas (OR=1.06, p=0.032), but to less walking in medium-sized towns (OR=0.97, p=0.029). Rural participants in MoMo wave 3 engaged in more walking than those in wave 2 (OR=1.40, p<0.001).

3.4.3 Relationship between perceived environment and non-motorised vehicle use

In rural areas, the presence of public sports facilities (OR=1.33, p=0.012), perceiving the neighbourhood to be pleasant for walking and cycling (OR=1.29, p=0.037), having access to shops

Table 3.2: Results of the cumulative link mixed models predicting walking across urbanicity levels

	Rural			Small town			Medium-sized town			City		
	OR	95% CI	*P*	OR	95% CI	*p*	OR	95% CI	*p*	OR	95% CI	*p*
Age	**1.15**	**1.07; 1.23**	**<0.001**	**1.19**	**1.13; 1.26**	**<0.001**	**1.12**	**1.06; 1.19**	**<0.001**	**1.11**	**1.04; 1.19**	**0.003**
Sex: female (Ref. male)	0.77	0.59; 1.01	0.056	1.08	0.89; 1.33	0.430	1.02	0.82; 1.27	0.845	0.83	0.62; 1.09	0.182
Measurement wave: wave 3 (Ref. wave 2)	**1.40**	**1.03; 1.90**	**0.032**	1.20	0.94; 1.54	0.144	1.14	0.87; 1.48	0.342	1.14	0.84; 1.56	0.400
Socioeconomic status	**1.06**	**1.02; 1.11**	**0.002**	1.00	0.97; 1.03	0.889	**0.97**	**0.94; 1.00**	**0.029**	1.01	0.97; 1.05	0.689
Presence of public sports facilities	**1.29**	**1.03; 1.61**	**0.025**	1.17	0.98; 1.39	0.076	**1.32**	**1.11; 1.58**	**0.002**	1.13	0.90; 1.41	0.292
Presence of sport clubs	0.97	0.77; 1.22	0.781	1.01	0.85; 1.20	0.930	1.12	0.94; 1.34	0.198	0.84	0.67; 1.05	0.122
Presence of commercial sports facilities	1.00	0.80; 1.24	0.978	0.92	0.79; 1.06	0.250	0.87	0.75; 1.02	0.097	1.13	0.92; 1.38	0.253
Presence of playgrounds	1.23	0.99; 1.53	0.057	1.10	0.93; 1.30	0.259	**1.28**	**1.07; 1.54**	**0.006**	0.96	0.77; 1.18	0.682
Presence of walking paths	1.05	0.87; 1.26	0.637	0.85	0.73; 1.00	0.051	1.07	0.87; 1.31	0.529	0.97	0.74; 1.26	0.796
Presence of cycling paths	**1.30**	**1.11; 1.52**	**0.001**	1.05	0.94; 1.18	0.377	0.90	0.79; 1.04	0.149	1.06	0.89; 1.25	0.531
Presence of cars	**0.81**	**0.67; 0.97**	**0.026**	0.96	0.83; 1.11	0.605	0.99	0.84; 1.18	0.936	1.00	0.81; 1.24	0.964
Other children playing outside	1.06	0.88; 1.27	0.547	1.12	0.97; 1.29	0.117	1.05	0.90; 1.22	0.554	0.95	0.77; 1.17	0.622
Safety from crime	1.08	0.87; 1.35	0.472	1.00	0.84; 1.18	0.964	0.84	0.69; 1.02	0.082	1.04	0.82; 1.32	0.734
Pleasant for walking and cycling	0.97	0.76; 1.23	0.775	1.08	0.90; 1.29	0.425	1.11	0.92; 1.34	0.279	0.87	0.70; 1.08	0.212
Access to bus stop by foot	0.88	0.73; 1.06	0.190	1.04	0.90; 1.20	0.559	0.93	0.79; 1.11	0.440	0.79	0.60; 1.05	0.105
Access to shops by foot	0.95	0.83; 1.09	0.500	0.99	0.88; 1.11	0.835	1.04	0.91; 1.19	0.587	**1.26**	**1.02; 1.55**	**0.029**
Random effects												
σ_2	3.29			3.29			3.29			3.29		
τ_{00}	0.02			0.03			0.14			0.18		
ICC	0.01			0.01			0.04			0.05		
$N_{samplepoints}$	48			65			63			39		
Observations	800			1323			1136			717		
Marginal R^2/Conditional R^2	0.111/0.116			0.048/0.056			0.059/0.096			0.036/0.085		

OR: odds ratio, CI: confidence interval (format: lower limit; upper limit), σ_2: residual variance, τ_{00}: variance between sample points, ICC: intraclass correlation coefficients

(OR=1.16, p=0.037) and to cycling paths (OR=1.29, p=0.002) were associated with NMV use (see table 3.3). In small towns, having public sports facilities (OR=1.23, p=0.020), a neighbourhood pleasant for walking and cycling (OR=1.26, p=0.015), and access to shops (OR=1.15, p=0.021) were related to a higher duration of NMV use, whereas access to bus stops was related to lower NMV use (OR=0.80, p=0.003). In medium-sized towns, cycling paths (OR=1.29, p<0.001) and lower presence of cars (OR=0.83, p=0.034) were linked to higher NMV use. In cities, public sports facilities (OR=1.33, p=0.011) and the presence of cars (OR=0.80, p=0.037) were associated with NMV use. Overall, girls used NMV less than boys did (OR=0.45–0.71, p<0.018). In rural areas (OR=0.87, p<0.001) and small towns (OR=0.87, p<0.001) NMV use decreased with age. Adolescents living in medium-sized towns with a higher SES used NMV longer than those with a lower SES (OR=1.04, p=0.012).

3.5 Discussion

This study aimed to investigate differences in physical environment perceptions and their relationship with walking and NMV use in adolescents across urbanicity levels in a nationwide study in Germany. In summary, perceptions of the neighbourhood environment differed across urbanicity levels. Different associations were found between the perceived neighbourhood environment and the active travel modes walking and NMV use across urbanicity levels. Overall, there were more associations between environment perceptions and NMV use than for walking. Apart from public sports facilities, different relationships were found with walking and NMV use across urbanicity levels. For example, the presence of cycling paths and a lower presence of cars was associated with walking in rural areas, whereas in cities, only the access to shops was relevant. Having a neighbourhood that is pleasant for walking and cycling and having access to shops by foot was associated with NMV use in rural areas and small towns while a lower presence of cars was related to NMV use in medium-sized towns and cities.

3.5.1 The role of recreational facilities and public spaces for active travel

Only the presence of public sports facilities in the neighbourhood was largely associated with AT across travel modes and urbanicity levels. Living close to recreational facilities and public spaces with opportunities for PA such as parks was associated with the use of such places and therefore an important source for PA in adolescents (Grow et al., 2008; Veitch et al., 2014). An Australian study found that 87% of trips to public spaces such as parks and playgrounds are done actively on foot or by using bikes, skateboards, or scooters across rural and urban areas (Veitch et al., 2014).

Table 3.3: Results of the cumulative link mixed model predicting non-motorised vehicle use across urbanicity levels

	Rural			Small town			Medium-sized town			City		
	OR	95% CI	*p*	OR	95% CI	*p*	OR	95% CI	*p*	OR	95% CI	*p*
Age	**0.87**	**0.81; 0.93**	**<0.001**	**0.87**	**0.83; 0.92**	**<0.001**	1.02	0.97; 1.08	0.457	0.99	0.92; 1.06	0.703
Sex: female (Ref. male)	**0.45**	**0.35; 0.59**	**<0.001**	**0.47**	**0.39; 0.58**	**<0.001**	**0.67**	**0.54; 0.83**	**<0.001**	**0.71**	**0.54; 0.94**	**0.017**
Measurement wave: wave 3 (Ref. wave 2)	0.89	0.65; 1.23	0.485	0.79	0.60; 1.03	0.084	0.83	0.63; 1.09	0.172	0.99	0.73; 1.35	0.957
Socioeconomic status	0.97	0.93; 1.01	0.135	1.00	0.97; 1.03	0.788	**1.04**	**1.01; 1.07**	**0.012**	1.04	1.00; 1.08	0.081
Presence of public sports facilities	**1.33**	**1.07; 1.66**	**0.012**	**1.23**	**1.03; 1.46**	**0.020**	1.00	0.84; 1.20	0.990	**1.33**	**1.07; 1.67**	**0.011**
Presence of sport clubs	0.99	0.79; 1.24	0.957	1.11	0.93; 1.32	0.232	1.11	0.93; 1.33	0.234	1.13	0.90; 1.42	0.297
Presence of commercial sports facilities	0.87	0.70; 1.09	0.223	1.10	0.94; 1.28	0.230	0.96	0.82; 1.13	0.662	0.97	0.79; 1.18	0.742
Presence of playgrounds	1.13	0.90; 1.42	0.278	0.87	0.73; 1.03	0.112	0.99	0.83; 1.19	0.932	0.95	0.77; 1.18	0.654
Presence of walking paths	1.02	0.84; 1.23	0.858	0.99	0.85; 1.17	0.941	0.94	0.76; 1.16	0.557	1.06	0.81; 1.39	0.655
Presence of cycling paths	**1.29**	**1.10; 1.51**	**0.002**	1.11	0.98; 1.25	0.094	**1.29**	**1.13; 1.48**	**<0.001**	1.13	0.95; 1.34	0.156
Presence of cars	1.03	0.85; 1.24	0.778	1.10	0.95; 1.28	0.183	**0.83**	**0.71; 0.99**	**0.034**	**0.80**	**0.64; 0.99**	**0.037**
Other children playing outside	0.97	0.81; 1.17	0.785	1.12	0.97; 1.29	0.108	1.09	0.93; 1.28	0.273	1.00	0.81; 1.24	0.983
Safety from crime	0.86	0.69; 1.07	0.164	1.02	0.86; 1.21	0.830	1.07	0.88; 1.30	0.472	0.91	0.72; 1.15	0.415
Pleasant for walking and cycling	**1.29**	**1.02; 1.64**	**0.037**	**1.26**	**1.05; 1.51**	**0.015**	0.91	0.75; 1.10	0.325	1.12	0.89; 1.40	0.349
Access to bus stop by foot	0.84	0.70; 1.02	0.072	**0.80**	**0.69; 0.92**	**0.002**	0.94	0.80; 1.12	0.504	0.81	0.62; 1.07	0.133
Access to shops by foot	**1.16**	**1.01; 1.34**	**0.037**	**1.15**	**1.02; 1.29**	**0.021**	0.97	0.84; 1.11	0.627	**1.06**	**0.86; 1.31**	**0.558**
Random effects												
σ_2	3.29			3.29			3.29			3.29		
τ_{00}	0.28			0.39			0.40			0.50		
ICC	0.08			0.11			0.11			0.13		
$N_{samplepoints}$	48			65			63			39		
Observations	800			1323			1136			717		
Marginal R^2/Conditional R^2	0.115/0.183			0.090/0.188			0.044/0.148			0.056/0.181		

OR: odds ratio, CI: confidence interval (format: lower limit; upper limit), σ_2: residual variance, τ_{00}: variance between sample points, ICC: intraclass correlation coefficients

Therefore, accessible recreational spaces are a key destination for adolescents' AT and thus offer great potential for PA promotion both in rural areas and cities.

3.5.2 Diverse infrastructure needs and traffic safety concerns for walking and non-motorised vehicle use

Walking and NMV use rely on different road infrastructures, which raise different traffic safety concerns. While the perceived presence of walking paths was very high in our study, the presence of cycling paths was rather low, indicating a mismatch in infrastructure support for different AT modes (Pucher & Buehler, 2010). Traffic safety is an important factor for AT (Klos, Eberhardt, et al., 2023) and given the lower infrastructure support, this was a higher concern for NMV users. For example, adolescents in New Zealand perceive cycling to be less safe than walking and also report less sufficient infrastructure for cycling on their way to school (Mandic, Hopkins, García Bengoechea, Flaherty, et al., 2017; M. L. Rahman et al., 2022). Other NMVs such as skateboards or inline skates have specific needs such as a smooth surface (Platt & Rybarczyk, 2021), requiring more demanding infrastructure to be considered as a means of transport. Thus, infrastructure and traffic safety-related aspects such as having bike paths, low presence of cars, and living in a neighbourhood that is pleasant for walking and cycling are more important for NMV use than for walking. In summary, adolescents use different environmental perceptions for their decision-making on whether to walk or use NMVs and therefore different AT behaviours should be considered separately. Given the higher safety requirements for cyclists, a stronger emphasis should be put on safe infrastructure for cyclists while also considering the needs of other NMV users, which often is not appropriately addressed both in research and urban planning (Cook et al., 2022).

3.5.3 Factors influencing travel mode choices: proximity, distance, and competing alternatives

Walking is the slowest travel mode, meaning that in most cases only destinations in direct proximity are reached by foot while for more distant destinations, adolescents might use a bike (Mandic et al., 2023). For example, in Belgian older adolescents, distances up to 2 km are considered feasible to walk to school while feasible cycling distances are up to 8 km (van Dyck et al., 2010). However, for longer distances, public transport might compete with cycling as a more convenient alternative (Simons et al., 2013). This supports the results of our study, with having access to bus stops being related to less NMV use in small towns. The decision to walk or use NMVs is determined not only by distance and the perceived environment but also by the type of destination and available alternatives (Marzi et al., 2023). While our study cannot provide context on frequency, distance, and destination of trips, other studies such as the ARRIVE study (Reimers et al., 2022) can provide more details on the decision-making process for walking and cycling trips in adolescents in the future.

3.5.4 Associations between urbanicity, active travel, and environmental perceptions

There are some differences in associations between urbanicity levels. Few studies have assessed associations between perceptions of the environment and AT in rural areas and few relationships have been found (Hofer-Fischanger et al., 2022; Kamargianni & Polydoropoulou, 2014). Both studies, conducted in Greece and Austria, report that having a well-maintained and safe walking and cycling network is related to AT in rural areas. Similar results were found in our study, with the presence of bike paths being related to both walking and NMV use and having a pleasant neighbourhood for walking and cycling being related to NMV use only. However, for medium-sized towns and cities, it is not the pleasantness of walking and cycling that is associated with NMV use but the lower presence of cars. Thus, in rural areas, a lack of well-maintained and safe walking and cycling networks might limit NMV use. By contrast, in more urban areas, heavy car traffic may be the main problem. Therefore, decreasing car traffic volume and enhancing infrastructure for NMVs are important measures for AT promotion (Benoit et al., 2022).

3.5.5 Variability in non-motorised vehicle use: regional factors and implications for policy and research

Finally, NMV use differs considerably across sample points in contrast to walking, where almost no variance between sample points was found. Even when accounting for urbanicity level, socio-demographic factors, and environmental perceptions the sample points explain between 8% and 13% of the variance in the NMV use models. Although cycling for transport has gained popularity in Germany over the past few decades, especially in cities (Hudde, 2022), there are large differences between cities regarding the friendliness of cycling (Klinger et al., 2013). While there were few perceptions directly related to cycling, there might be other region-specific environmental features that impact NMV use that were not measured in this study. Exploring characteristics of specific cities or towns with the highest and lowest NMV use could help to understand those differences, e.g. by looking at local cycling-related policies. This would make it possible to identify “cycling cities” or “cycling towns” to find good practice examples for public health advocates, policymakers, and transport planners. In research, large-scale, representative studies are needed to further analyse the differences in NMV use across regions while also incorporating more comprehensive measures of the perceived environment, objective measures of the built environment, and topography.

Creating sustainable cities and communities built for AT can create local social and economic benefits and improve the health and well-being of residents (C. Nigg & Nigg, 2021). On a global scale, AT contributes to planetary health by reducing greenhouse gas emissions. The transport sector in Europe contributes to over one fourth of the CO_2 emissions, which have been steadily growing over recent decades despite increasing efforts to reduce them (European Envrionment Agency, 2023), highlighting the need for more decisive actions. Therefore, it is important to bring together the disciplines of sports and exercise science, public health, transport planning, and urban planning to create sustainable and safe environments for AT (Koszowski et al., 2019). Transdisciplinary research focusing on a bottom–up approach to create sustainable and physical activity-friendly neighbourhoods can best account for the local context (Wäsche et al., 2021).

3.5.6 Strengths and limitations

This study is the first nationwide study in Germany focusing on the relationship between perceived environment and walking and NMV use in adolescents. Given the representative sampling in 167 points across Germany, we were able to present reliable cross-sectional data across different urbanicity levels pooled across two measurement waves.

Whereas most studies on AT focus on walking and cycling only (Cook et al., 2022), we summarised bikes and other NMVs such as skateboarding or inline-skating into one category - acknowledging transport niches or trends. Although we were able to also include other modes of NMV, we were not able to differentiate further how many of the NMV users were not cycling. While the environment questionnaire is reliable, more comprehensive questionnaires (e.g. ALPHA environment questionnaire; Spittaels et al., 2009) would facilitate a more thorough assessment of the environment perceptions. An analysis based on subscales rather than single items would have led to more generalisable results but was not possible due to opposing relationships with walking and NMV use within scales. Parents' perceptions also play a significant role in adolescents' travel choices (Klos, Eberhardt, et al., 2023; Mandic et al., 2020; Panter et al., 2008). However, those were not assessed in MoMo.

Cumulative link mixed models were chosen as they effectively accommodated the non-linear characteristics of the outcome variables while simultaneously considering the ordinal structure. The majority of variables in each model satisfied the parallel odds assumption, with only a few exceptions potentially leading to a few slightly less precise estimates. Compared to alternative approaches such as collapsing categories for binary logistic regression or employing unordered multinomial logistic regression, these models provided a superior solution that acknowledged the complex nature of the data without sacrificing interpretability.

It also needs to be acknowledged that this was a cross-sectional study and no causal relationships between environment perceptions and walking or NMV use can be assessed. Finally, the urbanicity measure was merely based on population size. While this measure, as the political community size system allows, facilitates communication to policymakers, other urbanicity measures that do not only account for population size but also take the geographic context into account (e.g. population density or the European Degree of Urbanisation) may be more suitable in the research context.

3.6 Conclusion

Promoting walking and use of non-motorised vehicles (NMV) can improve individual health and well-being, helps to create sustainable cities and communities, and contributes to climate action. In this representative, nationwide study, we showed that different environmental perceptions relate to walking and NMV use. These relationships differ across travel modes and urbanicity levels, highlighting the complex nature between the perceived environment and active travel. Based on these findings, public sports facilities or shops in proximity to adolescents' homes, and providing safe infrastructure for NMVs such as bikes, skateboards, and inline skates, should be the main goals for public health advocates and urban and traffic planners while keeping local conditions in mind. In research, more nationwide or representative studies are needed to validate our findings and to further explore differences in regional contexts.

4 Third paper: Groundwork for adolescent bikeability assessment in Germany: An open GIS and regularised regression approach across cities, towns and rural areas

This chapter is a slightly modified version of the manuscript submitted to the journal *Transportation Research Interdisciplinary Perspectives*.

Klos, L., Lazarides, C., Pedrick-Case, R., Fry, R., Wäsche, H., Niessner, C., & Woll, A. (under review). Groundwork for adolescent bikeability assessment in Germany: An open GIS and regularised regression approach across cities, towns and rural areas.

4.1 Abstract

Adolescents need safe infrastructure, accessible places and comfort to cycle for transport. However, the bikeability literature focuses almost exclusively on adult cycling in large cities. The aims of the study are to operationalise bikeability characteristics adapted to adolescents in the German context using open GIS data and assess the relation between bikeability characteristics within different cycling distances and cycling to school in adolescents living in cities, towns and rural areas.

Cycling infrastructure and access to different destinations relevant to adolescents were operationalised using open GIS data. German-wide cycling-to-school data of 1,133 adolescents aged 11-17 years (50.0% girls) from the Motorik-Modul Study were linked to the bikeability measures. A logistic ridge regression identified relevant bikeability characteristics in cities, towns and rural areas within five different cycling radii between 4-20 minutes.

Adolescents living in cities had higher odds of cycling if there were more residential streets with a slow speed limit within a 16-minute cycling radius from home and better access to outdoor sports facilities, shops and food outlets within 4-16 minutes of cycling. In towns, cycling was positively associated with both slow residential streets and separated cycling infrastructure, as well as access to schools, shops, food outlets, outdoor sports facilities, and a larger residential population within similar travel ranges.

Cycling may be facilitated by different infrastructure and accessibility characteristics in cities and towns. Future bikeability research should target vulnerable groups and people living in less densely populated areas. This work lays the groundwork for an adolescent bikeability index for Germany.

4.2 Introduction

Insufficient physical activity among adolescents is a major health concern. In response, the World Health Organisation has set the goal of a 15% relative reduction in the prevalence of physical inactivity in adolescents and adults by 2030 (Guthold et al., 2020). Active travel, particularly cycling, is a low-threshold activity that can be integrated into everyday life to increase physical activity (Martin et al., 2016; Prince et al., 2022). Cycling to school is associated with several health benefits, including higher cardiovascular fitness (Larouche, Saunders, et al., 2014; Lubans et al., 2011) and reduced psychosomatic symptoms (Kleszczewska et al., 2020). In addition, cycling may not only improve individual but also planetary health by reducing CO_2 emissions, air and noise pollution when used instead of motorised transport (Abu-Omar et al., 2023). Despite this, many short trips are still made using passive transport modes, and it is estimated that up to 44% of these could be replaced by cycling based on a study on mostly urban-living adolescents living in Victoria, Australia (Loh et al., 2022). Among adolescents and their parents, the most common barriers for cycling are access to places to cycle to, long distances and traffic safety aspects (Aranda-Balboa et al., 2021; Klos, Eberhardt, et al., 2023). The latter are especially important as adolescents are still inexperienced in managing traffic and begin to travel independently (Mitra, 2013). Further, adolescence is a key developmental period for establishing lifelong health behaviours, including physical activity and active travel habits (Kaseva et al., 2023; van Sluijs et al., 2021).

The term bikeability, meaning "an assessment of an entire bikeway network for perceived comfort and convenience and access to important destinations" (Lowry et al., 2012, p. 41) was established in recent years to identify neighbourhoods that are conducive to cycling and those that require improvements. Several reviews addressed the growing number of bikeability indices, most of which comprised indicators of cycling infrastructure, traffic safety, land use, accessibility, and hilliness measured via geographic information systems (GIS) (Castanon & Ribeiro, 2021;

Kellstedt et al., 2021; Muhs & Clifton, 2016; Valenzuela et al., 2022). However, they are almost exclusively developed for adults living in single large cities such as Vancouver, Barcelona or Munich (Codina et al., 2022; Hardinghaus et al., 2021; Kamel et al., 2020). Although bikeability measures were developed for primary school children in Stockholm (Paulusová & Sharmeen, 2025), an adolescent population has not been addressed yet. Further, there is a lack of bikeability assessments outside of large cities, e.g. in towns or rural areas, despite their potential for cycling promotion (Kircher et al., 2022).

Cycling should be inclusive of all age groups and across cities, towns and rural areas, as emphasised by the Global Action Plan on Physical Activity (World Health Organization, 2018) and the European Declaration on Cycling (European Commission, 2024). Rather than developing a comprehensive bikeability index, this study takes a foundational approach by identifying and operationalising key GIS-based measures focusing on cycling infrastructure, accessibility, and topography that are tailored to adolescent cycling. These measures are then evaluated in relation to cycling to school across varying cycling radii. This study provides the groundwork for developing a bikeability index for adolescents applicable to different urbanisation levels in Germany.

Therefore, the aims of the study are to (1) operationalise bikeability characteristics adapted to adolescents in the German context using open GIS data and (2) assess the relation between bikeability characteristics within different cycling distances and cycling to school in adolescents living in cities, towns and rural areas.

4.3 Methods

In this section, the selected GIS indicators and their operationalisation are documented. It follows a brief description of the Motorik-Modul (MoMo) Study, its data used for the analysis and the statistical approach.

4.3.1 Geographic information system indicators

The indicators selected for this study are based on the three categories most commonly represented in bikeability indices: cycling infrastructure and traffic safety, connectivity and urbanisation, and the surrounding environment (Castanon & Ribeiro, 2021; Paulusová & Sharmeen, 2024; Valenzuela et al., 2022). Within each category, indicators were identified following the suggestions of Paulusová and Sharmeen's (2024) review on school bikeability, adapted to the German context, and operationalised using open GIS data with nationwide coverage.

4.3.1.1 Cycling infrastructure and safety

Children and adolescents require safer cycling infrastructure than adults. Paulusová and Sharmeen (2024) highlight that both the presence and the type of cycling infrastructure, as well as traffic volume and speed, are decisive for adolescents' bikeability. For example, in a UK study, 88% of adults preferred cycling in a painted cycle lane, but only 42% would allow their 12-year-old to do so (Aldred, 2015). In contrast, physically separated cycle paths or shared cycle-foot paths disconnected from motor traffic were perceived as safe options for children by most adults. Similarly, a stated preference survey among 9,554 adolescents living in urban, rural, and insular areas in Greece and Cyprus indicated that the presence of physically separated cycle paths compared to cycle lanes would lead to substantially more adolescent cyclists based on their mode choice model (Kamargianni, 2015).

In addition to separated cycling infrastructure, residential streets with a low traffic volume and speed are also perceived as safe to cycle by Belgian adolescents (Benoit et al., 2022). Supporting this, Verhoeven, van Hecke, et al. (2018) compared the shortest and actual cycling routes taken by adolescents in Flanders and found that many chose detours to avoid arterial roads and instead cycle on streets with a 30 km/h speed limit, indicating a clear preference for calmer traffic conditions. Although empirical data on adolescents' cycling preferences are limited for Germany, findings from comparable European contexts are likely to be transferable. Moreover, concerns about crime are not related to active travel among adolescents in Germany (Klos et al., 2024) and thus crime-related safety indicators were excluded from this analysis.

Three types of street infrastructure were operationalised using OpenStreetMap (OSM) data (see table 4.1): Main streets with a physically separated cycle path, total designated cycling infrastructure including paths disconnected from car traffic, and residential streets with a speed limit of 30 km/h or less. Further cycling infrastructure indicators stated by Paulusová and Sharmeen (2024), such as the width and quality of the cycle path, signage or signalling, were not included due to limitations in OSM data coverage and mapping consistency.

4.3.1.2 Connectivity and urbanisation

Connectivity plays a dual role in cycling environments. On one hand, a highly connected street network offers cyclists greater route flexibility and accessibility. On the other hand, it increases the number of intersections, which may require cyclists to slow down, stop at traffic lights, or navigate potential conflicts with other road users (Paulusová & Sharmeen, 2024). To account for connectivity, time penalties for intersections were applied when defining the feasible cycling radius.

Table 4.1: GIS-measures used to operationalise bikeability characteristics

Construct	Operationalisation	Data source and date	OSM keys & values
Overall designated cycling infrastructure	Any cycling infrastructure that is physically separated or disconnected from car traffic	OSM, 01/11/2023	highway = cycleway (highway = path, footway) & (bicycle = yes, designated) (highway = trunk, trunk_link, primary, primary_link, secondary, secondary_link, tertiary, tertiary_link) & cycleway = track
Main streets safe for cycling	Main streets that have a physically separated cycleway	OSM, 01/11/2023	(highway = trunk, trunk_link, primary, primary_link, secondary, secondary_link, tertiary, tertiary_link) & (bicycle = yes, designated or cycleway = track, separated)
Residential streets safe for cycling	Residential streets with a speed limit of $\leqslant$30 km/h and living or bicycle streets	OSM, 01/11/2023	(highway = residential, unclassified) & (maxspeed $\leqslant$30 or bicycle_road = yes) highway = living_street
Schools	(Centroid) location/Number of schools	OSM, 01/11/2023	amenity = schools
Shopping facilities	(Centroid) location/Number of shopping and food facilities	OSM, 01/11/2023	shop = convenience, kiosk, general, department_store, mall, supermarket, bakery, food amenity = café, fast_food, ice_cream
Parks	(Centroid) location and area (m^2) of parks	OSM, 01/11/2023	leisure = park
Sports facilities	(Centroid) location and area (m^2) of outdoor sports facilities	OSM, 01/11/2023	leisure = pitch
Home of friends and relatives	(Centroid) location and number of residents in 100m x 100m tiles	German Census, 09/05/2011	-
Hilliness	Bare-earth heights at 8-10m vertical accuracy at 1:100000 scale	EuroDEM, 04/2008	-
Urbanisation	Classification of the home municipality based on the degree of urbanisation (city, town, rural area)	Eurostat, 31/12/2022	-

OSM: Open Street Map; EuroDEM: European Digital Elevation Model

Closely related to connectivity is accessibility to different destinations that are context- and age-dependent. In Germany, approximately 36% of adolescents' trips are school-related, 40% are for leisure activities (e.g. visiting friends or sports facilities), and 15% are for shopping or errands (Nobis & Kuhnimhof, 2018). Between 30% and 50% of these trips are regularly made by bicycle (Marzi et al., 2023), highlighting the importance of these destinations and their potential for cycling in adolescents.

Therefore, five different destinations were included as accessibility measures: schools, sports facilities, parks, shops and food outlets, and friends and relatives. Schools, shops and food outlets were operationalised as counts. Sports facilities were limited to outdoor sports facilities, as indoor sports facilities are tagged inconsistently in OSM and could therefore not be used. For parks and outdoor sports facilities, area size rather than count was used to reflect capacity differences (e.g. a football pitch can be used by more people at the same time than a tennis pitch). Population count at a 100 x 100m resolution from the German Census was used as a proxy for proximity to friends and relatives.

Cycling behaviour differs significantly between urbanisation levels. For example, only 12% of children cycle to school in rural areas compared to 30% of children in medium-sized towns in Germany (Reimers et al., 2021). In addition, environmental perceptions such as the presence of cycling paths and car traffic show different associations with cycling across urbanisation levels (Klos et al., 2024). To account for these differences, the analysis was nested within cities, towns, and rural areas, rather than using interaction terms. This approach allows for identifying which bikeability characteristics are relevant within each urbanisation level, rather than comparing differences between them.

The degree of urbanisation from Eurostat (2021) was used. It first classifies 1 km^2 grid cells based on population density and contiguity into urban centres (>50000 inhabitants and $\geqslant$1500 inhabitants/km^2), urban clusters (>5000 inhabitants and $\geqslant$300 inhabitants/km^2), and rural grid cells (everything else). Municipalities are then categorised into cities ($\geqslant$50% of population lives in urban centres), towns (<50% of population lives in an urban centre and $\geqslant$50% of population lives in urban clusters) and rural areas ($\geqslant$50% of population lives in rural grid cells).

4.3.1.3 Surrounding environment

Most important indicators of the surrounding environment relate to slopes or hilliness and natural elements (Paulusová & Sharmeen, 2024). Cycling in hilly terrain is less comfortable (Ghekiere et al., 2014) and requires more effort and time (Tscharaktschiew & Müller, 2021). To account for this, slopes were integrated into the routing algorithm by applying time penalties, thereby reducing the effective cycling distance within a given time frame. Elevation data was sourced from the European Digital Elevation Model (EuroDEM) using the bare-earth heights excluding vegetation and buildings at 8-10 m vertical resolution. In addition to topography, natural elements such as parks contribute to the cycling experience. Parks serve a dual function: they are both destinations for leisure and pleasant environments to cycle through. For the purpose of this analysis, parks were primarily considered as an accessibility measure.

4.3.2 The Motorik-Modul Study

The Motorik-Modul (MoMo) Study is a nationwide study that assesses physical fitness, physical activity, health, and their determinants in a representative sample of children and adolescents aged 4-17 years in Germany (Woll et al., 2021). It consists of four cross-sectional cohorts spanning from 2003-2022 and a longitudinal sample that was followed up at each measurement point after the baseline (2003-2006). Originally, MoMo was an in-depth study module of the German Health Interview and Examination Survey for Children and Adolescents (KiGGS) (Kurth et al., 2008). Its third measurement wave applied the same sampling procedure: 167 sample points were systematically drawn, stratified by degree of urbanisation and geographic distribution. At each point, a pre-specified number of children and adolescents were selected via addresses obtained from local population registries. This analysis used data from Wave 3 (2018–2022), including age, sex, cycling behaviour, socioeconomic status (SES), and geocoded home addresses of adolescents aged 11–17. We restricted our analysis to adolescents, as children's school travel differs substantially in terms of cycling prevalence, parental accompaniment, and legal restrictions on cycling infrastructure use, which makes results not directly comparable. On-site assessments were interrupted due to the COVID lockdowns. Therefore, only data collected before the governmental restrictions in March 2020 were used in this analysis. Up until this point, data collection at 128 of 167 sample points was completed. Participation was voluntary, with written consent obtained from participants (aged >16 years) or their legal guardians (if participants were aged ⩽16 years). The study was conducted according to the Declaration of Helsinki, and ethics approval was granted by the Karlsruhe Institute of Technology.

4.3.2.1 Cycling to school

Cycling to school was assessed via a single question on the most frequently used travel mode to and from (pre-)school, choosing from the options "by foot", "by bicycle", "by bus/train", "by car", "by motorbike", or "others". Responses were dichotomised into "by bicycle" and "not by bicycle".

4.3.2.2 Home address

The address data of the participants were provided by the registration office and geocoded using data from the Federal Agency for Cartography and Geodesy. Exact residential addresses were obtained from the participants and geocoded to building centroids, which served as the starting points for the routing algorithm.

4.3.2.3 Covariates

In Germany, several individual and contextual factors influence adolescent cycling. Boys, younger adolescents, and those with a high socioeconomic status (SES), are more likely to cycle to school (Marzi et al., 2023; Reimers et al., 2013, 2021; Schönbach, Brindley, et al., 2020). Therefore, these variables were included in the analysis as covariates. Age and sex were assessed via questionnaire. SES was assessed via a health interview, asking for parental education, occupation, and household income. Each dimension was scored from 1 to 7, and the highest parental scores were summed (range: 3-21) and categorised into low (lowest quintile), medium (middle three quintiles), and high (highest quintile) SES (Lampert et al., 2018). Cycling rates also vary significantly between municipalities (Klos et al., 2024) and those were also included as a covariate.

4.3.3 Cycling radius and time-based routing

As only the home location is known, the bikeability characteristics cannot be provided on a trip but rather on a neighbourhood level. Previous studies used buffers, i.e. zones around a point at a specified distance, either based on the Euclidean distance or the distance through a street network, that range from 100 m up to 5 km around home to approximate the most relevant area in which environment characteristics can be linked to active travel data (Smith et al., 2021). In general, there is a trade-off between small buffers, which may miss some areas that are important for the travel behaviour that lie outside the buffer and large buffers, which include all relevant characteristics and destinations but also contain large areas that are irrelevant and therefore weaken the relationships. There is no consensus on the optimal buffer size to use for a neighbourhood that can be reached by bike for adolescents. In Germany, adolescents on average cycle 4 km to school and 2 km to shops, leisure activities, and friends or relatives (Marzi et al., 2023). Therefore, a cycling distance up to 5 km seems adequate as environment characteristics within that rather large range were related to cycling in Australian school children (Carver et al., 2015). To find out which cycling distances are most relevant and to understand the implications of different buffer sizes, five different cycling ranges are calculated for this analysis. Instead of distance-based calculations, a time-based routing algorithm is used to apply time penalties for intersections and hilliness (Conveyal, 2024; Tobler, 1993) for a more realistic cycling radius estimation.

All GIS data was processed in R version 4.3.0 using the package “sf” (Pebesma, 2018; Pebesma & Bivand, 2023). Street network data from OSM was accessed via Geofabrik.de. OSM data to calculate the accessibility were accessed using the “osmextract” package (Gilardi & Lovelace, 2025). The open-source Rapid Realistic Routing on Real-world and Reimaged networks (R5) was used to assess accessibility and street infrastructure within a bikeable distance of participants’ homes. The *accessibility* function from the “r5r” package (Pereira et al., 2021) calculated accessibility (i.e. to schools, outdoor sports pitches, parks, shops and food outlets, population tiles) within 4, 8, 12, 16, and 20 min cycling radii at an average cycling speed of 15 km/h. To calculate the accessibility to each population tile, centroids were snapped to the closest street before analysis, as the exact locations of those points are arbitrary. Time penalties were applied for intersections and hilliness for a more realistic distance-time estimation (Conveyal, 2024; Tobler, 1993). The same settings were used to calculate isochrones and therefore the areas that can be reached within the set time and the length of each street infrastructure type (i.e. total designated cycling infrastructure including paths disconnected from car traffic, main streets with a physically separated cycle path, and residential streets with a speed limit of 30 km/h or less) within those areas. Finally, the cumulative measures were transformed to incremental measures by subtracting the next smaller buffer's measure from the larger one (i.e. 0-4 min, >4-8 min, >8-12 min, >12-16 min, and >16-20 min). This approach avoids buffer overlap, reduces multicollinearity, and improves interpretability.

4.3.4 Statistical analysis

All analyses were done in R version 4.3.0. To identify relevant GIS measures related to cycling to school across different buffer sizes, we used regularisation in combination with logistic regression. Regularised logistic regression is particularly useful for feature selection in datasets with a large number of predictors and high multicollinearity (Zou & Hastie, 2005). We chose regularised logistic regression rather than non-parametric machine learning approaches such as random forests, because our primary aim was not prediction accuracy but the identification and quantification of associations. Regularised logistic regression provides interpretable effect estimates in the form of odds ratios, while simultaneously addressing multicollinearity and enabling feature selection. According to Friedman et al. (2010, p. 8), the logistic elastic net regression can be expressed as:

$$\max_{(\beta_0,\beta)\in\mathbb{R}^{p+1}} \left[\frac{1}{N} \sum_{i=1}^{N} \{ I(g_i = 1) \log p(x_i) + I(g_i = 2) \log(1 - p(x_i)) \} - \lambda P_\alpha(\beta) \right]$$

where the first part represents the log-likelihood function for binary classification with $g_i \in \{1, 2\}$ and the second part is the elastic net penalty where the shrinking parameter λ determines the strength of regularisation applied to $\beta_1, \ldots, \beta_p$, but not to the intercept β_0. The elastic net mixing parameter $\alpha \in [0, 1]$ determines the balance between ridge (L2) and lasso (L1) regularisation:

$$P_\alpha(\beta) = (1 - \alpha) \frac{1}{2} ||\beta||_{l_2}^2 + \alpha ||\beta||_{l_1}$$

For example, in case of the ridge regression (α = 0), the penalty simplifies to:

$$P_0\left(\beta\right) = \frac{1}{2}||\beta||_{l_2}^2$$

The ridge penalty shrinks coefficients towards zero by penalising their squared magnitudes, but retains all variables.

The optimal configuration of the hyperparameters α and λ was determined through a 10-fold cross-validation with an automatically chosen range of λ using the packages "glmnet" (Friedman et al., 2010; Tay et al., 2023) and "glmnetUtils" (Ooi, 2017). Twenty-one different α-values were provided, ranging from 0 to 1 in 0.05 increments, therefore including ridge (α = 0), elastic net (α = 0.05-0.95), and lasso regressions (α = 1). For each model with a fixed α-value, the optimal λ was selected based on cross-validation performance. Subsequently, the models corresponding to each α-value and its optimal λ were compared based on their mean squared error (MSE), and the model with the lowest MSE was chosen as the best-performing configuration. The one-standard-error rule was applied to model selection; specifically, the model with λ one standard error above the minimum was used to report the coefficients. This approach yields a more parsimonious model and helps reduce the risk of overfitting, particularly given the relatively small sample size (James et al., 2021, p. 237).

The outcome variable was a binary indicator of whether an adolescent reported cycling to school (yes/no). Explanatory variables included GIS-based bikeability measures - cycling infrastructure (total cycleways, separated cycleways along main streets, and residential streets with $\leqslant$30 km/h speed limits) and access to destinations (schools, outdoor sports pitches, parks, shops and food outlets, and population) - calculated within incremental cycling radii of 4, 8, 12, 16, and 20 min. The GIS measures were entered standardised within each urbanisation level and modelled as nested within each urbanisation level (cities, towns, rural areas) to allow estimation and interpretation of associations within strata. This approach corresponds to nested contrast coding (Schad et al., 2020) and was chosen over a full interaction model because we aimed to identify relevant predictors within each context rather than to test omnibus interactions. Moreover, given the limited rural sample, this specification reduces model complexity and risk of overfitting.

Covariates comprised age, sex, socioeconomic status, and municipality, with the latter included as a fixed effect to account for clustering. Sex, socioeconomic status, and municipality were centred to reflect deviations from the overall mean rather than a reference group as not to distort the differences from the reference group due to the regularisation. The R code for the statistical model and its outputs can be found in the Supplement A.2 of this thesis. Estimates are reported as odds ratios (OR). Typically, p-values or confidence intervals cannot be provided for the individual coefficients in models using regularisation unless working with very large data sets and meeting specific assumptions (Zhao et al., 2021).

4.4 Results

Geocoded address data were available for 1,253 adolescents. Of these, 77 participants had missing data in the cycling to school variable, and an additional 43 had missing SES data. These cases were excluded, resulting in a final sample of 1,133 adolescents, with an equal gender distribution (50.0% girls). As shown in table 4.2, 27% of the sample lived in cities, 53% in towns, and 20% in rural areas. SES was highest among adolescents residing in cities. The prevalence of cycling to school varied by urbanisation level, with the highest rate observed in towns (36.6%) and the lowest in rural areas (3.4%).

Table 4.2: Description of the sample

	Cities (N=293)	Towns (N=573)	Rural areas (N=267)	Overall (N=1,131)
Sex				
Boys	147 (50.2%)	291 (50.8%)	129 (48.3%)	567 (50.0%)
Girls	146 (49.8%)	282 (49.2%)	138 (51.7%)	566 (50.0%)
Age (years)				
Mean (SD)	14.3 (2.03)	14.3 (2.01)	14.2 (1.90)	14.3 (1.99)
Socioeconomic status				
Low	43 (14.7%)	129 (22.5%)	69 (25.8%)	241 (21.3%)
Medium	165 (56.3%)	333 (58.1%)	166 (62.2%)	664 (58.6%)
High	85 (29.0%)	111 (19.4%)	32 (12.0%)	228 (20.1%)
Cycling to school				
No	212 (72.4%)	367 (64.0%)	256 (95.9%)	835 (73.7%)
Yes	81 (27.6%)	206 (36.0%)	11 (4.1%)	298 (26.3%)

The ridge regression model with $\alpha = 0$ and $\lambda = 0.1047$ yielded the lowest mean squared error (MSE = 0.9227), indicating the best model fit (see Figure 4.1). After applying the one-standard-error rule, coefficients of the model one standard error from the minimal λ, $\lambda_{1se} = 0.3508$, are reported.

Figure 4.2 presents the coefficients for the bikeability characteristics. Among the covariates, age showed a negative association with cycling to school (OR = 0.96). Boys were more likely to cycle

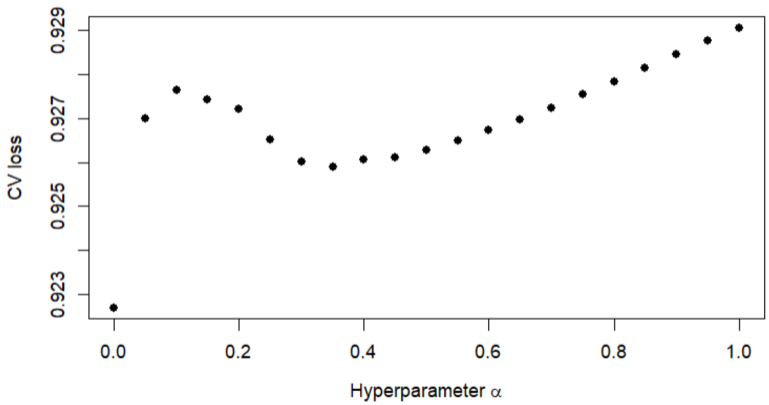

Figure 4.1: Comparison of model fit based on the Mean Squared Error (MSE) for models with varying α-values

than girls (OR = 1.06 vs. OR = 0.95). SES was positively associated with cycling, with odds ratios increasing from low (OR = 0.87) to medium (OR = 1.00) and high (OR = 1.15) SES groups. Cycling rates were highest in towns (OR = 1.26), followed by cities (OR = 1.05), and lowest in rural areas (OR = 0.69). A complete table of the results can be found in Supplement A.2.

Regarding the bikeability characteristics, a greater presence of safe residential streets within 8–12 and 16–20 minutes of the home was positively associated with cycling to school in cities. Additionally, access to outdoor sports pitches within 4–16 minutes and to shops and food outlets within 8–16 minutes was linked to higher cycling rates. In towns, the total length of separated cycleways and the availability of safe residential streets within 4–12 minutes were positively associated with cycling. The number of schools within a 4-minute radius was negatively associated with cycling, whereas schools within a 4–12-minute radius showed a positive association. Access to outdoor sports pitches within 8–16 minutes, shops and food outlets within 8–12 minutes, and higher population density within 4–16 minutes were also positively related to cycling to school. In rural areas, separated cycling infrastructure along main streets within 4–12 minutes was positively associated with cycling, as was access to schools within 8–12 minutes, outdoor sports pitches within 4–8 minutes, parks within 0–12 minutes, and population density within 8–12 minutes of cycling distance. However, given the low number of cyclists in rural areas (n = 11), the results in rural areas should be interpreted with caution.

4.5 Discussion

This study aimed to operationalise bikeability characteristics relevant to adolescents in Germany using open GIS data and to examine their associations with cycling to school across different

Cycling radius (incremental)	Cycleways total	Cycleways along main streets	Safe residential streets	Schools	Outdoor sports pitches	Parks	Shops and food outlets	Population
Cities								
0-4 min	0.99	1.01	1.02	1.02	0.97	0.97	1.02	0.97
>4-8 min	0.99	0.98	1.03	0.99	1.06	0.97	1.00	0.97
>8-12 min	1.01	1.01	1.09	1.02	1.05	0.96	1.05	0.98
>12-16 min	0.99	0.99	1.01	1.00	1.09	0.94	1.06	1.00
>16-20 min	1.05	1.01	1.06	0.96	0.96	0.98	0.99	0.98
Towns								
0-4 min	1.06	1.01	1.00	0.90	1.03	0.97	1.01	0.97
>4-8 min	1.05	1.02	1.05	1.03	1.00	1.01	1.02	1.06
>8-12 min	1.06	1.01	1.06	1.06	1.05	1.02	1.10	1.08
>12-16 min	1.06	1.01	1.02	1.03	1.08	1.03	1.01	1.04
>16-20 min	1.08	1.02	0.98	1.00	0.98	0.99	0.98	0.96
Rural areas								
0-4 min	0.99	1.00	1.02	0.98	0.99	1.06	1.01	1.02
>4-8 min	1.01	1.07	0.99	1.02	1.06	1.05	1.01	1.00
>8-12 min	1.03	1.04	1.00	1.05	1.00	1.10	1.00	1.05
>12-16 min	1.00	0.99	0.98	0.98	1.00	1.02	1.00	0.99
>16-20 min	0.99	0.98	0.98	0.99	0.99	1.02	1.00	0.99

Figure 4.2: Coefficients of the ridge regression for cycling to school (yes/no): Bikeability characteristics across incremental buffers in cities, towns and rural areas

Coefficients of the ridge regression for cycling to school (yes/no): Bikeability characteristics across incremental buffers in cities, towns and rural areas. Displayed are odds ratios based on the standardised bikeability characteristics of the ridge regression (including age, sex, socioeconomic status and municipality as covariates). Cell colours are based on the odds ratio values (>1–green, 1–white, <1–red); higher opacity indicates larger effect sizes.

urbanisation levels in Germany. Three types of street infrastructure and five accessibility measures were derived, and hilliness was integrated directly into the routing algorithm. Using regularised logistic regression, distinct patterns were found linking bikeability characteristics to cycling to school within different cycling radii in cities, towns, and rural areas.

In both cities and towns, the presence of safe residential streets was positively associated with cycling to school. Additionally, separated cycling infrastructure was particularly important in towns. Accessibility to key destinations such as sports facilities, shops, and schools within a 4-16-minute cycling radius was linked to higher cycling rates. These findings align with previous research that links environment characteristics to cycling behaviour and also show that the strength of these associations varies by urbanisation level in Germany and the Netherlands (Y. Gao et al., 2018; Klos et al., 2024). For instance, in cities, several accessibility indicators, such as proximity to schools, parks, and population, showed less favourable associations with cycling compared to towns. One possible explanation is a saturation effect, where in highly urbanised areas, accessibility may already be sufficient for adolescents to reach desired destinations, so further increases offer little additional benefit. In addition, when considering population within cycling distance, a threshold effect may occur (Y. Zhang & Hu, 2024). Beyond a certain point, higher population density could lead to increased traffic volumes, which in turn may negatively impact perceived and actual traffic safety. Supporting this interpretation, a study on adolescents in Germany found that perceived access to shops and bus stops was positively associated with cycling in rural areas and small towns, but not in more urban settings. Conversely, the presence of cars was negatively associated with cycling in medium-sized towns and cities only (Klos et al., 2024). Notably, access to parks was negatively associated with cycling in cities, a pattern also observed in an Israeli study (Moran et al., 2013). Rather than being a popular destination for adolescents, parks may act as barriers by increasing trip length or obstructing direct routes, which can discourage cycling (Y. Gao et al., 2018) or people may prefer to walk when parks are nearby.

One of the main challenges in linking GIS and survey data is the modifiable areal unit problem (MAUP), stating that analyses may provide different results depending on the spatial scale used (D. W. Wong, 2009). To address this, time-based routing buffers were used that account for intersection delays and hilliness, providing a more realistic estimate of travel distance than traditional network buffers. The use of multiple buffer sizes also allowed us to identify the most influential areas (Mitra & Buliung, 2012; Smith et al., 2021). The sequential buffers used in this study provide valuable new insights: Most accessibility measures, such as outdoor sports pitches, are associated with cycling within a 4-16-minute radius. This range aligns with average cycling distances among adolescents in Germany: around 2 km for leisure and shopping trips and up to 4 km for school journeys (Marzi et al., 2023). Relevant destinations may lie within 16 minutes of the adolescents' home, aligning with the 15-minute city concept, stating that most daily necessities and services should be easily reachable by foot, bike or urban transport within 15 minutes to promote healthy and sustainable living (Khavarian-Garmsir et al., 2023). Interestingly, access to e.g. schools in very close proximity (<4 minutes) was negatively associated with cycling, particularly in towns. This supports previous findings that adolescents are more likely to walk short distances (<1 km), while cycling becomes more common for longer trips (van Dyck et al., 2010). Future research should consider accessibility within a cycling radius as a core component of bikeability, especially to capture destinations beyond typical walking distances.

Consistent with the literature, residential streets with speed limits of 30 km/h or less that are typically associated with lower traffic volumes were positively associated with cycling in both towns and cities, a finding that was also reported in Belgian adolescents (Benoit et al., 2022; Vanparijs et al., 2020). This preference is not only found among adolescents but also for other vulnerable groups such as parents with their children, adults with a low SES, and older cyclists (Beirens et al., 2024; Hardinghaus & Weschke, 2022). "Interested but concerned" cyclists that require safe infrastructure to feel comfortable are often found in those vulnerable groups (Dill & McNeil, 2013; Pearson et al., 2024). Cycling promotion for adolescents, i.e. by enforcing a low speed limit in residential streets, could therefore also greatly benefit other vulnerable groups and enable the potential for new and more frequent cyclists among those interested but concerned.

Our findings also highlight the influence of individual and socio-structural factors. Boys and adolescents with higher SES living in cities were more likely to cycle to school. In Germany, bike availability is unlikely to explain these differences (Marzi et al., 2023). However, little is known about whether environmental requirements, such as traffic safety or accessibility, differ by gender or SES. The “cycling boom” in Germany has been largely concentrated in urban, high-SES populations (Hudde, 2022). This raises concerns about growing social inequalities in access to safe cycling environments. Deprived neighbourhoods may have a higher cycling injury risk due to poorer infrastructure, as was shown by Vidal Tortosa et al. (2021) using the English National Travel Survey, and adolescents from lower SES backgrounds in Germany are more likely to maintain or adopt passive commuting habits into adulthood (Klos, Burchartz, et al., 2023). These disparities warrant further investigation in future bikeability research.

Finally, the strong association between separated cycleways and cycling in towns, even beyond 16 minutes, may reflect differences in infrastructure quality between towns rather than within them. It is also important to consider data quality as OSM coverage differs between regions (Ferster et al., 2020) and is generally more complete in cities than in less populated areas (Bres et al., 2023), which may influence the observed associations. Cycling infrastructure may also be better mapped in areas with more active cyclists, potentially introducing bias.

4.5.1 Policy implications

This study underscores the importance of low-speed residential streets, as their presence was positively associated with cycling. Introducing a 30 km/h speed limit in urban and town settings not only encourages active travel, but also reduces crashes, injuries, and fatalities, lowers air and noise pollution and fuel consumption, and can enhance traffic flow and street liveability (Yannis & Michelaraki, 2025). The recent nationwide implementation of a 20-mph default limit in Wales in 2023 illustrates that such large-scale policy changes are both feasible and politically achievable (Currie, 2024). On arterial roads with high traffic volumes, physically separated cycling facilities remain essential to ensure comfort and safety, features that adolescents in particular value highly (Verhoeven, Ghekiere, et al., 2018). Moreover, everyday destinations such as schools, shops, and sports facilities should be located within a bikeable distance. Ensuring safe, direct, and well-connected cycling networks that minimise hazardous crossings and unnecessary detours is critical to avoid gaps in the system and to support consistent cycling uptake (Buehler & Dill, 2016).

4.5.2 Strengths and limitations

This study used German-wide data from over 100 different municipalities providing a unique perspective on bikeability in cities, towns and rural areas. Still, the small sample size in relation to the number of municipalities might not suffice for representative findings, as it does not adequately reflect all regions in Germany. Especially the low number of adolescents in rural areas who cycle to school limits the interpretation of these results. Additionally, smaller sample sizes in both cities and rural areas prevented the use of separate train and test datasets to evaluate model performance and feature importance. New data from the ongoing MoMo 2.0-Study (Woll et al., 2025) may be used to test the model performance in the future and help to validate these results in an independent sample of similar composition.

Time-based routing and incremental cycling buffers were used to get detailed insights into the cycling environment of adolescents and to appropriately address the MAUP, introducing a new analytical approach. The use of incremental buffers resulted in a large number of highly correlated predictors, which led to the regularised regression approach. Although regularisation was initially chosen for feature selection, ridge regression emerged as the best-fitting model compared to elastic net and lasso regression, suggesting the presence of numerous small but meaningful effects (James et al., 2021, p. 246). Due to ridge regression's inability to perform variable selection, interpretation focused on the magnitude of coefficients only. Additional metrics to assess feature importance require cross-validation, for which the sample size is not sufficient. Alternative approaches, such as random forest models, could have been considered for feature selection; however, they do not handle multicollinearity as effectively as regularised regression models and lack interpretable coefficients essential for the exploratory approach of this study. While we acknowledge the limitations of ridge regression, including the lack of inferential statistics and the inability to exclude variables, we interpret the results as exploratory and hypothesis-generating. The patterns identified are intended to inform future research and model development, rather than to provide confirmatory statistical inference.

Choosing an open data approach enables future research to validate the model using independent datasets or replicate the approach in other European countries. Nevertheless, data availability and data quality may differ between regions and countries, e.g. when it comes to cycling infrastructure, which may result in different findings (Bres et al., 2023; Ferster et al., 2020). Additionally, the relatively coarse vertical resolution of the elevation data may have led to an over- or underestimation of hilliness in the routing algorithm.

4.6 Conclusion

This study identified key bikeability characteristics for adolescents in Germany. By using open GIS data, these characteristics were linked to cycling-to-school data across cities, towns and rural areas. Separated cycleways and safe residential streets emerged as critical infrastructure components, with their relevance varying by urbanisation level. Accessibility to destinations within a 4-16-minute cycling radius was positively associated with cycling, suggesting that most cycling trips occur beyond typical walking distances but within a manageable cycling range.

The findings highlight the need for differentiated strategies to promote cycling in cities, towns, and rural areas. Providing safe and accessible infrastructure not only supports adolescent cyclists but also benefits other vulnerable groups, such as older adults and parents with children. This aligns with the vision of "cycling for everyone" as outlined in the European Declaration on Cycling (European Commission, 2024). Importantly, the results also point to socioeconomic disparities in cycling behaviour, with adolescents from higher SES backgrounds more likely to cycle to school. This underscores the need to address equity in cycling infrastructure and ensure that safe, accessible environments are available in all neighbourhoods, particularly those that are socio-economically disadvantaged.

Future research should continue to refine bikeability measures for adolescents and other vulnerable populations using open GIS data, with a particular focus on less densely populated areas. Expanding the scope beyond school commutes to include, e.g. leisure and shopping trips will also provide a more comprehensive understanding of adolescent cycling behaviour.

5 General discussion

The general discussion comprises three parts: First, the main findings of this thesis are summarised and brought into relation with each other. Second, the strengths and limitations of its scope, underlying theoretical considerations, methodological approaches, and data used are outlined. Third, new perspectives, current issues and future directions in active travel research are discussed, including psychological mechanisms explaining the link between the environment and active travel, challenges in the communication and collaboration of active travel research across disciplines, and technological and societal trends that influence active travel and its research in the future.

5.1 Summary

Active travel is increasingly recognised as a key strategy for promoting physical activity and improving health. It fosters independent mobility, offering adolescents new opportunities for exploring their neighbourhood environment and supporting their personal development (Mitra, 2013). When active travel replaces other travel modes, it reduces CO_2 emissions and air and noise pollution, making it an important component of sustainable development (Abu-Omar et al., 2023). To support active travel for everyone, including children, adolescents, and older adults in rural areas, towns, and cities, it is essential to create environments that are conducive to walking and cycling (European Commission, 2024; World Health Organization, 2018). Therefore, this thesis aimed to examine the relationship between perceived and built environmental characteristics and adolescents' active travel, with a particular focus on different urban and rural contexts. Specifically, the thesis addressed six research questions, which are outlined below along with a brief summary of the findings.

1. **Are perceived environment characteristics related to active travel in adolescents?**
2. **Are there differences in associations between adolescents' and parents' environment perceptions and active travel in adolescents?**

The first paper (see chapter 2; Klos, Eberhardt, et al., 2023) synthesised international evidence on perceived environment characteristics associated with active travel. There is convincing evidence that shorter distances to the destination are associated with active travel. Additional possible associations were found for traffic safety, walking and cycling infrastructure, aesthetics, street connectivity, and general perceived environment scores. Both adolescents' and parents' perceptions were associated with active travel, underscoring the significance of accessible destinations, safe walking and cycling infrastructure, and the influential role of both adolescents' and parents' perceptions. These results are in line with previous reviews that mainly focused on children rather than adolescents (D'Haese et al., 2015; Ikeda, Hinckson, et al., 2018; Nordbø et al., 2020). However, this was the first review to find a possible association between aesthetics and active travel in youth.

Based on this systematic review, several specific research gaps were identified, such as the limited focus on rural areas, the lack of differentiation between travel modes (e.g. walking vs. cycling), and the predominant emphasis on school-related travel. These gaps were addressed in the second paper (see chapter 3; Klos et al., 2024), which focused on the German context and explored the following questions:

3. **Which perceived environment characteristics are related to walking in adolescents in rural areas, small towns, medium-sized towns, and cities?**
4. **Which perceived environment characteristics are related to non-motorised vehicle use, including cycling, longboarding and others, in adolescents in rural areas, small towns, medium-sized towns, and cities?**

Findings from the second paper (see chapter 3; Klos et al., 2024) revealed that environmental perceptions vary significantly between rural and urban areas. The relationship between these perceptions and active travel was context-dependent, differing by both travel mode and urbanicity. For instance, in rural areas and small towns, a pleasant neighbourhood and access to shops were linked to non-motorised vehicle use, while in more urban areas, the presence of cars was negatively associated with such travel. Notably, only the presence of public sports facilities was consistently related to active travel across all contexts, suggesting their importance as accessible and appealing destinations for adolescents. While differences in active school travel rates between urban and rural areas have been previously documented (Johansson et al., 2012; Marzi et al., 2023; Reimers et al., 2021), this study was the first to examine how environmental perceptions relate to active travel - beyond just the school commute - across varying levels of urbanicity.

These findings highlight the need for context-sensitive strategies to promote active travel. In addition to behaviour-based interventions, such as those targeting attitudes, norms, and perceptions, particularly in school travel contexts (Schönbach, Altenburg, et al., 2020; Villa-González et al., 2018), environmental interventions that focus on walking and cycling infrastructure and accessibility are crucial. Creating walkable and bikeable neighbourhoods can support active travel more broadly. However, existing approaches to measuring bikeability are limited, focusing almost exclusively on adults and urban areas (Paulusová & Sharmeen, 2024; Valenzuela et al., 2022). It is essential to understand the specific neighbourhood characteristics relevant to cycling, as well as the geographical contexts of cities, towns, and rural areas, to develop a bikeability index tailored to adolescents in Germany. The final set of research questions therefore aims to lay the groundwork for a context-sensitive index:

5. **How can the bikeability characteristics for adolescents be operationalised in Germany using open GIS data?**
6. **How do the bikeability characteristics within different cycling distances relate to cycling to school in adolescents living in cities, towns and rural areas in Germany?**

The third paper (see chapter 4) identified nine relevant bikeability characteristics in the literature and operationalised them using open GIS data across three dimensions: Cycling infrastructure and safety (all designated cycling infrastructure, separated cycleways along main streets, safe residential streets), connectivity and urbanisation (access to schools, outdoor sports facilities, parks, shops and food outlets, and population count), and the surrounding environment (hilliness) (Paulusová & Sharmeen, 2024). The results of the ridge regression analysis indicated that safe residential streets were positively associated with cycling in towns and cities, while separated cycling infrastructure was particularly relevant in towns. Furthermore, access to destinations within a 4–16-minute cycling radius showed positive associations with cycling, suggesting that adolescents are most likely to cycle within this time frame, an observation that aligns with the concept of the 15-minute city (Khavarian-Garmsir et al., 2023). Conversely, access within a 4-minute radius was negatively associated with cycling, implying that very short distances may be more commonly covered on foot (van Dyck et al., 2010). Nevertheless, accessibility, e.g. to school, was only relevant in towns and not in cities, confirming the varying influence of the built environment on cycling there (J. Gao et al., 2018; Klos et al., 2024). Due to the low number of cyclists in rural areas, no definitive conclusions could be drawn there.

The analysis revealed distinct patterns between the environment and cycling across rural areas, towns, and cities consistent with the findings of the second paper, highlighting the importance of the urban-rural context in active travel. This study is among the first to explore bikeability in school-aged youth (Paulusová & Sharmeen, 2024, 2025), thereby contributing to a better understanding of the needs of a vulnerable population with significant potential for environment-driven behavioural change.

To summarise, this thesis has found that *short distances to destination, safe walking and cycling infrastructure and a pleasant built neighbourhood* are important for adolescents' active travel. In the German context, those associations between the perceived environment and active travel are *context-dependent, both in terms of travel mode and urbanicity*. Moreover, the development and application of open-access GIS-based bikeability measures revealed distinct patterns across urban and rural settings. These findings emphasise the importance of providing safe cycling infrastructure and ensuring access to key destinations within a 16-minute cycling radius from home. They also provide an *empirical foundation for bikeability measures* for adolescents in Germany.

5.2 Strengths and limitations

This thesis draws on large, though primarily cross-sectional, literature, survey, and GIS datasets. These provide a broad and informative overview but limit the ability to make causal or highly specific claims. For instance, while the research questions were grounded in established theoretical frameworks and current literature, internal factors such as individual attitudes could not be included due to data availability. Nonetheless, each paper applies solid and appropriate methodologies, incorporating innovative approaches, such as machine learning, data pooling, and geospatial data linking, to address relevant gaps in active travel research. In the following sections, the strengths and limitations of this dissertation are discussed in relation to the research perspective, the underlying theoretical frameworks, and the employed data and methods.

5.2.1 Perspective

This thesis offers a distinctive perspective on the relationship between the neighbourhood environment and adolescents' active travel. The three papers span a wide geographical scope: the first includes international studies (chapter 2), while the second and third cover a representative selection of urban and rural municipalities across Germany (chapters 3 and 4). As a result, the findings are broadly generalisable within both global and national contexts. This generalisability supports broad recommendations, such as improving access and infrastructure to promote walking and cycling among adolescents that may be used on the (inter-)national policy level (World Heath Organization, 2025). Despite this broad focus, this thesis provides valuable detail in two key ways: first, by distinguishing between different active travel modes, and second, by including adolescents from rural areas, towns, and cities. Both distinctions revealed different relationships between the environment and active travel, making an important contribution to the research in this field. On the other hand, however, this work can not justify or recommend specific interventions, e.g. which cycling street network is best for a specific municipality or suburb or whether a cycling path should be separated by a curb or a hedge (Verhoeven et al., 2017). While short distances and safe infrastructure were consistently associated with higher levels of active travel, the relevance of specific features such as cycling lanes, crossings, or network types varied between urban and rural contexts, underlining the need for locally adapted planning strategies.

5.2.2 Theoretical considerations

To capture the multifaceted relationship between environment and behaviour, the thesis integrates both subjective assessments and objective GIS-based measures, acknowledging their distinct contributions to adolescents' travel decisions (Panter et al., 2008). However, these were not analysed jointly due to mismatches between the available GIS data and the perceived environment variables. For example, the presence of cars, other children playing outside, or safety from crime are not directly transferable to GIS-based indicators. This limited the ability to explore potential mediation effects of perception. Nevertheless, the separate analyses provide complementary insights into how adolescents perceive and respond to environmental conditions, insights that are essential for future integrated models.

According to the Framework for Youth's Active Travel (Panter et al., 2008), individual and parental characteristics and attitudes influence how the environment is perceived, which in turn affects travel behaviour. While some personal and parental characteristics (e.g. age, sex, socioeconomic status) were controlled for in the conducted analyses, the MoMo study did not include data on travel attitudes. Consequently, only selected pathways within the framework could be examined. Still, this thesis provides solid evidence that the built environment and both adolescents' and parents' perceptions thereof play an important role in active travel behaviour of adolescents in accordance with the frameworks by Panter et al. (2008) and Sallis et al. (2006). A more comprehensive discussion of the interplay between environment, attitudes, and behaviour is provided in section 5.3.1.

5.2.3 Data and methods

A major strength of this thesis lies in its use of large datasets. These include 51 studies in the systematic review, two cross-sectional cohorts from the MoMo study comprising over 3,900 adolescents across 167 sample points, and GIS data covering cycling infrastructure and accessibility characteristics for over 1,200 neighbourhoods. This extensive data foundation provides high statistical power, enabling the detection of even small effects and reducing the risk of false negatives (i.e. type II errors) (Cohen, 1992). However, the reliance on cross-sectional data, apart from two longitudinal studies in the systematic review, limits causal inference.

To manage large-scale data, appropriate and innovative methods were employed. In the first paper (chapter 2), the systematic review, a new active machine learning tool was used in the screening process that can speed up the process while decreasing the risk of screening errors (van de Schoot et al., 2021). Although significance-based vote-counting is common in active travel reviews (e.g. D'Haese et al., 2015; Nordbø et al., 2020; Pont et al., 2009; B. Y.-M. Wong et al., 2011), it has severe limitations such as misclassifying underpowered studies and having low statistical power, especially with large numbers of studies (Hedges & Olkin, 1980). Therefore, the effect direction plot was chosen as an appropriate method to quantitatively synthesise the results (Boon & Thomson, 2021) in combination with a qualitative review to add context.

In the second paper (chapter 3), cumulative link mixed models were applied to account for the nested data structure and ordinal outcomes. Data from two consecutive MoMo waves were pooled, enabling separate analyses for rural and urban areas. The consistency in data collection procedures and the close timing of the waves (2014–2017 and 2018–2020) ensured comparability. Using mixed models, variations in active travel behaviour between different municipalities could be accounted for, showing that non-motorised vehicle use depends stronger on the local context than walking.

The third paper (chapter 4) linked participants' home addresses to GIS data, a method increasingly used in public health and physical activity research since the early 2000s (Brown et al., 2001; Cromley, 2012). The growing availability of open data and computational tools has expanded the potential for such analyses. However, methodological challenges remain, such as inconsistencies in buffer sizes, types, and data sources (Giles-Corti et al., 2019). To address these, only open GIS data and software were used, ensuring reproducibility and transparency. Additionally, a data-driven machine learning approach using a ridge regression addressed the modifiable areal unit problem to find patterns in high-dimensional and highly correlated data (Mitra & Buliung, 2012; D. W. Wong, 2009).

To summarise, this thesis draws on large and diverse datasets, including systematic review data, two MoMo survey cohorts, and GIS data, providing high statistical power but limiting causal inference due to its primarily cross-sectional design. Innovative and appropriate methods were employed, such as machine learning for literature screening, effect direction plots for synthesis, and cumulative link mixed models and ridge regression for advanced statistical analysis. The use of open GIS data and reproducible workflows in spatial analysis further strengthens the methodological approach, despite challenges like the modifiable areal unit problem and inconsistencies in geospatial data sources.

5.3 Discussing new perspectives, current issues and future directions in active travel research

This thesis was grounded in the ecological model of four domains of active living from Sallis et al. (2006) and the Framework for Youth's Active Travel by Panter et al. (2008), focusing on the role of the perceived and built environment on active travel in adolescents. To fully understand how the environment influences such behaviour and to inform the development of effective promotion strategies, it is important to consider these findings in the context of these theoretical frameworks. This includes psychological mechanisms at the individual level and external factors at the policy level, as well as emerging societal, technological, and research developments. The following discussion addresses these additional layers to provide a complete and integrated perspective.

First, section 5.3.1 focuses on the *psychological mechanisms* behind active travel behaviour. The relation between the environment, travel attitudes and travel behaviour is described, with a special focus on the reverse causality hypothesis, i.e. how the built environment and travel behaviour influence travel attitudes. This section then discusses the concept of habits in the active travel context and how context changes during adolescence may facilitate travel behaviour changes.

Second, section 5.3.2 addresses *challenges in the communication and collaboration* of active travel research between different scientific disciplines, highlighting the need for more integrated approaches and shared terminologies to bridge the gaps between physical activity, public health, and urban and transport planning research.

Third, section 5.3.3 elaborates on *technological and societal trends* that may offer new opportunities but also pose potential threats for adolescents' active travel in the future. It is then discussed how new research methods may help advance the research on the environment and active travel, e.g. by new methods to measure active travel and by using artificial intelligence to characterise the environment.

5.3.1 Attitudes and habits: The (missing) links between the environment and active travel?

This thesis focused on the relations between the built environment, its perception, and active travel behaviour. While travel attitudes are often found to be stronger predictors of travel mode choice, recent research suggests that their role is more complex. Rather than acting solely as predictors, attitudes may function as multidirectional moderators or mediators between the built environment and travel behaviour (see figure 5.1; De Vos, 2022).

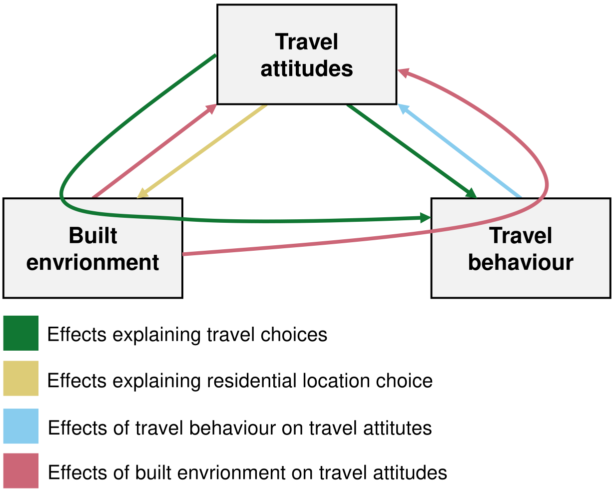

Figure 5.1: Pathways between travel attitudes, travel behaviour and the built environment (adapted from De Vos, 2022)

The built environment influences the active travel behaviour indirectly through its influence on perceptions of the environment (Ma & Cao, 2019). These perceptions, in turn, are shaped by personal attitudes and characteristics, which also directly influence travel decisions (Ma & Cao, 2019; Panter et al., 2008).

Traditionally, attitudes were considered stable constructs used primarily to explain behaviour through intention, e.g. in the Theory of Planned Behaviour (Ajzen, 1991). However, recent literature challenges this view (M. Rahman & Sciara, 2022; van Wee et al., 2019). For example, van Wee et al. (2019) introduces the concept of reverse causality, meaning that travel attitudes are influenced both by the built environment and travel behaviour and not only the other way around. A person with a positive attitude towards cycling might not only be more likely to cycle more frequently, but frequent cycling can also reinforce or reshape that attitude. Similarly, living in a neighbourhood unsuitable for walking, e.g. due to long distances and heavy car traffic, may negatively influence attitudes towards walking. Attitude change can occur through cognitive (i.e. acquiring new knowledge), behavioural (i.e. engaging in new activities), and affective (i.e. experiencing new emotions) processes, often triggered by "external initiators of internal processes" (van Wee et al., 2019, p. 2) at the individual, social, or environmental level. Life transitions, such as moving from primary to secondary school or starting university or work, can act as such triggers that may change the active travel behaviour (Klos, Burchartz, et al., 2023). Adolescence is framed by these life events that itself is marked by growing independence, new social influences and new travel experiences. It is therefore reasonable to assume that travel attitudes are dynamic and subject to significant change, especially during this life stage.

Another psychological concept to explain travel behaviour is habits. While the theory of planned behaviour, among others, assumes that one makes a conscious, reasoned choice (Ajzen, 1991), habits may bypass the reasoned behaviour in favour of an automatic travel behaviour in very routinised, repetitive behaviours such as walking or cycling to school (M. Rahman & Sciara, 2022). Habits have a strong impact on travel mode choice in a stable context (Gardner, 2009). Therefore, a behaviour change is more likely during a context change, e.g. a relocation or change in environment, that disrupts individuals' habits according to the habit discontinuity hypothesis (Haggar et al., 2019; Verplanken et al., 2008). Despite describing two different internal processes, travel attitudes and habits do not necessarily contradict each other. Both have been shown to contribute significantly to explaining the school travel mode in children (Murtagh et al., 2012) and both psychological concepts provide useful links between the environment and travel behaviour (M. Rahman & Sciara, 2022).

Future research should investigate the multidirectional relationship between the built environment, attitudes, habits, and active travel behaviour, particularly during adolescence, when life transitions are frequent (M. Rahman & Sciara, 2022). These insights underscore how environmental characteristics such as infrastructure quality, perceived safety, and accessibility interact with psychological mechanisms to shape active travel behaviour. From a practical perspective, recognising these complex interdependencies is crucial. Promoting positive attitudes and active travel habits early on, through walking- and cycling-friendly environments that offer enjoyable and safe active travel experiences, is important for initiating and sustaining active travel behaviours during key transitional phases.

5.3.2 The issue about *active travel* - An interdisciplinary perspective or a public health silo?

Active travel, also referred to as active transport or active commuting, is an established term in physical activity and public health research (Cook et al., 2022; Reimers & Demetriou, 2024; Sallis et al., 2004). It is defined as "travel in which the sustained physical exertion of the traveller directly contributes to their motion" (Cook et al., 2022, p. 154), closely aligning with the definition of physical activity by Caspersen et al. (1985). This definition emphasises the health benefits of physical activity during travel and has been instrumental in promoting walking and cycling as health-enhancing behaviours. The term active travel was invented to highlight the health benefits of transport-related walking and cycling, a goal it has successfully achieved (World Health Organization, 2018), but it has yet to be recognised by other disciplines. Despite its utility in public health research, the term active travel is not widely used in other disciplines, such as transport planning or urban design (Cook et al., 2022). These disciplines often prioritise traffic efficiency, safety, and environmental concerns over physical activity. For instance, traffic planners may focus on reducing congestion or emissions, viewing health primarily through the lens of injury prevention (Kasraian et al., 2024). Consequently, they use alternative classifications such as low-speed modes, micromobility, or sustainable mobility, which may include but are not limited to active travel modes (Cook et al., 2022).

Although interdisciplinary collaboration has long been encouraged (Koszowski et al., 2019; Sallis et al., 2004), active travel research remains largely confined to public health journals (Cook et al., 2022). This "siloing" limits the visibility of findings in other domains. Moreover, the term active travel may hide important distinctions between travel modes. Many studies overlook the fact that the two most popular active travel modes, walking and cycling, differ significantly in speed, distance, and infrastructure needs (Forsyth & Krizek, 2011; Kaplan et al., 2016). Studies that group them together risk producing findings that are less insightful for planners or policymakers focused on one specific mode (Klos, Eberhardt, et al., 2023).

To enable more effective interdisciplinary collaboration and enhance the practical relevance of research, it is essential to reconsider how the term *active travel* is used and communicated. While active travel remains a valuable term for highlighting the health benefits of transport-related physical activity, its use may inhibit interdisciplinary collaborations. Referring more explicitly to specific travel modes, such as walking and cycling, can reduce ambiguity, improve the discoverability of research across disciplines, and make findings more directly applicable to the needs of urban and transport planners.

Apart from the terminology, integrating physical activity and health experts into urban mobility planning processes can help ensure that health-related outcomes are considered alongside traditional planning goals. An analysis of sustainable urban mobility plans across Europe has shown that only a few cities refer to physical activity during walking and cycling as a pathway to health outcomes (Kasraian et al., 2024). Rather, only road traffic injuries, air and noise pollution are addressed as health threats. The role of physical activity during active travel and how environments can support walking and cycling should be included in the education of urban planners and transport professionals. For example, only a small number of landscape architecture and urban design degree programs in Switzerland address the relationship between the environment, physical activity, and health (Zedi & Kayser, 2021), indicating a significant gap in training that limits the potential for cross-sectoral understanding. Revising curricula in urban design and planning programs to include lectures on this relationship would help to create an integrated understanding of how urban design influences travel behaviour and health.

5.3.3 Technological and societal advances and emerging active travel research perspectives

To understand and facilitate societal and technology-driven changes in the mobility landscape, it is important to monitor mobility behaviour in relation to the infrastructure and broader environment (Chevance et al., 2024). Therefore, current developments in mobility behaviour that may support or inhibit active travel are discussed in the first section. New approaches and methods to better capture active travel and the environment are presented in the second section to highlight new research opportunities.

5.3.3.1 Active travel in a changing mobility landscape

In recent decades, rates of active travel to school have remained relatively stable across many regions, including Germany (Reimers et al., 2021), other parts of Europe (Haug et al., 2021), North America (Rothman et al., 2018), South America, Africa, and Oceania (Felez-Nobrega et al., 2023), despite growing scientific attention (Jing et al., 2021) and various intervention approaches (Jones et al., 2019; Larouche et al., 2018). However, with increasing awareness of the climate crisis, the interest in sustainable mobility has grown significantly and new, technology-driven innovations start to shape the mobility of the coming decades (Chen et al., 2025). In recent years, one of those new trends, e-mobility, has emerged not only in cars, but also in the form of e-bikes and e-scooters. E-bikes and e-scooters, in particular, are becoming increasingly relevant for adolescents as they do not require a driver's license and may influence future mobility patterns for this generation.

E-bikes, or electrically assisted bikes, are considered a form of active travel (Cook et al., 2022). Although e-cycling generally involves lower physical intensity than conventional cycling, it still falls within the moderate-intensity range (Bourne et al., 2018). The health benefits of e-cycling therefore depend on the travel mode it replaces. Compared to regular bikes, e-bikes allow users to travel longer distances, tackle hilly terrain more easily, and maintain a steady effort even when carrying loads, features that are especially valuable for utility cycling and in rural areas (Dahl Wikstrøm & Böcker, 2020; Rérat, 2021). Still, e-bikes share the same infrastructure with conventional bikes (Rérat, 2021), but due to the higher speed may come with a higher accident risk. It would therefore be even more relevant to provide safe infrastructure should this trend continue. Among adults, access to e-bikes has been shown to reduce car use and support healthier, more sustainable travel patterns (Chevance et al., 2025). However, few adolescents currently use e-bikes in Germany (Klos et al., 2025), and the topic has received limited attention in the research literature so far. Possible reasons may be safety concerns, especially in young adolescents, the high cost and the limited availability of e-bikes with smaller frame sizes.

In contrast to e-bikes, e-scooters are not considered an active travel mode as the forward momentum is only generated by the engine (Cook et al., 2022). Their physical activity intensity is significantly lower than walking (Payne et al., 2025; Wen et al., 2025), and they often replace walking (42.8%), public transport (19.1%), and cycling (14.2%) trips in Germany (Weschke et al., 2022). While e-scooters may offer convenience, especially in cities with shared schemes, they also raise safety concerns, particularly for adolescents who may ride without helmets and have higher risk-taking tendencies (Douglas & Fine, 2024). From a physical activity and health promotion perspective, the use of e-scooters should be discouraged, given that these often substitute active trips and reduce physical activity.

Alongside technological developments, social and policy shifts are also influencing mobility patterns. Public transport, while not an active mode itself, plays a key role in promoting sustainable and active travel through active trips made to and from the bus stop or train station (Durand et al., 2016). The introduction of the "Deutschlandticket", a low-priced nationwide public transport pass for local and regional travel, has made public transport more affordable, increasing public transport use in Germany (Helferich et al., 2024). Cities like Luxembourg and Tallinn have implemented fare-free systems to reduce car use and improve mobility access. For adolescents, who often cannot drive a car yet, public transport is especially important. Studies show that free public transport increases its use while slightly reducing cycling, though overall levels of active travel remain stable due to walking to and from transit stops (Green et al., 2014; Pesola et al., 2022). In fact, public transport use is positively associated with transport-related physical activity (Durand et al., 2016; Voss et al., 2015), and is therefore considered a complementary component of active travel promotion by the *Walking and Cycling Promotion tool kit* of the World Heath Organization (2025). However, with the growing use of e-scooters for the so-called “last mile” to or from transit, this relationship may need to be re-evaluated.

Despite their current low prevalence among adolescents, both e-bikes and e-scooters represent emerging trends that warrant close monitoring. E-bikes have the potential to increase feasible active travel ranges, which might be especially relevant for adolescents living in more rural areas. To guide the development of a more sustainable and active mobility landscape, future research should prioritise the collection of data on these new modes and explore innovative methods for capturing evolving travel behaviours. Affordable or free public transport supports adolescents’ independence and increases the range of places they can access while maintaining or even increasing their transport-related physical activity.

5.3.3.2 Innovative approaches to monitoring active travel and the environment

This thesis used a simple cross-sectional questionnaire and GIS data based on the participants' home addresses. While this approach comes with a low time burden for the participants and is very cost-effective, it is limited by the very coarse spatio-temporal resolution of the data. There are several new methods that could be used to increase the resolution that would be feasible to use in a nationwide study similar to the MoMo Study, and therefore improve monitoring efforts.

Active travel is usually measured using questionnaires (Klos, Eberhardt, et al., 2023) as they are very cost-efficient and can easily capture different travel modes in varying contexts. For example, the assessment of school travel mode via questionnaires is highly reliable and valid, as it is a routinised behaviour (Larouche, Oyeyemi, et al., 2014). However, fewer studies assess trip frequencies, travel duration, or active travel trips apart from school travel (Klos, Eberhardt, et al., 2023), highlighting the difficulties when relying on self-reported active travel data in non-routinised contexts. As with other physical activities, the assessment is susceptible to recall and social desirability bias as it is only a subjective assessment (C. R. Nigg et al., 2020). Therefore, other methods such as accelerometry and global positioning system (GPS) trackers may be good alternatives to capture all active travel activities.

In recent years, accelerometry has gained popularity due to its ability to objectively monitor physical behaviour patterns continuously over a 24-hour period (Burchartz et al., 2020). It has already been used in the MoMo 2.0-Study (Woll et al., 2025), proving its feasibility in large monitoring studies. Advances in classification algorithms have now made it possible not only to assess physical activity intensity but also to distinguish between specific activity types such as walking, cycling, and running (Lendt et al., 2024). This development opens up new possibilities for accelerometer data in active travel research by providing a better temporal resolution. However, accelerometers alone still lack contextual information, e.g. distinguishing between walking within the home vs. walking to school, or between cycling to shops or recreational cycling, which limits their usability for transport-specific analyses (Schipperijn & Heidler, 2025). Supplementing accelerometer data with travel diaries could provide this context, but would significantly increase participant burden (Burchartz et al., 2020).

Instead of or in addition to accelerometers, GPS trackers have been used to assess active travel patterns, adding a spatial dimension (Katapally et al., 2020). GPS enables the tracking of precise travel routes and allows for the classification of transport modes, such as walking, cycling, or motorised travel, based on speed profiles (Berjisian & Bigazzi, 2022). Data can be collected via dedicated GPS devices or smartphone applications, with the latter offering a more user-friendly and less disruptive option. Nevertheless, privacy concerns, particularly among children and adolescents, may hinder participant recruitment (Gillis et al., 2023). Further limitations of GPS data lie in the continuous data collection that leads to large amounts of irrelevant data (e.g. time spent at home) and the identification of walking and cycling trips (Berjisian & Bigazzi, 2022; Lißner & Huber, 2021).

A novel solution to these limitations has been proposed by Bhowmick et al. (2025), who developed a method for selectively tracking cycling trips. Participants attach a Bluetooth beacon to their bicycle, which connects to a smartphone app that activates GPS tracking only when the beacon is within range, i.e. when the participant is riding the bike. This targeted data collection approach reduces privacy concerns, minimises irrelevant data, and lowers the risk of classification errors and data preprocessing. Although this method is not applicable to walking, it has already been successfully implemented in a large, representative sample in the Greater Melbourne area (Bhowmick et al., 2025).

The greater spatio-temporal resolution gained from the methods described above, especially when combining accelerometers and GPS (Katapally et al., 2020), enables analyses on the trip level, e.g. using the time and duration of the trip, the origin, destination and path taken and even the speed at different street segments. Such detailed data allow for more precise linkage between environmental characteristics and active travel behaviours (Zhou et al., 2024), for example, by comparing environment characteristics of the shortest and the actual route taken (Verhoeven, van Hecke, et al., 2018).

In this thesis, perceived environmental characteristics were assessed using validated questionnaires, while objective environmental data were derived primarily from open GIS sources, mostly OpenStreetMap. Despite ongoing improvements in the quality and coverage of GIS data, notable gaps remain, particularly in the representation of cycling infrastructure (Bres et al., 2023; Ferster et al., 2020). To address these limitations, emerging machine learning techniques using street view imagery offer promising alternatives (Biljecki & Ito, 2021). For instance, such approaches have been successfully applied to classify cycling infrastructure (Backman et al., 2024), detect street signs (Campbell et al., 2019), and quantify green space (T. Zhang et al., 2024). Beyond isolated, objective features, Ye et al. (2019) introduced a method to assess visual quality by integrating multiple design elements to recreate and quantify the environment similar to how humans would perceive their surroundings. Given the rapid advancements in machine learning and the widespread availability of street-level imagery, these techniques are likely to play an increasingly important role in future research on walkability and bikeability.

5.4 Conclusion

In the face of rising physical inactivity and the escalating climate crisis, active travel offers a promising way to promote both individual and planetary health (Abu-Omar et al., 2023). For adolescents, it also fosters independence and helps establish lifelong active travel habits when supported by walking- and cycling-friendly environments. Therefore, this thesis focused on the relationship between the perceived and built environment and active travel across urban and rural areas in order to advance research and inform practitioners to better understand and promote active travel environments for adolescents.

The first paper (chapter 2) synthesised global evidence on environment perceptions, finding that especially perceptions of distances, traffic safety and walking and cycling infrastructure were important for adolescents' active travel. The second paper (chapter 3) highlighted the context-dependence of this relationship, that different perceived environmental features influence walking and cycling in distinct ways, and that these associations vary between urban and rural areas. The third paper (chapter 4) identified and validated objective, GIS-based indicators of bikeability, particularly street infrastructure and accessibility, using a nationwide German sample, providing an empirical foundation for a bikeability index tailored to adolescents living in cities, towns, and rural areas.

This thesis contributes new insights into how adolescents' active travel behaviours are shaped by their environments across urban and rural areas. While associations between environmental features and active travel were found in cities, towns, and rural areas, the strength and nature of these associations differ by context. Although the cross-sectional design limits causal inference, the use of large, geographically diverse samples and the integration of both subjective perceptions and objective measures provide a robust foundation for future research.

There is a need for more studies in less densely populated rural areas, as findings from urban areas may not be directly transferable. Future research should also explore the mechanisms, such as attitudes and habits, that mediate the relationship between the built environment and travel behaviour, to inform more effective interventions. While *active travel* emphasises the health-enhancing physical activity effects, it may inhibit interdisciplinary collaboration with urban and transport planners. Addressing walking and cycling directly may be beneficial both in research and practice, while continuing to anchor the relationship between the built environment, active travel and health in sustainable urban mobility plans and in the curricula of urban and transport planning programs.

The mobility landscape of adolescents may change significantly in the coming years with the increasing use of e-bikes and e-scooters, and developments should be closely monitored. Given its close links to active travel, public transport use should be an integral part of active travel promotion. New research methods leveraging accelerometers and GPS to capture active trips can provide data with a high spatio-temporal resolution that enables novel analyses, all while remaining feasible for large-scale studies. New machine-learning approaches to analyse street view imagery may allow for a widely available, even more detailed representation of environmental characteristics.

By addressing both subjective environment perceptions and objective environment measures, this thesis provides actionable insights for researchers and planners aiming to create environments that support adolescent active travel in diverse contexts. Ultimately, designing environments that encourage walking and cycling is not only an investment in adolescent health but also a step toward more sustainable, resilient, and inclusive communities.

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A Supplement

A.1 Data extraction table from chapter 2

The data extraction table starts on the next page.

Table A.1: Data extraction of included studies in the systematic review

Study	Region	Study design	Sample size	Age	% female	Study quality	Desti-nation	Mode	Self-/parent report	Environment question-naire	Results (only associations with p <0.05 reported)
Agyeman et al., 2022	Ghana, Bono Region	cross-sectional	460	9-15y; 13.72 (2.30)	50%	poor	school	walk, cycle	self		**Other vs. walk:** school bus accessibility: OR=11.58 **Bike vs. walk:** distance to school OR=1.71 school bus accessibility OR=0.39 public transport accessibility OR=2.63
Aranda-Balboa et al., 2021	Spain	cross-sectional	299	14 (1.1)	NA	fair	school	active	both	BATACE, PABACS	**Adolescents (barriers):** distance OR=0.26 traffic safety OR=0.64 built environment OR=0.67 crime safety OR=0.40 built environment (walk) OR=0.44 built environment (bike) OR=0.64 **Parents (barriers):** distance OR=0.48 traffic safety OR=0.64 built environment OR=0.33
Babey et al., 2009	US, California	cross-sectional	3451	12-17y; 14.4	49%	poor	school	active	parent		n.s.

Table A.1 continued from previous page

Study	Region	Study design	Sample size	Age	% female	Study quality	Desti-nation	Mode	Self-/ parent report	Environment question-naire	Results (only associations with p <0.05 reported)
Barnett et al., 2019a	Hong Kong	cross-sectional	1299	11-18y; 14.7 (1.57)	57%	good	school	healthy latent profiles	both	NEWS-Y	**Adolescents (NEWS-Y):** regular vs. occasional walkers: proximity of school OR=2.32 proximity of recreational facilities OR=0.64 access to services OR=1.70 walk vs. public transport: proximity of school OR=2.82 proximity of transit stops OR=0.72 barriers to walking OR=0.76 **Parents (perceived barriers):** regular vs. occasional walkers: distance OR=0.39 walk vs. public transport: distance OR=0.40
Barnett et al., 2019b	Hong Kong	cross-sectional	1299	11-18y; 14.7 (1.57)	57%	good	school, other	active	parent	NEWS-Y	**AST frequency: zero vs. non-zero frequency:** school proximity OR=0.49 **AST frequency:** school proximity eb=1.08 access to services eb=1.05 **AST duration: zero vs. non-zero minutes:** school proximity OR=0.49 **AST duration:** school proximity eb=0.77 **Frequency of AT to other destinations:** proximity to destinations eb=1.004 (p<0.001)

Table A.1 continued from previous page

Study	Region	Study design	Sample size	Age	% female	Study quality	Destination	Mode	Self-/ parent report	Environment questionnaire	Results (only associations with $p < 0.05$ reported)
Berger et al., 2019	UK, London	longitudinal	2260	11-12y (at baseline)	.	fair	school, other	walk	self	ALPHA	**Walking to school:** n.s. **Walking for leisure:** crime safety: slightly disagree vs. strongly disagree OR=1.28, slightly agree vs. strongly disagree OR=1.31 trajectory analysis: increased bus stop proximity decreases odds OR=0.86 of leisure walking over time
Carlson et al., 2014	US, Washington	cross-sectional	294 [a]	12-15y	.	good	school	active	parent	NEWS-Y	**1-4 vs. no trips per week:** perceived street connectivity OR=1.88 **5-10 vs. no trips per week:** pedestrian safety OR=2.20
Christiansen et al., 2014	Denmark, Southern Denmark	cross-sectional	1250	11-13y; 12.5	48%	fair	school	active	self		safe route OR=1.86 many paths OR=1.28 speeding traffic OR=0.05
Da Silva et al., 2018	Brazil, Curitiba	cross-sectional	495	12-17y	51%	good	school	active	both	NEWS, NEWS-Y	**Adolescents:** high SES: n.s. low SES: seeing other pedestrians/cyclists around home PR=1.18 **Parents:** low SES: safe to cross streets PR=1.10 high SES: crime in neighbourhood PR=1.33
De Meester et al., 2013	Belgium, Ghent	cross-sectional	637	13-15y	51%	good	school, other	active, walk, cycle	self	NEWS	**AST:** land use mix diversity β=-0.112 distance β=0.164 connectivity β=0.116 Walking infrastructure β=-0.179 **Walking during leisure time:** Safety for traffic β=0.116 **Cycling during leisure time:** n.s.

Table A.1 continued from previous page

Study	Region	Study design	Sample size	Age	% female	Study quality	Desti-nation	Mode	Self-/ parent report	Environment question-naire	Results (only associations with p <0.05 reported)
Deforche et al., 2010	Belgium, Flanders	cross-sectional	1445	17.4 (0.6)	56%	good	all	active	self	NEWS	land use mix diversity β=0.020, d=0.10 connectivity β=0.023, d=0.09 aesthetics β=0.024, d=0.09 access to recreational facilities β=-0.022, d=0.12
DeWeese et al., 2013	US, New Jersey	cross-sectional	345	12-18y	.	poor	school	active	parent		unpleasant for walking OR=0.32
Dias et al., 2020	Brazil, Porto Alegre	cross-sectional	1113	14-20y	47%	good	other	walk	self	NEWS-Y	**Low SES girls:** access to services OR=2.17 **Middle SES girls:** n.s. **High SES girls:** n.s. **Low SES boys:** crime safety OR=0.63 **Middle SES boys:** recreation facilities OR=1.60 **High SES boys:** land use mix diversity OR=1.81 recreation facilities OR=2.28 (1.35-3.86) places for walking OR=2.22(1.10-4.46)
Dias et al., 2021	Brazil, Rio Grande do Sul State, Porto Alegre	cross-sectional	1130	14-20y; 16.49 (1.05)	53%	good	school	active	self	NEWS-Y	land use-mix diversity r=0.211 neighbourhood recreational facilities r=0.198 access to services r=0.118 neighbourhood aesthetics r=0.075
Duncan et al., 2016b	US, Oregon	cross-sectional	372	12-14y; 12.06 (1.69)	100%	good	school	active	self		accessibility to neighbourhood PA facilities coeff=0.220
Emond and Handy, 2012	US, California, Davis	cross-sectional	1357	grade 10-12	48%	fair	school	cycle	self		too far from school OR=0.69

Table A.1 continued from previous page

Study	Region	Study design	Sample size	Age	% female	Study quality	Desti-nation	Mode	Self-/ parent report	Environment question-naire	Results (only associations with p <0.05 reported)
Esteban-Cornejo et al., 2016	US, Baltimore, Washington D.C., Seattle	cross-sectional	928	12-16y; 14.10 (1.40)	50%	fair	other	active	both	NEWS-Y	**Parent:** traffic safety B=0.179 crime safety B=0.077 stranger danger safety B=0.110 **Adolescent:** n.s.
Fitch et al., 2019	US, California	cross-sectional	2993	grade 9-12y	52%	poor	school	cycle	self		too far (no effect size reported)
Gao et al., 2018	China, Jinjiang	cross-sectional	449	junior high school students (approx. age 12-15)	NA	poor	school	active	parent		**AT to school:** non-motorized traffic facilities B=0.72 road traffic conditions B=0.63 **AT from school:** non-motorized traffic facilities B=0.78 Road traffic conditions B=0.81
García-Cervantes et al., 2014	Spain, Madrid	cross-sectional	140	12-17y; 13.11 (1.46)	44%	poor	other	active	self	ALPHA	**Girls:** r=0.34 **Boys:** n.s **Total:** n.s.
Grow et al., 2008	US	cross-sectional	124 (+22 adoles-cent self-report)	11-18y; 14.4 (1.7)	47.6%	fair	other	active	both	NEWS	**Adolescent:** pedestrian infrastructure β=0.20 traffic safety β=0.30 crime threat β=-0.21 proximity of recreation sites β=0.10 **Parent:** traffic safety β=0.55 proximity of recreation sites β=0.07
Hermosillo-Gallardo et al., 2020	Mexico, Mexico City and Oaxaca	cross-sectional	4079	15-18y	51%	fair	school	active	self	NEWS-Y	**Boys:** n.s. **Girls:** n.s.
Huertas-Delgado et al., 2017	Spain, Granada	cross-sectional	151	12-16y	58%	poor	school	active	parent		absence of policemen at cross-walks (no effect size reported) distance to school (no effect size reported)

Table A.1 continued from previous page

Study	Region	Study design	Sample size	Age	% female	Study quality	Desti-nation	Mode	Self-/ parent report	Environment question-naire	Results (only associations with p <0.05 reported)
Huertas-Delgado et al., 2018	Ecuador, Riobamba	cross-sectional	209	13-18y	30%	poor	school	active	parent		dangerous intersections OR=3.21 distance to school OR=4.59
Hume et al., 2009	Australia, Melbourne	longitu-dinal	188	14.5 (0.65)	53%	fair	school	active	parent		**increasing trips vs non-changers (ref.):** no traffic lights or crossings OR=0.4 satisfied with pedestrian crossings OR=2.4
Kamargianni and Poly-doropoulou, 2014	Greece	cross-sectional	1988	12-18y; 15.7	52%	poor	school	active	self		**Urban:** wide sidewalks β=4.55 green β=1.28 traffic lights β=4.02 winter β=-0.72 WalkCon (general safety) β=-0.52 **Rural:** wide sidewalks β=2.14 network condition of sidewalk β=-1.92 green β=1.91 winter β=0.65 WalkCon (general safety) β=-0.91 **Insular:** network condition of sidewalk β=2.07 green β=3.78 winter β=-0.34 WalkCon (general safety) β=-1.63

Table A.1 continued from previous page

Study	Region	Study design	Sample size	Age	% female	Study quality	Desti-nation	Mode	Self-/ parent report	Environment question-naire	Results (only associations with p <0.05 reported)
Leung and Le, 2019	Vietnam, Ho Chi Minh City	cross-sectional	525	11-16y	NA	poor	other	active	self		too hot OR=0.50 exhaust fumes OR=0.73 obstacle free roads OR=1.29 stores occupying paths OR=0.79 trees OR=1.35 open spaces to exercise OR=1.38 stores in neighbourhood OR=1.35 stores on way to school OR=1.32 afraid of traffic injury OR=0.58 too much traffic OR=0.55 drivers oblivious to pedestrians/cyclists OR=0.47 warning about strangers OR=0.59 more likely to cycle/walk shorter distances OR=2.69
Loucaides et al., 2010	Cyprus	cross-sectional	1966	grade 6-12	48%	poor	school	active	self		my parents think it's safe OR=1.5 big distance OR=0.9
Loureiro and Gaspar de Matos, 2014	Portugal	cross-sectional	3494	14.9 (1.3)	54%	poor	school	active	self		nightlife entertainment OR=0.73 violence and theft OR=0.56 beautiful area OR=1.76 isolated area OR=0.66 good public services OR=1.79 school travel time (Ref. >10 min) OR=0.57
Mäki-Opas et al., 2014	Netherlands, Amsterdam	cross-sectional	697	10-18y; 14.4	49%	fair	school	cycle	self	NEWS	n.s.
Mandic et al., 2015	New Zealand, Otago	cross-sectional	2018	13-19y; 14.8 (1.3)	47%	fair	school	active	self		takes too much time OR=0.46 nice scenery OR=1.69 parents think it's not safe to walk/cycle OR=2.32

Table A.1 continued from previous page

Study	Region	Study design	Sample size	Age	% female	Study quality	Desti-nation	Mode	Self-/ parent report	Environment question-naire	Results (only associations with p <0.05 reported)
Martins et al., 2017	Portugal, Lisbon	cross-sectional	272 [a]	14-18y; 16.0 (1.5)	52%	good	school	active	self		**Passive vs. One-way AST:** too far OR=0.48 **Passive vs. both ways AST:** too far OR=0.30
Mendonça et al., 2018	Brazil, Paraiba State, Joao Pessoa	cross-sectional	2874	14-19y; 16.4 (1.2)	58%	good	other	active	self		Places with opportunities for physical activity OR=0.79 no violence in neighbourhood OR=1.29
Mitáš et al., 2018	Czech Republic, Moravian regions & Poland, Silesian-Katowice region	cross-sectional	2001	boys: 15.81 (0.79); girls 15.89 (0.75)	58%	fair	all	walk	self	NEWS-A	**Boys:** n.s. **Girls:** neighbourhood safety: η=0.007
Molina-García et al., 2018	Spain, Valencia	cross-sectional	108	14-18y; 16.5 (0.78)	55%	good	school	active	self		**Clusters with highest AT vs. cluster with lowest AT** lower environment/safety barriers (no effect size reported)
Nelson and Woods, 2010	Ireland	cross-sectional	2159 [a]	15-17y; 16.04 (0.66)	47%	good	school	active	self	NEWS	**Boys:** land use mix diversity (number of destinations within 10 min) 6-10 vs 0-5 OR=2.89, 16-20 vs. 0-5 OR=2.11 public park OR=1.63 **Girls:** unsafe to walk at night OR=1.98 shops within walking distance OR=4.27 cars separate paths from road OR=1.63
Oyeyemi et al., 2014	Nigeria, Maiduguri City	cross-sectional	1006	12-19y; 15.6 (1.72)	50%	good	school	active	self	PANES	**Boys:** access to destinations β=0.18 **Girls:** n.s.
Ozbil et al., 2021	Turkey, Istanbul	cross-sectional	749 [a]	12-14y; 13.4	50%	good	school	walk	parent	NEWS	maintained sidewalks b=0.32 trees along roads b=0.32

Table A.1 continued from previous page

Study	Region	Study design	Sample size	Age	% female	Study quality	Desti-nation	Mode	Self-/ parent report	Environment question-naire	Results (only associations with p <0.05 reported)
Palma et al., 2020	Chile, Valparaiso	cross-sectional	78	13-18y	51%	poor	school	active	parent		traffic volume (no effect size reported) traffic speed (no effect size reported)
Pizarro et al., 2012	Portugal, Porto	cross-sectional	538	16.56 (1.27)	54%	good	school	active	self		**Boys:** n.s. **Girls:** streets well-lit at night (disagree (ref.) vs. neither agree nor disagree) OR=3.88 Safety to walk or jog (disagree (ref.) vs. agree) OR=2.93
Pocock et al., 2019	New Zealand, Dunedin	cross-sectional	471 [a]	13-18y; 15.2 (1.4)	56%	good	school	active	self	NEWS-Y	unsafe to walk: Strongly agree (vs. Strongly disagree (ref.)) OR=0.15, somewhat agree OR=0.31
Pojani and Boussauw, 2014	Albania, Tirana	cross-sectional	472	11-13y	54%	poor	school	walk	parent		safety OR=0.49 many major road crossings OR=0.38 time distance OR=0.48
Prins et al., 2009	Netherlands, Rotterdam	cross-sectional	654	12-15y; 14.1 (1.2)	46%	fair	other	active	self		availability of parks OR=1.66
Rahman et al., 2020	New Zealand, Otago	cross-sectional	1260 [a]	13-18y; 15.2 (1.4)	56%	poor	school	active	self	NEWS-Y	too much traffic r=-0.82 dangerous crossings r=-0.75 unsafe to walk=-0.76 parents think it’s unsafe to walk r=-0.84 unsafe to cycle r=-0.78 parents think it’s unsafe to cycle r=-0.82

Table A.1 continued from previous page

Study	Region	Study design	Sample size	Age	% female	Study quality	Desti-nation	Mode	Self-/ parent report	Environment question-naire	Results (only associations with p <0.05 reported)
Silva et al., 2011	Brazil, Caxias do Sul/RS	cross-sectional	1672	11-17y; 14.37 (1.92)	53%	fair	school	active	self		**Frequency of AST:** trip time (Ref.: <10min): 10-20min PR=1.73; >20min PR=2.08 traffic PR=1.60 crime danger PR=2.13 long distance PR=2.42 **Mode of school transport (active vs. passive):** trip time (Ref.: <10min): 10-20min PR=1.53; >20min PR=1.93 traffic PR=1.75 crime danger PR=2.65 long distance PR=3.02
van Dyck et al., 2013	Belgium, Ghent	cross-sectional	477	13-15y	50%	good	all	active	self	NEWS	n.s.
van Dyck et al., 2010	Belgium, Flanders	cross-sectional	888 [a]	17-18y; 17.14 (0.51)	57%	good	school	active	self	NEWS	walkability OR=1.10
Verhoeven et al., 2016	Belgium, Flanders	cross-sectional	306 [a]	16-19y; 17.8 (0.7)	55%	good	school, other	walk, cycle	self	ALPHA, NEWS	**Walking to school (yes/no):** n.s. **Walking to school duration: n.s.** **Cycling to school (yes/no):** n.s. **Cycling to school duration:** distance b=1.05 **Walking to other destinations (yes/no):** Residential density OR=0.79 **Walking to other destinations duration:** n.s. **Cycling to other destinations (yes/no):** n.s. **Cycling to other destinations duration:** residential density: b=0.86 crime safety b=0.75

Table A.1 continued from previous page

Study	Region	Study design	Sample size	Age	% female	Study quality	Desti- nation	Mode	Self-/ parent report	Environment question- naire	Results (only associations with p <0.05 reported)
Voorhees et al., 2010	US	cross-sectional	890 [a]	11-12y	100%	good	school	walk	self		places to walk to OR=1.82 safe to walk OR=1.84
Voorhees et al., 2011	US, Maryland, Baltimore	cross-sectional	273	grade 9-12	58%	good	school	walk	self	NEWS	land-use mix accessibility β=0.39 neighbourhood satisfaction β=0.26
Woldeama-nuel, 2016	US	cross-sectional	7550	12-16y	47%	poor	school	active	parent		**AT to school:** crime β=0.11 traffic amount β=-0.29 weather β=-0.15 **AT from school:** crime β=0.15 distance β=-0.14 traffic amount β=-0.29

[a] Sample size includes only participants living within a certain distance to school; AT: active transport; ALPHA: Assessing Levels of PHysical Activity environment questionnaire; BATACE: Barreras en el Transporte Activo al Centro Educativo questionnaire; NEWS: neighbourhood Environment Walkability Score; NEWS-A: Abbreviated neighbourhood Environment Walkability Score; NEWS-Y: neighbourhood Environment Walkability Score youth version; PABACS: Parental Perception of Barriers Towards Active Commuting to School Questionnaire; SES: socioeconomic status; n. s.: not significant (p>0.05); OR: odds ratio; PR: prevalence ratio; β: beta-coefficient (positive values indicate a higher frequency or duration of AT)

A.2 Supplemental material from chapter 4

A.2.1 Supplement 1: Regularised logistic regression model and results in R

Load packages and data

```
library(glmnet)
library(glmnetUtils)

data <- readRDS("MoMo_bikeability_data.rds")
```

Cross-validation of Ridge, Elastic Net and Lasso regressions

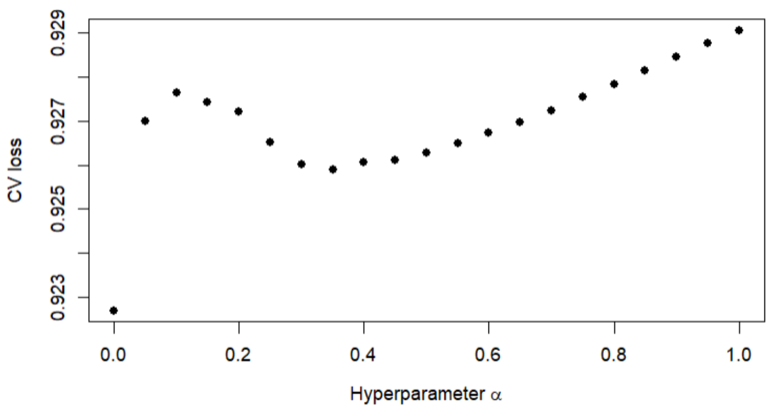
```
set.seed(123)

model <- cva.glmnet(data = data,
                    family="binomial",
                    alpha = seq(0, 1, 0.05),
                    commute_cycle ~ age + sex + socioeconomic_status +
                        municipality +
                        urbanisation / (  cycleway_total_04 +
                                          cycleway_total_08 +
                                          cycleway_total_12 +
                                          cycleway_total_16 +
                                          cycleway_total_20 +
                                          main_separated_04 +
                                          main_separated_08 +
                                          main_separated_12 +
                                          main_separated_16 +
                                          main_separated_20 +
                                          residential_safe_04 +
                                          residential_safe_08 +
                                          residential_safe_12 +
                                          residential_safe_16 +
                                          residential_safe_20 +
                                          school_04 +
                                          school_08 +
                                          school_12 +
                                          school_16 +
                                          school_20 +
                                          pitchsize_04 +
```

```
                                          pitchsize_08 +
                                          pitchsize_12 +
                                          pitchsize_16 +
                                          pitchsize_20 +
                                          parksize_04 +
                                          parksize_08 +
                                          parksize_12 +
                                          parksize_16 +
                                          parksize_20 +
                                          shopfood_04 +
                                          shopfood_08 +
                                          shopfood_12 +
                                          shopfood_16 +
                                          shopfood_20 +
                                          population_04 +
                                          population_08 +
                                          population_12 +
                                          population_16 +
                                          population_20 ))
```

Plot to determine the optimal α

Based on the plot, the model with $\alpha = 0$, i.e. a ridge regression, was chosen.

```
minlossplot(model, cv.type = c("min"),
            xlab = expression(paste("Hyperparameter␣", alpha)),
            pch = 19)
```



λ of the selected model with $\alpha = 0$

This includes λ-values for the best model (minimal λ) and the λ according to the one-standard-error rule.

```
model$modlist[[1]]$lambda.min
# [1] 0.1046623

model$modlist[[1]]$lambda.1se
# [1] 0.3507865
```

Coefficients of the selected model

Coefficients of the model with $\alpha = 0$ and $\lambda_{1se} = 0.3507865$.

```
exp(coef(model$modlist[[1]], s = model$modlist[[1]]$lambda.1se))
```

A.2.2 Supplement 2: Coefficients of the selected ridge regression model

Table A.2: Coefficients of the cycling-to-school (ref. no) model with $\alpha = 0$ and $\lambda_{1se} = 0.3507865$

Predictors	Odds Ratios
Intercept	0.304
Age	0.963
Socioeconomic status: low	0.875
Socioeconomic status: middle	0.997
Socioeconomic status: high	1.154
Sex: male	1.056
Sex: female	0.947
Urbanisation: city	1.050
Urbanisation: town	1.257
Urbanisation: rural	0.692
In cities: cycleways total within >4-8 min	0.988
In cities: cycleways total within >8-12 min	1.011
In cities: cycleways total within >12-16 min	0.990
In cities: cycleways total within >16-20 min	1.050
In cities: cycleways total within 4 min	0.988
In cities: cycleways along main streets within >4-8 min	0.976
In cities: cycleways along main streets within >8-12 min	1.009
In cities: cycleways along main streets within >12-16 min	0.986
In cities: cycleways along main streets within >16-20 min	1.008
In cities: cycleways along main streets within 4 min	1.015
In cities: park size within >4-8 min	0.966
In cities: park size within >8-12 min	0.959
In cities: park size within >12-16 min	0.939
In cities: park size within >16-20 min	0.980
In cities: park size within 4 min	0.966
In cities: pitch size within >4-8 min	1.062

Table A.2 continued from previous page

Predictors	Odds Ratios
In cities: pitch size within >8-12 min	1.050
In cities: pitch size within >12-16 min	1.086
In cities: pitch size within >16-20 min	0.964
In cities: pitch size within 4 min	0.968
In cities: population within >4-8 min	0.971
In cities: population within >8-12 min	0.981
In cities: population within >12-16 min	0.998
In cities: population within >16-20 min	0.982
In cities: population within 4 min	0.967
In cities: safe residential streets within >4-8 min	1.027
In cities: safe residential streets within >8-12 min	1.086
In cities: safe residential streets within >12-16 min	1.008
In cities: safe residential streets within >16-20 min	1.057
In cities: safe residential streets within 4 min	1.022
In cities: schools within >4-8 min	0.987
In cities: schools within >8-12 min	1.022
In cities: schools within >12-16 min	1.003
In cities: schools within >16-20 min	0.959
In cities: schools within 4 min	1.015
In cities: shops and food outlets within >4-8 min	1.000
In cities: shops and food outlets within >8-12 min	1.053
In cities: shops and food outlets within >12-16 min	1.057
In cities: shops and food outlets within >16-20 min	0.995
In cities: shops and food outlets within 4 min	1.015
In towns: cycleways total within >4-8 min	1.052
In towns: cycleways total within >8-12 min	1.058
In towns: cycleways total within >12-16 min	1.061
In towns: cycleways total within >16-20 min	1.079
In towns: cycleways total within 4 min	1.063
In towns: cycleways along main streets within >4-8 min	1.024

Table A.2 continued from previous page

Predictors	Odds Ratios
In towns: cycleways along main streets within >8-12 min	1.010
In towns: cycleways along main streets within >12-16 min	1.007
In towns: cycleways along main streets within >16-20 min	1.018
In towns: cycleways along main streets within 4 min	1.009
In towns: park size within >4-8 min	1.009
In towns: park size within >8-12 min	1.024
In towns: park size within >12-16 min	1.027
In towns: park size within >16-20 min	0.990
In towns: park size within 4 min	0.975
In towns: pitch size within >4-8 min	0.998
In towns: pitch size within >8-12 min	1.054
In towns: pitch size within >12-16 min	1.082
In towns: pitch size within >16-20 min	0.983
In towns: pitch size within 4 min	1.032
In towns: population within >4-8 min	1.061
In towns: population within >8-12 min	1.085
In towns: population within >12-16 min	1.042
In towns: population within >16-20 min	0.962
In towns: population within 4 min	0.967
In towns: safe residential streets within >4-8 min	1.046
In towns: safe residential streets within >8-12 min	1.058
In towns: safe residential streets within >12-16 min	1.024
In towns: safe residential streets within >16-20 min	0.981
In towns: safe residential streets within 4 min	0.996
In towns: schools within >4-8 min	1.035
In towns: schools within >8-12 min	1.064
In towns: schools within >12-16 min	1.028
In towns: schools within >16-20 min	0.998
In towns: schools within 4 min	0.904
In towns: shops and food outlets within >4-8 min	1.022

Table A.2 continued from previous page

Predictors	Odds Ratios
In towns: shops and food outlets within >8-12 min	1.103
In towns: shops and food outlets within >12-16 min	1.006
In towns: shops and food outlets within >16-20 min	0.981
In towns: shops and food outlets within 4 min	1.007
In rural areas: cycleways total within >4-8 min	1.015
In rural areas: cycleways total within >8-12 min	1.026
In rural areas: cycleways total within >12-16 min	1.003
In rural areas: cycleways total within >16-20 min	0.988
In rural areas: cycleways total within 4 min	0.990
In rural areas: cycleways along main streets within >4-8 min	1.065
In rural areas: cycleways along main streets within >8-12 min	1.038
In rural areas: cycleways along main streets within >12-16 min	0.994
In rural areas: cycleways along main streets within >16-20 min	0.979
In rural areas: cycleways along main streets within 4 min	0.995
In rural areas: park size within >4-8 min	1.047
In rural areas: park size within >8-12 min	1.101
In rural areas: park size within >12-16 min	1.024
In rural areas: park size within >16-20 min	1.025
In rural areas: park size within 4 min	1.060
In rural areas: pitch size within >4-8 min	1.059
In rural areas: pitch size within >8-12 min	0.995
In rural areas: pitch size within >12-16 min	1.001
In rural areas: pitch size within >16-20 min	0.991
In rural areas: pitch size within 4 min	0.990
In rural areas: population within >4-8 min	0.998
In rural areas: population within >8-12 min	1.048
In rural areas: population within >12-16 min	0.989
In rural areas: population within >16-20 min	0.988
In rural areas: population within 4 min	1.016
In rural areas: safe residential streets within >4-8 min	0.990

Table A.2 continued from previous page

Predictors	Odds Ratios
In rural areas: safe residential streets within >8-12 min	1.001
In rural areas: safe residential streets within >12-16 min	0.981
In rural areas: safe residential streets within >16-20 min	0.976
In rural areas: safe residential streets within 4 min	1.016
In rural areas: schools within >4-8 min	1.022
In rural areas: schools within >8-12 min	1.055
In rural areas: schools within >12-16 min	0.981
In rural areas: schools within >16-20 min	0.986
In rural areas: schools within 4 min	0.983
In rural areas: shops and food outlets within >4-8 min	1.009
In rural areas: shops and food outlets within >8-12 min	1.004
In rural areas: shops and food outlets within >12-16 min	0.999
In rural areas: shops and food outlets within >16-20 min	0.996
In rural areas: shops and food outlets within 4 min	1.010
Municipality 1	1.716
Municipality 2	0.751
Municipality 3	0.705
Municipality 4	0.721
Municipality 5	0.719
Municipality 6	0.752
Municipality 7	0.758
Municipality 8	0.731
Municipality 9	1.042
Municipality 10	0.846
Municipality 11	1.456
Municipality 12	1.957
Municipality 13	0.847
Municipality 14	1.631
Municipality 15	0.734
Municipality 16	1.168

Table A.2 continued from previous page

Predictors	Odds Ratios
Municipality 17	0.723
Municipality 18	0.726
Municipality 19	0.648
Municipality 20	0.692
Municipality 21	0.620
Municipality 22	0.619
Municipality 23	0.591
Municipality 24	2.549
Municipality 25	2.304
Municipality 26	0.841
Municipality 27	1.675
Municipality 28	0.694
Municipality 29	0.603
Municipality 30	0.989
Municipality 31	0.589
Municipality 32	0.657
Municipality 33	0.787
Municipality 34	2.160
Municipality 35	0.643
Municipality 36	0.587
Municipality 37	1.577
Municipality 38	2.159
Municipality 39	0.808
Municipality 40	0.891
Municipality 41	0.550
Municipality 42	1.282
Municipality 43	1.632
Municipality 44	1.168
Municipality 45	0.866
Municipality 46	1.567

Table A.2 continued from previous page

Predictors	Odds Ratios
Municipality 47	0.708
Municipality 48	1.257
Municipality 49	0.772
Municipality 50	0.920
Municipality 51	0.706
Municipality 52	1.761
Municipality 53	1.139
Municipality 54	0.998
Municipality 55	0.699
Municipality 56	0.957
Municipality 57	0.716
Municipality 58	0.743
Municipality 59	0.684
Municipality 60	0.637
Municipality 61	0.803
Municipality 62	0.740
Municipality 63	0.713
Municipality 64	0.740
Municipality 65	0.725
Municipality 66	0.684
Municipality 67	0.730
Municipality 68	3.789
Municipality 69	0.690
Municipality 70	0.670
Municipality 71	2.663
Municipality 72	0.743
Municipality 73	1.076
Municipality 74	0.484
Municipality 75	1.137
Municipality 76	1.289

Table A.2 continued from previous page

Predictors	Odds Ratios
Municipality 77	0.708
Municipality 78	0.697
Municipality 79	0.780
Municipality 80	0.588
Municipality 81	0.838
Municipality 82	1.282
Municipality 83	0.894
Municipality 84	0.902
Municipality 85	0.718
Municipality 86	1.209
Municipality 87	1.460
Municipality 88	1.966
Municipality 89	0.718
Municipality 90	2.049
Municipality 91	0.684
Municipality 92	0.587
Municipality 93	1.203
Municipality 94	1.403
Municipality 95	0.703
Municipality 96	0.706
Municipality 97	0.619
Municipality 98	0.771
Municipality 99	1.085
Municipality 100	1.788
Municipality 101	0.712
Municipality 102	4.904
Municipality 103	1.450
Municipality 104	0.730
Municipality 105	0.715
Municipality 106	0.744

Table A.2 continued from previous page

Predictors	Odds Ratios
Municipality 107	0.645
Municipality 108	0.672
Municipality 109	0.905
Municipality 110	0.727
Municipality 111	0.724
Municipality 112	1.226
Municipality 113	1.087
Municipality 114	0.971
Municipality 115	1.211
Municipality 116	1.875
Municipality 117	0.643
Municipality 118	0.687
Municipality 119	0.709
Municipality 120	1.982
Municipality 121	1.184
Municipality 122	0.714
Municipality 123	1.360
Municipality 124	0.710
Municipality 125	0.683
Municipality 126	0.765
Municipality 127	1.752
Municipality 128	0.704
Municipality 129	0.701
Municipality 130	0.828
Municipality 131	0.739
Municipality 132	0.698
Municipality 133	0.705
Municipality 134	1.673
Municipality 135	1.977
Municipality 136	0.730

Table A.2 continued from previous page

Predictors	Odds Ratios
Municipality 137	0.673
Municipality 138	1.042
Municipality 139	0.617
Municipality 140	1.300
Municipality 141	0.704
Municipality 142	0.707
Municipality 143	0.915
Municipality 144	1.429
Municipality 145	1.493
Municipality 146	0.653
Municipality 147	0.703
Municipality 148	0.693
Municipality 149	0.681
Municipality 150	0.667
Municipality 151	0.932
Municipality 152	3.621
Municipality 153	0.852
Municipality 154	0.648
Municipality 155	0.596

B Publications

Peer-reviewed research articles

2025

Brehm, E., Tschuschke, L., **Klos, L.**, Burchartz, A., Volk, C., Hanssen-Doose, A., Jekauc, D., Niessner, C. & Woll, A. (2025). Physical activity and weight status of children in Germany: cross-sectional results from the MoMo Wave 3 (2018–2020). *European Journal of Pediatrics, 184*, 360. https://doi.org/10.1007/s00431-025-06183-9

Kolb, S., Burchartz, A., **Klos, L.**, Jekauc, D., Niessner, C., & Woll, A. (2025). Association between physical activity and physical health in German children and adolescents — Results from the MoMo Longitudinal Study. *BMC Public Health, 25*, 607.https://doi.org/10.1186/s12889-025-21684-w

Reiß, F., Volk, C., Behn, S., Kaman, A., **Klos, L.**, Burchartz, A., Hinz, T., Hanssen-Doose, A., Woll, A., Niessner, C., & Ravens-Sieberer, U. (2025). Psychische Gesundheit und körperliche Aktivität von Heranwachsenden unterschiedlicher sozialer Herkunft. Ergebnisse der bundesweiten COMO-Studie. *Zeitschrift für Kinder- und Jugendpsychiartrie und Psychotherapie*. Advance online publication. https://doi.org/10.1024/1422-4917/a001045

Woll, A., **Klos, L.**, Worth, A., Hanssen-Doose, A., Hinz, T., Völkle, M., Burchartz, A., & Niessner, C. (2025). The German national cohort study on the development of motor performance, physical activity and health in children and adolescents: The MoMo 2.0-Study protocol. *BMJ Open, 15*(4), e094895. https://doi.org/10.1136/bmjopen-2024-094895

2024

Burchartz, A., Kolb, S., **Klos, L.**, Schmidt, S. C. E., Haaren-Mack, B., Niessner, C., & Woll, A. (2024). How specific combinations of epoch length, non-wear time and cut-points influence physical activity. *German Journal of Exercise and Sport Research, 54*, 169–178. https://doi.org/10.1007/s12662-023-00892-9

Klos, L., Fiedler, J., Nigg, C., Niessner, C., Wäsche, H., & Woll, A. (2024). Walking and non-motorized vehicle use in adolescents: The role of neighborhood environment perceptions across urbanization levels. *German Journal of Exercise and Sport Research, 54*, 145–155. https://doi.org/10.1007/s12662-023-00931-5

Klos, L., Stratton, G., Mackintosh, K. A., McNarry, M. A., Fogelholm, M., Drummen, M., Macdonald, I., Martinez, J. A., Navas-Carretero, S., Handjieva-Darlenska, T., Bogdanov, G., Gant, N., Poppitt, S. D., Silvestre, M. P., Brand-Miller, J., Muirhead, R., Schlicht, W., Huttunen-Lenz, M., Brodie, S., ... Swindell, N. (2024). Combining diaries and accelerometers to explain change in physical activity during a lifestyle intervention for adults with pre-diabetes: A PREVIEW sub-study. *PLOS ONE, 19*(3), e0300646. https://doi.org/10.1371/journal.pone.0300646

2023

Klos, L., Burchartz, A., Niessner, C., Reimers, A. K., Thron, M., Woll, A., & Wäsche, H. (2023). Active school transport routines during school transitions: Socio-structural predictors of changes from childhood into early adulthood. *Health & Place, 81*, 103005. https://doi.org/10.1016/j.healthplace.2023.103005

Klos, L., Eberhardt, T., Nigg, C., Niessner, C., Wäsche, H., & Woll, A. (2023). Perceived physical environment and active transport in adolescents: A systematic review. *Journal of Transport & Health, 33*, 101689. https://doi.org/10.1016/j.jth.2023.101689

König, T. T., Frankenbach, M.-L., Gianicolo, E., Holler, A.-S., Sochaczewski, C. O., Wessel, L., Widenmann, A., **Klos, L.**, Kolb, S., Siaplaouras, J., & Niessner, C. (2023). Habitual physical activity in patients born with oesophageal atresia: A multicenter cross-sectional study and comparison to a healthy reference cohort matched for gender and age. *European Journal of Pediatrics, 182*, 2655–2663. https://doi.org/10.1007/s00431-023-04923-3

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Kolb, S., Burchartz, A., Krause, L., **Klos, L.**, Schmidt, S. C. E., Woll, A., & Niessner, C. (2022). Physical Activity and Recurrent Pain in Children and Adolescents in Germany-Results from the MoMo Study. *Children, 9*(11). https://doi.org/10.3390/children9111645

Richards, A. B., **Klos, L.**, Swindell, N., Griffiths, L. J., Martelaer, K., Edwards, L. C., Brophy, S., & Stratton, G. (2022). Associations between swimming & cycling abilities and fitness in 9-11 year old boys and girls. *Journal of Sports Sciences, 40*(6), 658–666. https://doi.org/10.1080/02640414.2021.2013616

2021

Woll, A., **Klos, L.**, Burchartz, A., Hanssen-Doose, A., Niessner, C., Oriwol, D., Schmidt, S. C. E., Bös, K., & Worth, A. (2021). Cohort Profile Update: The Motorik-Modul (MoMo) Longitudinal Study-physical fitness and physical activity as determinants of health development in German children and adolescents. *International Journal of Epidemiology, 50*(2), 393–394. https://doi.org/10.1093/ije/dyaa281

2020

Klos, L., Feil, K., Eberhardt, T., & Jekauc, D. (2020). Interventions to Promote Positive Affect and Physical Activity in Children, Adolescents and Young Adults - A Systematic Review. *Sports, 8*(2), 26. https://doi.org/10.3390/sports8020026

Articles and book chapters without peer-review

2025

Wolbring, L., Krafft, J., **Klos, L.**, & Woll, A. (2025). Bedeutung und Effekte von Bewegung und Sport: Gesundheitsförderung. In M. Matzner & T. Wojciechowski (Hrsg.), *Handbuch Bewegung und Sport in der Sozialen Arbeit* (S. 64-79). Beltz Juventa.

Klos, L., Wolbring, L., & Woll, A. (2025). Aktive Schulwege in städtischen und ländlichen Gebieten. (Un)genutzte Gesundheitspotenziale? *Stadtforschung und Statistik, 38*(1), 33–39.

Wolbring, L., **Klos, L.**, Woll, A., & Wäsche, H. (2025). Kommunale Netzwerke der Sport- und Bewegungsförderung. Analyse und Entwicklung interorganisationaler Kooperationsstrukturen. *Stadtforschung und Statistik, 38*(1), 40–46.

2021

Woll, A., Scharenberg, S., **Klos, L.**, Opper, E., & Niessner, C. (2021). Fünf Thesen und elf Empfehlungen zur Bewegungs- und Sportförderung für Kinder und Jugendliche vor dem Hintergrund der Corona-Pandemie. „Es ist bereits fünf nach Zwölf – wir fordern einen Bewegungspakt!“. *KIT Scientific Working Papers*, 174. https://doi.org/10.5445/IR/1000139901/V2

2019

Woll, A., **Klos, L.**, & Knoll, M. (2019). Prävention und Gesundheitsförderung im Erwachsenenalter. In M. Tiemann & M. Mohokum (Hrsg.), *Prävention und Gesundheitsförderung*. Springer. https://doi.org/10.1007/978-3-662-55793-8_85-1

Conference presentations

2025

Klos, L., Kolb, S., Niessner, C., Tschuschke, L., Volk, C., Wäsche, H., Wolbring, L., & Woll, A. (2025). Aktive Schulwege in Deutschland: Ergebnisse der MoMo 2.0-Studie. In B. Strauß, M. Tietjens, E. van Meurs, & L. Henning (Hrsg.), *Sportwissenschaft: Vielfalt und Nachhaltigkeit!? Abstracts zum 27. Hochschultag der Deutschen Vereinigung für Sportwissenschaft* (S. 419). Feldhaus Verlag.

2024

Klos, L., Pedrick-Case, R., Fry, R., Wäsche, H., Niessner, C., & Woll, A. (2024). S10-1: Using open GIS data to identify bikeable neighbourhoods for adolescents across Germany: Results of the MoMo-Study. *European Journal of Public Health, 34*(Supplement_2), ckae114.241. https://doi.org/10.1093/eurpub/ckae114.241

2023

Klos, L. (2023, June 23). *Nutzen von Machine Learning im Screening-Prozess von systematischen Reviews am Beispiel der Software „ASReview".* Sports, Medicine and Health Summit 2023, Hamburg.

Klos, L., Fiedler, J., Nigg, C., Burchartz, A., Hinz, T., Wäsche, H., Niessner, C., & Woll, A. (2023). O.5.1-1 Physical environment perceptions in rural and urban areas and their influence on adolescents' walking and non-motorized vehicle use. *European Journal of Public Health, 33*(Supplement_1), ckad133.231. https://doi.org/10.1093/eurpub/ckad133.231

2022

Klos, L., Niessner, C., Wäsche, H., Reimers, A. K., & Woll, A. (2022). Entwicklung und Stabilität von Mobilitätsroutinen auf dem Schul- bzw. Arbeitsweg vom Kindes- bis ins junge Erwachsenenalter. In M. Wegner & J. Jürgensen (Hrsg.), *Sport, Mehr & Meer—Sportwissenschaft in gesellschaftlicher Verantwortung. Abstracts zum 25. Hochschultag der Deutschen Vereinigung für Sportwissenschaft* (S. 196). Feldhaus Verlag.

Active travel, such as walking or cycling, has several health and environmental benefits. The neighbourhood environment plays a crucial role in shaping adolescents' active travel behaviour; therefore, this work investigates how environmental perceptions and built environment characteristics relate to adolescents' active travel. It addresses three main questions: (1) which perceived environmental factors influence adolescents' active travel, (2) how these relationships vary across active travel modes and between urban and rural areas in Germany, and (3) which GIS-based bikeability characteristics are relevant for adolescent cycling across different levels of urbanisation. By addressing both subjective environment perceptions and objective environment measures, this work provides actionable insights for researchers and planners aiming to create environments that support adolescent active travel in diverse contexts.

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