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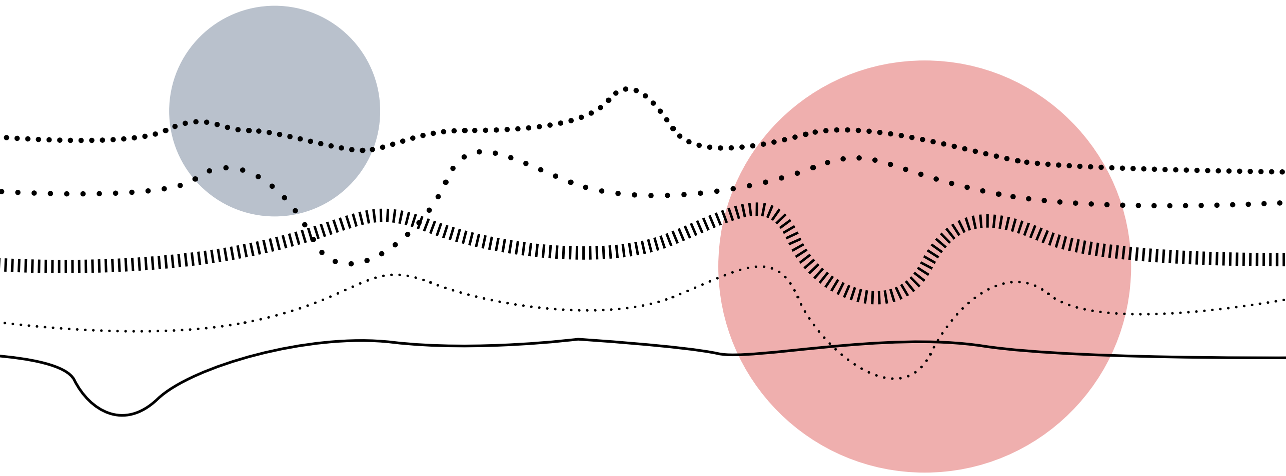

URBAN CO-ACCESSIBILITY

Vasileios Milias

URBAN CO-ACCESSIBILITY

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Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus, prof. dr. ir. T.H.J.J. van der Hagen,
chair of the Board for Doctorates
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To everyone who went out for a drink with me and found themselves entrapped in unnecessarily lengthy discussions about co-accessibility

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SUMMARY

Accessibility is a widely employed concept across a variety of disciplines to evaluate the degree to which individuals can reach a desired destination. In this dissertation, with the term "accessibility" we refer to "urban accessibility", which focuses on how structural elements of planning and urban development, such as the configuration of transportation (mobility) corridors and the spatial distribution of people and land uses, affect people's ability to access opportunities.

Conventionally, accessibility is determined by the attractiveness of a destination and the associated travel cost to reach it. The attractiveness of a destination encapsulates a variety of factors, such as the number and type of activities, amenities provided, or employment opportunities available at that location. In turn, the costs refer to time, monetary expenditures, or other costs required for an individual to reach a desired location. Accordingly, the optimization of existing accessibility measures involves the concurrent maximization of the attractiveness of destinations and the minimization of the costs for individuals to reach them. This optimization goal exhibits certain limitations. First, it often lacks the capacity to differentiate between disparate destinations accessible to distinct individuals and the same destination accessible to different individuals. Second, existing place-based measures fail to distinguish between destinations that can be accessed by individuals from a single demographic group and those that can be accessed by individuals across various demographic groups. Given that access to shared spaces is critical for physical encounters and interactions among individuals, these constraints impede our capacity to unveil the potential of destinations in fostering encounters between various individuals or groups.

We address these limitations by introducing the concept of *co-accessibility* and proposing a place-based measure to assess how accessible a given destination is to different individuals and demographic groups. Considering the broad nature of the concept of co-accessibility, to empirically analyze and measure it, we limit our scope to pedestrians. We begin by laying the groundwork for a methodological framework for measuring co-accessibility (Chapter 2). We demonstrate how a measure of co-accessibility could enhance traditional accessibility metrics and alleviate some of their inherent biases. We also outline the components of co-accessibility and propose a mathematical formulation for its measurement. Furthermore, we highlight potential opportunities and prospective measurement challenges to support future research endeavors in related fields.

Next, building on the definition and formulation of co-accessibility we propose a method for measuring co-accessibility and apply it for the assessment of spatial age segregation, meaning the degree to which different age groups occupy the same space (Chapter 3). In particular, we use spatially disaggregated data about urban destinations across the cities of Amsterdam, Rotterdam, The Hague, Utrecht, and Eindhoven in the Netherlands to calculate several spatial accessibility metrics and estimate co-accessibility scores for

each destination. These analysis results demonstrate how the proposed co-accessibility measure can provide new insight into the potential moderating effect that exposure to other age groups in places outside of the home can bring to the level of spatial age segregation.

Common assumptions in the applied measurement of accessibility include narrowing down the *travel cost* solely to time-related expenditures and assuming all destinations to be equally *attractive*. However, diverse perceptions of the urban environment between individuals and groups can significantly affect both travel costs and the attractiveness of a destination. For instance, individual preferences of different demographic groups may play a crucial role in either encouraging or dissuading travel to specific destinations, thereby influencing the choices made regarding space use for different activities. This underscores the necessity of examining the influence of these assumptions on measuring co-accessibility.

We begin with the *travel cost*, directing our attention towards investigating the impact of streetscape features on the perceived safety and attractiveness of city streets, perceptions that have been found to either positively or negatively impact pedestrian trip generation. To do so, we pursued two distinct approaches (Chapters 4 and 5). The first approach involved crowdsourcing perceptions from individuals. We developed a crowdsourcing tool that enables people to virtually navigate streets represented as a sequence of street-level images, rate locations based on perceived safety and attractiveness, and explain their ratings. To study the extent to which different street features impact these perceptions, we conducted an experiment with 403 participants, while controlling for different age and gender groups.

The second approach draws from contemporary urban design theories and principles that often advocate urban forms that encourage natural surveillance or eyes on the street" to promote community safety. In particular, we examined the degree to which the existence of windows with a view toward the street can be used as an estimator of the street's perceived safety. To do so, we propose a method that employs street-level imagery and computer vision techniques to detect windows on building facades and calculate sightlines from the street level and surrounding buildings. To empirically evaluate our method we applied it across forty neighborhoods in Amsterdam, the Netherlands, and examined the correlations between our measurements and the city's Safety Index. Ultimately, the findings of these two studies are used to make evidence-informed recommendations for designing safer and more attractive streets and for measuring pedestrian co-accessibility.

Then, we focus on understanding how the physical characteristics of urban locations impact the *destination attractiveness* component of co-accessibility. To do so, we focus on public open spaces which are an essential component of every city, and when designed to appeal to a variety of individuals and demographic groups, they witness a high frequency of use, accommodating a multitude of activities, thereby serving as hubs of social interaction and activity. Specifically, we explore how the physical characteristics of public open spaces influence the likelihood of use across individuals and different age and gender groups by combining crowdsourcing, street-level images, statistical comparisons, and reflexive thematic analysis (Chapter 6). Our findings allow us to gain an improved understanding of how the physical characteristics of a space can impact the degree to which different people and groups are likely to perform activities there and, consequently, the co-accessibility of such spaces.

In the concluding chapter of this dissertation, Chapter 7, we summarize our findings and suggest potential avenues for future research in the realm of co-accessibility. We provide answers to the research questions posed in this dissertation and discuss the contributions of this work. Moreover, we outline this work's limitations and propose potential ways to address them. Additionally, we delve into the broader implications of this dissertation, including their relevance to urban planning, revisiting recently popular urban models, and the development of related computational methods and tools. Finally, we deliberate on future research endeavors that extend beyond the scope of this work.

Samenvatting

In een brede verscheidenheid aan disciplines is bereikbaarheid een veelgebruikt concept voor het evalueren van de vraag in hoeverre mensen een gewenste bestemming kunnen bereiken. In dit proefschrift verwijzen we met de term 'bereikbaarheid' naar 'stedelijke bereikbaarheid', een begrip dat ingaat op de invloed van structurele elementen in stadsplanning en stadsontwikkeling waaronder de inrichting van (mobiliteits) vervoerscorridors en de ruimtelijke distributie van mensen en landgebruik op de mate waarin mensen toegangsmogelijkheden hebben.

Gebruikelijk is dat bereikbaarheid wordt bepaald door de aantrekkelijkheid van een bepaalde locatie en door de reiskosten om die locatie te bereiken. De aantrekkelijkheid van een bestemming omvat een veelheid van factoren, waaronder het aantal en het soort activiteiten en voorzieningen die worden aangeboden en de werkgelegenheid die op de locatie voorhanden is. De kosten daarentegen verwijzen naar de hoeveelheid tijd, geld en andere kosten die iemand moet besteden om de gewenste locatie te bereiken. Optimalisering van de bestaande bereikbaarheidsaanpak omvat de actuele maximalisering van de bereikbaarheid van locaties en de minimalisering van de kosten die iemand moet maken om de locatie te bereiken. Deze optimalisering is aan bepaalde beperkingen gebonden. Ten eerste wordt er geen onderscheid gemaakt tussen verschillende bestemmingen die voor verschillende individuen bereikbaar zijn. Ten tweede wordt er geen onderscheid gemaakt tussen bestemmingen die toegankelijk zijn voor leden van één bepaalde demografische groep en bestemmingen die toegankelijk zijn voor een verscheidenheid van demografische groepen. Aangezien de toegang tot gedeelde ruimten voor fysieke ontmoetingen en interacties tussen mensen van groot belang is, verhinderen deze beperkingen de mogelijkheid tot het ontsluiten van het potentieel aan bestemmingen om ontmoetingen tussen individuen en groepen te bevorderen.

We gaan nader in op deze beperkingen door het introduceren van het concept 'co-bereikbaarheid' en we opperen een aanpak voor het beoordelen van de vraag hoe bereikbaar een bepaalde bestemming is voor individuen en demografische groepen. Gezien de brede toepasbaarheid van het analyseren en meten van het concept 'co-bereik-baarheid', beperken we ons tot voetgangers. We beginnen met het formuleren van een methodologische basis voor het meten van co-bereikbaarheid (Hoofdstuk 2). We laten zien hoe het meten van co-bereikbaarheid tot een verbetering kan leiden van traditionele maatstaven van bereikbaarheid en we corrigeren de inherente verstoringen van deze maatstaven. Ook schetsen we de contouren van de verschillende elementen van co-bereikbaarheid en stellen we een wiskundige formule voor het meten ervan voor. Daarnaast gaan we in op potentiële kansen en op mogelijke uitdagingen met betrekking tot het meten van co-bereikbaarheid ten behoeve van toekomstig onderzoek op verwante vakgebieden.

Voortbouwend op de definitie en formulering van co-bereikbaarheid, stellen we vervolgens een methode voor het meten van co-bereikbaarheid voor en passen we deze toe op de beoordeling van ruimtelijke segregatie naar leeftijd, d.w.z. de mate waarin verschillende leeftijdsgroepen één en dezelfde ruimte delen (Hoofdstuk 3). In het bijzonder gebruiken we ruimtelijk fijnschalige data met betrekking tot stedelijke bestemmingen in de Nederlandse steden Amsterdam, Rotterdam, Den Haag, Utrecht en Eindhoven, met het doel om verschillende ruimtelijke maatstaven van bereikbaarheid te berekenen en voor elk van deze bestemmingen bereikbaarheidsscores te berekenen. Deze analyse laat zien hoe de voorgestelde maatstaf van co-bereikbaarheid nieuwe inzichten kan opleveren in de potentieel matigende invloed van de blootstelling aan diverse leeftijdsgroepen buitenshuis op de mate van ruimtelijke segregatie naar leeftijd.

Tot de gebruikelijke opvattingen wat betreft de meting van bereikbaarheid behoort het idee dat het omlaag brengen van reiskosten alleen van invloed is op tijdsgebonden uitgaven en dat alle bestemmingen even aantrekkelijk zijn. Maar verschillen in perceptie van de stedelijke omgeving door individuen en groepen kunnen aanzienlijke invloed hebben op zowel reiskosten voor een bepaalde bestemming als de aantrekkelijkheid van die bestemming. Zo spelen de verschillende voorkeuren van demografische groepen mogelijk een cruciale rol in het aangaan dan wel afzien van reizen naar bepaalde bestemmingen, waardoor ze van invloed zijn op keuzes met betrekking tot het gebruik van de stedelijke ruimte voor diverse activiteiten. Dit benadrukt de noodzaak tot het onderzoeken van de invloed van deze veronderstellingen met betrekking tot het meten van co-bereikbaarheid.

We beginnen met de reiskosten en richten ons op het onderzoek naar de invloed die straatvoorzieningen hebben op de waargenomen veiligheid en aantrekkelijkheid van straten, percepties die een positieve dan wel negatieve invloed uitoefenen op de frequentie van voetgangersreizen. Daartoe hebben we twee aparte benaderingen gevolgd (Hoofdstukken 4 en 5). De eerste benadering betreft crowdsourcing-percepties van individuen. We hebben een crowdsourcing-instrument ontwikkeld waarmee we mensen in staat stelden om op virtuele wijze door straten te wandelen; straten werden weergegeven in een reeks beelden op straatniveau, waarna deelnemers locaties konden waarderen op veiligheid en aantrekkelijkheid en hun waardering konden toelichten. Om te analyseren in hoeverre verschillende straatvoorzieningen van invloed waren op deze percepties, deden we een proef met 403 deelnemers van verschillende leeftijden en uit diverse gendergroepen.

De tweede benadering is gebaseerd op hedendaagse designtheorieën en -principes waarin vaak wordt gepleit voor stedelijke vormen die aanmoedigen tot natuurlijke observatie en tot sociale controle, met het doel een gedeeld gevoel van veiligheid te bevorderen. We onderzochten in het bijzonder de mate waarin de aanwezigheid van ramen met uitzicht op straat gebruikt kon worden als indicator van de waargenomen veiligheid van een straat. Daartoe stellen we een methode voor waarin gebruik wordt gemaakt van beelden op straatniveau en beeldherkenningstechnologie voor het registreren van ramen in façades en het berekenen van zichtlijnen op de straat en de omringende gebouwen. Om onze benadering empirisch te evalueren pasten we haar toe op veertig buurten in Amsterdam, Nederland, en analyseerden we de overeenkomsten tussen onze metingen en de ‘Veiligheidsindex’ van de stad Amsterdam. Tenslotte worden de bevindingen van deze beide onderzoeken gebruikt om enkele op data gebaseerde aanbevelingen te doen met betrekking tot het ontwerp van veiliger en aantrekkelijker straten en tot het meten van co-bereikbaarheid voor voetgangers.

Vervolgens staan we stil bij de vraag welke invloed fysieke kenmerken van stedelijke locaties hebben op de aantrekkelijkheid en co-bereikbaarheid van een bestemming. Daartoe richten we ons op de openbare ruimten die een wezenlijk onderdeel van elke stad uitmaken en in hun ontwerp geacht worden een grote verscheidenheid van mensen en demografische groepen aan te spreken; deze ruimten worden veel en vaak gebruikt en voorzien in een groot aantal activiteiten, waarmee ze als knooppunten van sociale interactie en activiteit fungeren. We onderzoeken daarbij vooral de vraag welke invloed de fysieke kenmerken van openbare ruimten hebben op de gebruiksfrequentie bij individuen en bij verschillende leeftijds- en gendergroepen. We doen dat met een combinatie van crowdsourcing, beelden op straatniveau, statistische vergelijkingen en reflexief-thematische analyse (Hoofdstuk 6). Onze bevindingen stellen ons in staat betere antwoorden te krijgen op de vraag in hoeverre de fysieke kenmerken van openbare ruimten van invloed zijn op de mate waarin mensen en groepen activiteiten in die ruimten ondernemen, en daarmee in de co-bereikbaarheid van deze ruimten.

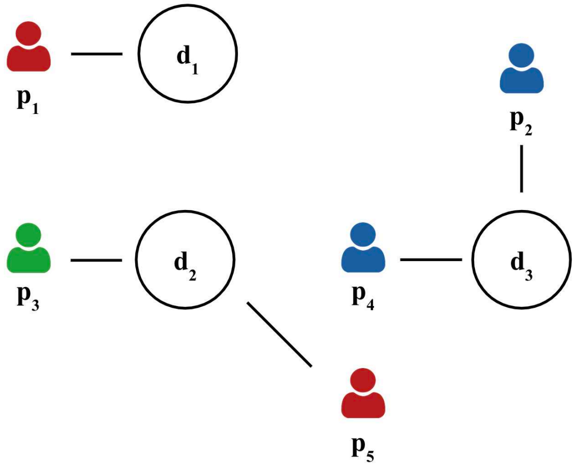
In het afsluitende hoofdstuk van dit proefschrift, Hoofdstuk 7, vatten we onze bevindingen samen en stellen nieuwe benaderingen voor toekomstig onderzoek op het gebied van co-bereikbaarheid voor. We geven antwoord op de onderzoeksvragen die in dit proefschrift zijn opgeworpen en bespreken de inzichten die daarin worden aangedragen. Daarnaast schetsen we de grenzen van onze benadering en opperen diverse mogelijkheden om die beperkingen te overwinnen. Bovendien gaan we nader in op de bredere implicaties van dit proefschrift, waaronder de relevantie van dit onderzoek voor de stadsplanning, waarbij we enkele populaire stedelijke modellen en de ontwikkeling van de daarmee verbonden digitale methoden en instrumenten opnieuw onder de loep nemen. Tenslotte bezinnen we ons op toekomstig onderzoek dat de grenzen van dit onderzoek zal overstijgen.

1

INTRODUCTION

The city is what it is because our citizens are what they are.

attributed to Plato



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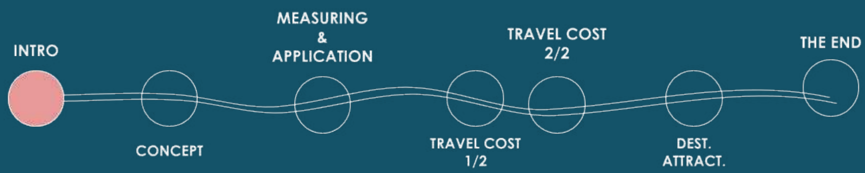
SUMMARY

Accessibility is a widely employed concept across a variety of disciplines to evaluate the degree to which individuals can reach a desired destination. Conventionally, accessibility is determined by the attractiveness of a destination and the associated travel cost to reach it. However, existing place-based accessibility measures do not differentiate between destinations accessible to individuals from a single demographic group and those accessible to individuals from diverse demographic groups. This hinders our ability to discern the encounter potential of different destinations. We address this gap by introducing the concept of co-accessibility to measure how accessible a given destination is to different individuals and demographic groups.



1.1. BACKGROUND

The major role access plays in people's well-being has been long-standing. Easy access to essential amenities, goods, healthcare, jobs, and cultural and recreational activities has been found to encourage their use [1], expand the range of activities citizens can engage in, and reduce social exclusion [1–4]. A variety of measures have been proposed to provide an enhanced understanding of the factors that make a place accessible and a fundamental prerequisite step in this process is understanding how to measure access.

To define and measure access, scholars introduced the concept of accessibility. In this dissertation, with the term "accessibility" we refer to "urban accessibility" which focuses on how structural aspects of planning and urban development, such as the configuration of transport (mobility) corridors and the spatial distribution of people and urban destinations, affect peoples ability to access opportunities. Accessibility serves as a fundamental concept across diverse disciplines, including land-use planning, transportation planning, and urban design, wherein it plays a pivotal role in assessing the ease with which individuals can reach essential activities and services, together referred to as opportunities [5–9]. The measures of accessibility stand out because they are unique in capturing, and thereby emphasizing, the interaction between land-use and transportation.

The difficulty of defining and measuring this concept has long been recognized, as Gould already observed in 1969 "*...[accessibility] is a slippery notion...one of those common terms that everyone uses until faced with the problem of defining it and measuring it.* [10]". Over the years, various definitions for accessibility have been suggested and there is still no widespread consensus on how to define or measure it. In dictionaries such as the Oxford English Dictionary or the American Heritage Dictionary, accessibility has been defined as "*capable of being entered or approached*" [11] or "*easily approached or entered*" [12], respectively. In the academic and planning context accessibility is often defined based on Hansen's definition from 1959: *"the potential of opportunities for interaction"* [5]. Other definitions include Dalvi and Martin's "the ease of individuals to reach a destination based on the transport system" [13] or the "benefits the transport system provides" [14]. More recently, Mehta wrote in [15] that "a place is considered accessible if it can be physically reached and used" and Handy in [9] that accessibility is "*...a way of characterizing the choices available*".

Similarly, the conceptualization of accessibility and approaches to measuring it vary between studies and across disciplines. A shared principle driving most approaches is that accessibility is determined by the distribution of potential destinations across space, the characteristics of these destinations, and the ease of reaching them [4]. The most common mathematical formulation of accessibility in the literature builds upon the seminal work of Hansen [5], and is defined by two main components: the attractiveness of destinations and the associated costs required to reach them. The attractiveness of a destination encapsulates a variety of factors, such as the number of activities, amenities provided, or employment opportunities available at that location. In turn, the costs refer to time, monetary expenditures, or other costs required for an individual to reach a desired location.

Over the years, numerous metrics have emerged in the literature that expand Hansen's formulation, aiming to capture the multi-dimensional nature of accessibility [16]. Some of these extended metrics enrich the cost component, considering different travel modes and traffic conditions [17], time schedules of individuals, [18–21], individual perceptions of travel costs [22], or how different population subgroups such as minorities or persons with disabilities experience access [23]. Additionally, the destination attractiveness, initially used to reflect the number of accessible destinations or jobs in area [5, 7], has evolved to encompass a wider array of factors pertaining to why individuals are attracted to particular destinations. This includes considerations such as the type of activities at a destination, the size and quality of facilities, or the lifestyle-based preferences of individuals [24].

To encompass and distinguish the various perspectives within accessibility-related literature, the concept of accessibility, including its associated measures and mathematical formulations, has been further specialized into *active* and *passive* accessibility. Active accessibility reflects the ease with which an individual can reach a destination or engage in activities at a specific location (e.g., work, education, leisure). It is the most prevalent conceptualization of spatial accessibility and aligns with the fundamental definition of [5]. In contrast, passive accessibility indicates the ease with which an opportunity can be reached by the population [6, 25, 26]. Despite their considerable potential and expanding applications, passive accessibility measures have received limited attention compared to measures of active accessibility [26–28].

Measures of either active or passive accessibility can be further distinguished into place-based and person-based measures [18, 29, 30]. Place-based measures assess the spatial separation of different locations. Such locations often represent individuals anchor locations (e.g., home or work) and key destinations where activities occur. Person-based measures reflect the extent to which individuals or specific groups can access different destinations while accounting for each individuals spatial and temporal constraints.

1.2. PROBLEM STATEMENT

Derived from the existing formulations of accessibility and its identified components, the optimization objective for accessibility involves the concurrent maximization of destination attractiveness and minimization of travel cost. Nevertheless, this optimization goal exhibits certain limitations. For active accessibility, it cannot differentiate between various destinations being accessible to different individuals and the same destination being mutually accessible to multiple individuals. We refer to this as *isolation accessibility bias*. In contrast, passive accessibility measures can overcome this shortcoming by considering the number of people who have access to each destination. However, most passive accessibility measures have another limitation: they do not differentiate between destinations accessible to individuals from a single demographic group and those accessible to individuals from diverse demographic groups. We refer to this as *homogeneity accessibility bias*.

To illustrate these biases, we present two examples inspired by the schematic activity space representation proposed from [31] and [32] and depicted in Figs. 1.1 and 1.2. This representation serves as a means to depict the destinations an individual can access using links to denote people's mobility paths and nodes to represent the destinations they have access to.

Fig. 1.1 illustrates the *isolation accessibility bias* by contrasting two cases. On the left, there are three destinations (d_1, d_2, d_3) and each destination is accessible to exactly one individual. On the right, the same single destination (d_1) is accessible to all three individuals. While these two cases are different in terms of the number of individuals who have access to each destination they are not differentiated when solely examining the number of destinations each individual has access to (one destination).

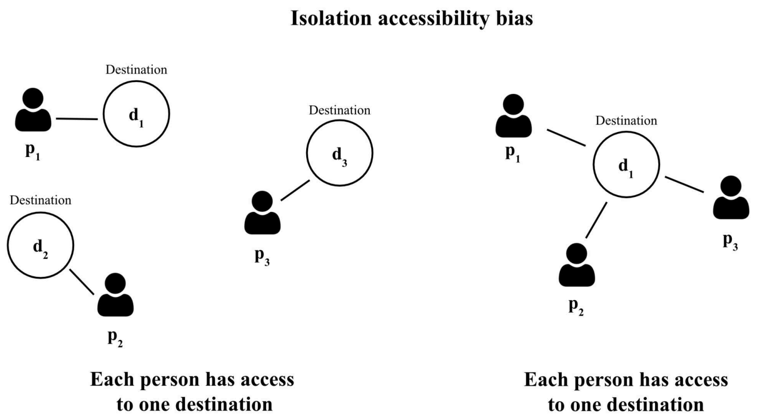


Figure 1.1.: *Isolation accessibility bias.* Disparate destinations being accessible to distinct individuals is incorrectly equated with the same destination being accessible to different individuals.

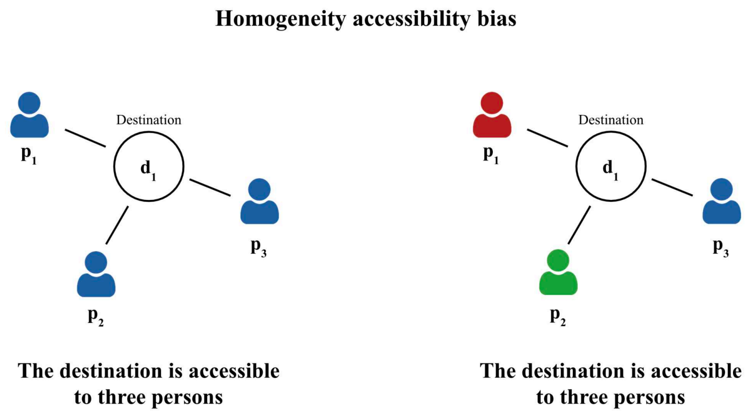


Figure 1.2.: *Homogeneity* accessibility bias. A destination being accessible to individuals from a homogeneous group is erroneously equated with a destination being accessible to individuals from different demographic groups.

1

Fig. 1.2, illustrates the *homogeneity accessibility bias* by contrasting two different cases. The one on the left depicts three individuals having access to the same destination. The one on the right shows three individuals belonging to different demographic groups having access to the same destination. These two cases are considered identical in terms of the number of individuals who have access to the same destination since in both cases each destination is accessible to three individuals. However, in the right case, d_1 is accessible by individuals from different demographic groups.

A possible way to overcome the aforementioned *isolation* and *homogeneity* biases limitations is by employing a *time-geography* approach [18]. In time-geography, which constitutes the primary theoretical framework for conceptualizing person-based accessibility [29], an individual's accessibility is modeled using a space-time prism [19]. The space-time prism represents the possible movements of an individual through both space and time, considering factors such as personal mobility constraints and time schedules [33]. The intersection of multiple individuals' space-time prisms across the continuous geographic space has been conceptualized through *joint accessibility* [20, 34]. Nevertheless, such an approach is hindered by the requirement for data on individuals' time allocations for activities and travel, and the associated privacy and ethical concerns [35]. Consequently, it also suffers from issues of reproducibility and transferability [36]. Thus, there is a need for a measure that mitigates the *isolation* and *homogeneity* biases and unveils the potential of different places to promote encounters among people and population groups.

1.3. RESEARCH OBJECTIVE

In this dissertation, we introduce co-accessibility as a place- based measure that assesses a destination's potential to bring together different individuals and individuals from diverse demographic groups by being accessible to them. Co-accessibility considers spatial constraints without accounting for individual time constraints. This allows for its measurement without being hindered by the requirement for detailed data on the precise nature of an individual's (completed) activity patterns and trips, and the associated privacy and ethical concerns [6, 27, 35]. To address the *isolation accessibility bias*, the co-accessibility of a destination is determined by the number of individuals who have access to that destination. To address the *homogeneity accessibility bias* we also need to consider the individuals' demographic groups and the co-accessibility of a destination is determined by the number of individuals who have access to that destination and the number of demographic groups these individuals belong to.

This dissertation's main research objective is twofold: (1) to define and formulate a measure of co-accessibility and (2) to identify and capture physical characteristics of the urban environment that impact the components of co-accessibility measures across different scales; from a city scale down to the level of individual streets. The primary research question driving this dissertation is:

How to measure the extent to which a destination is accessible to different individuals and population groups?

The studied physical characteristics of the urban environment that impact co-accessibility are related to the two central components of co-accessibility, the *travel cost* to reach a destination and the *destination attractiveness*. Throughout this dissertation, we examine these components under the lens of co-accessibility, research how they impact it, and propose methods to measure them. Our research objective is organized around the following research questions:

RQ1: What are the formulation and components of co-accessibility? (Chapter 2)

RQ2: How can co-accessibility facilitate the evaluation of potential encounters among different individuals and population groups? (Chapter 3)

RQ3: To what extent do physical characteristics of urban streets impact the travel cost in co-accessibility's formulation? (Chapters 4 and 5)

RQ4: To what extent do physical characteristics of urban destinations impact the destination attractiveness in co-accessibility's formulation? (Chapter 6)

1.4. RESEARCH METHODOLOGY

1.4.1. APPROACH

To develop the concept of co-accessibility, we first review spatial accessibility-related literature from a variety of fields such as urban design, urban planning, and transportation planning. Reviewing the literature allows us to identify some of the limitations of the existing accessibility measures and build the concept of co-accessibility upon existing work. Based on this, a measure of co-accessibility is proposed to tackle certain limitations of existing accessibility measures.

For the empirical part of this work, our aim is to identify and measure the physical characteristics of the urban environment that impact co-accessibility across different scales; from a city scale down to the neighborhood and street level. Traditional approaches, typically employing participant observation methods or interviews, often face challenges in including a broad and diverse range of areas and neighborhoods, necessary for conducting city-scale analysis. For that reason, we adopt a computational approach, informed by methods from the fields of computer science and urban analytics such as crowdsourcing and geospatial analysis.

Finally, this work leverages the increasing availability of open data sources, such as OpenStreetMap [37] or the Dutch Central Bureau of Statistics [38], that describe the urban environments at high spatial resolution. It is conducted based on principles of *Open Science* [39] so that all academic output, data, and software developed within the process of writing this thesis are openly shared and made available for reuse.

1.4.2. SCOPE

Considering the broad nature of the concept of co-accessibility, to empirically analyze and measure it, we limit our scope according to the following aspects, also depicted in Fig. 1.3:

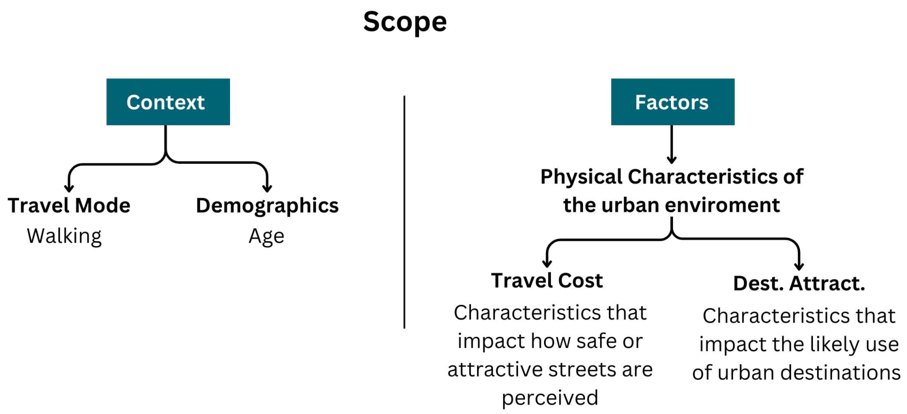


Figure 1.3.: Scope of the dissertation

Travel Mode: Our work is centered on pedestrians. Walking is the most affordable and accessible travel mode to people of virtually any demographic group, compared to cars, bikes, or public transport, it is sustainable and contributes positively to people's well-being. At the same time, walking is usually part of every trip, regardless of the chosen travel mode (i.e., one needs to walk to reach the nearby bus station or their car). These qualities establish walking as an ideal lens through which to explore co-accessibility. Nevertheless, co-accessibility could also be measured and assessed considering other travel modes (e.g., bikes, cars, or public transport).

Demographics: The concept of co-accessibility is strongly tied to people's demographic characteristics. To be consistent throughout all the chapters of this thesis, the demographic characteristic we primarily focus on is age. This choice is partially made to align with the emergent global mandates coming from the United Nations' Sustainable Development Target 11.7, where the emphasis is given to accommodating certain age groups, in particular children, and older persons [40]. Another reason driving this choice is that the need for urban spaces that bring people of different ages together and encourage intergenerational encounters is universal and related to most cities. When dealing with other demographics, such as ethnicity, this need might be more dependent on the specific context of each city. Yet, the definition and mathematical formulation of co-accessibility can support the study of other demographic characteristics as well.

Factors that impact co-accessibility: While a broad range of factors could impact co-accessibility, we focus on factors related to the cities' physical characteristics. Essentially, we are interested in measuring how the urban environment promotes or discourages different individuals and groups to access and use the same destination rather than, for instance, how different cultures or social norms could impact this.

Travel Cost: The range of factors that can be associated with the *travel cost* in co-accessibility's formulation is broad. Especially when looking at different individuals and population groups, the reasons they might be discouraged or promoted to walk on a certain street can vary. To provide methods that adequately capture and analyze these factors, we found it necessary to limit our scope and select only a subset of them.

To scope our view, our work draws from Alfonzo's hierarchy model of walking needs [41]. The five-level hierarchically structured walking needs according to Alfonzo's model, from the most basic needs to higher-order needs, are: feasibility, reachability, safety, comfort, and attractiveness[1]. Feasibility mostly considers factors such as individuals' mobility, time, or other responsibilities. Reachability, encompasses factors related to the quality and spatial distribution of amenities or the actual and perceived barriers to walking such as a wide road or a natural river. Safety entails the degree to which an individual feels safe to walk. Comfort entails factors that reflect the ease of walking, such as the quality of the sidewalk or the width and length of the streets. Lastly, attractiveness is related to factors related to the appeal of the environment and how enjoyable and interesting an area is.

In this work, we focus on reachability, safety, and attractiveness. Hence, our starting point is the presence of a pedestrian network that links individuals to certain destinations. Then, to assess the extent to which the physical characteristics of pedestrian streets impact the travel cost in co-accessibility's formulation, we explore methods for capturing how safe and attractive streets are perceived by different (groups of) people. Additionally, we investigate the degree to which the physical characteristics of streets influence these perceptions.

Destination Attractiveness: To assess if a destination is co-accessible by different individuals or groups of people it is crucial to identify, not only if these people can reach a destination but also if they would perform activities there [15]. This is reflected in co-accessibility's formulation through the *destination attractiveness* component. To study the *destination attractiveness* component, this research narrows its focus to examining how the physical characteristics of various urban destinations affect the likelihood of different individuals or age groups to perform activities there.

1.4.3. OVERVIEW OF METHODOLOGY

This work is structured in four main parts organized around the aforementioned research questions and depicted in Fig. 1.4. In step I, we introduce and formulate the concept of co-accessibility. In step II, we operationalize co-accessibility and apply a co-accessibility measure to demonstrate its utility through an empirical analysis. In steps III and IV, we focus on the two main components of accessibility, namely the *travel cost* and

[1]Alfonzo's model uses different terms to describe what we refer to as "reachability" and "attractiveness", namely, "accessibility" and "pleasurability". For consistency, we adhere to the terminology established in this dissertation and have substituted the original terms.

1

destination attractiveness, research how the physical characteristics of the urban environment impact them within the context of co-accessibility, and propose new methods to measure them. In more detail, our methodology consists of the following steps:

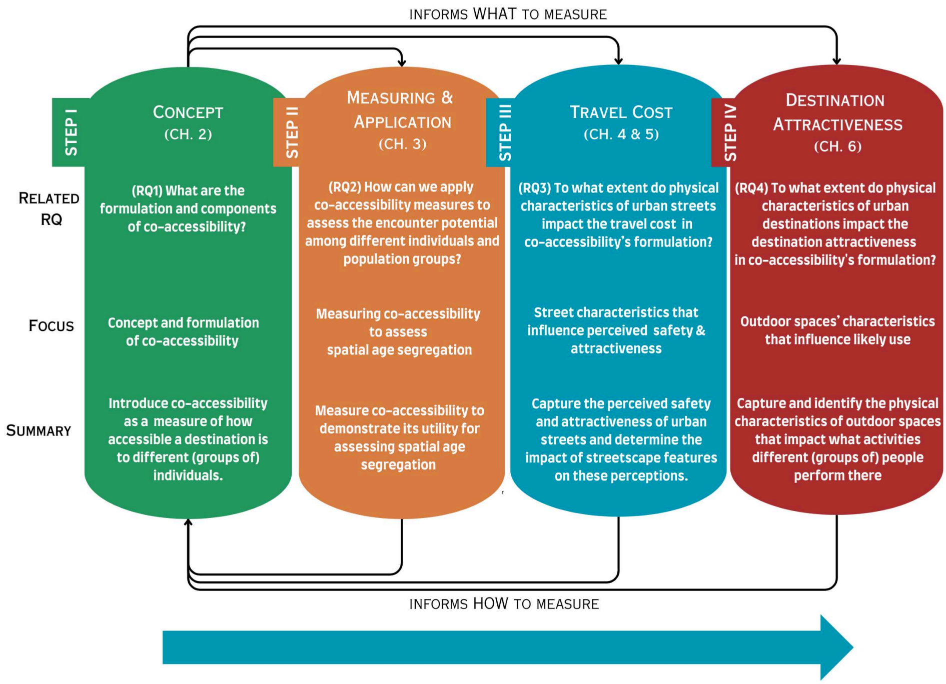


Figure 1.4.: Overall methodology

1. Concept formulation — RQ1

In step I, we introduce the concept of co-accessibility as an indicator of how accessible a given destination is to different individuals and demographic groups. We demonstrate how measuring co-accessibility can alleviate biases inherent to existing accessibility measures, describe its components, and suggest a mathematical formulation for quantifying it. Moreover, we apply our measure to a sample case study where we measure and compare the accessibility and co-accessibility of various destinations in Amsterdam, the Netherlands to highlight the complexities and challenges inherent in measuring co-accessibility. Building upon existing literature and the results of our analysis, we discuss the potential implications of co-accessibility, highlight the key challenges in assessing it, and recommend directions for future research. This step is detailed in Chapter 2.

2. Measuring & Application — RQ2

In step II, we demonstrate the practical value of co-accessibility by applying a co-accessibility measure to assess spatial age segregation (i.e., the degree to which different age groups occupy the same space). We use spatially disaggregated data about various destinations across the cities of Amsterdam, Rotterdam, The Hague, Utrecht, and Eindhoven in the Netherlands to calculate several spatial accessibility metrics and to estimate co-accessibility scores for each destination. Our analysis shows how co-accessibility can provide new insight into the potential of places outside of the home to promote encounters among different age groups and shed new light on the level of spatial age segregation across different areas. This step is detailed in Chapter 3.

3. Travel cost — RQ3

Step III of our methodology comprises two studies centered on how streetscape characteristics affect the travel cost in co-accessibility's formulation. In other words, the primary objective of step III is to capture and understand the impact of the physical characteristics of streets on how safe or attractive they are perceived.

The first study, detailed in Chapter 4, focuses on capturing the perceived safety and attractiveness along city streets and disentangling the streetscape characteristics that impact these perceptions while controlling for different age and gender groups. To determine how different streetscape characteristics contribute to a streets perceived safety and attractiveness we adopt a crowdsourcing approach. In particular, we developed a crowdsourcing tool and conducted a study with 403 participants, who were asked to virtually navigate city streets through a sequence of street-level images, rate locations based on perceived safety and attractiveness, and explain their ratings. In this way, we study how participants perceptions develop along the street and investigate to what degree the characteristics different participants encounter along a street influence how they perceive it.

The second study, described in Chapter 5, presents a novel method for measuring (perceived) safety levels along city streets. It is founded upon contemporary urban design guidelines that often advocate urban forms that encourage natural surveillance or "eyes on the street" to promote community safety [42–45]. A common denominator across theories and design approaches aimed at improving actual and perceived safety is the provision of natural (or passive) surveillance in urban public spaces [46]. Originating in what Jane Jacobs referred to as eyes on the street [47], enhancing a streets level of natural surveillance has become a widely adopted design guideline towards safer urban environments [48, 49]. In our approach, we propose a method for measuring natural surveillance at scale using street-level imagery and computer vision techniques and validate how our method can be used as an estimator of streets' (perceived) safety.

4. Destination Attractiveness — RQ4

In the 4th step of our methodology, we investigate the physical characteristics of urban destinations that impact the *destination attractiveness* in co-accessibility's formulation and how to capture them. In particular, we investigate the characteristics of outdoor spaces that influence the activities different individuals and population groups are likely to perform there, using crowdsourcing and street-level imagery data. This approach, allows us to recruit a balanced sample of participants in terms of age and gender and provides participants with the opportunity to digitally explore outdoor spaces independently of where they are currently residing. In our experiments, each participant is given five different spaces, represented as 360° panoramic street-level images and coming from three European cities: Rotterdam, Barcelona, and Gothenburg. We ask them to explore these places, rate to what degree they find them suitable for social, relaxation, physical, commuting, or children activities, and explain their ratings in their own words. Based on the collected data, we test different hypotheses and perform thematic analysis to qualitatively explore which characteristics of these spaces affect their suitability for various activities. This step is detailed in Chapter 6.

1.5. CONTRIBUTIONS

The original contributions of this thesis, in alignment with the research questions are the following [2]:

- A conceptual contribution regarding the definition and formulation of co-accessibility. This contribution is presented in Chapter 2 and addresses **RQ1**. It is based on a journal article currently under review in the *Journal of Transport Geography* [50] (***V. Milias***, *A. Psyllidis, and A. Bozzon*).
- A method to measure co-accessibility towards assessing spatial age segregation. This method is described in Chapter 3 and addresses **RQ2**. It is based on a journal article published in *Computers, Environment, and Urban Systems* [51] (***V. Milias*** *and A. Psyllidis*).
- An open-access web-based tool named CTwalk Map that serves as a demonstrator of a co-accessibility measure and enables users to compare the accessibility and co-accessibility of various destinations for the five most populous cities in The Netherlands: Amsterdam, Rotterdam, The Hague, Utrecht, and Einhdoven. CTwalk Map was showcased at the Dutch Design Week in 2023 [52] and received the first prize demo award at the NWO ICT.OPEN conference in 2024. [53].
- A study to determine how different streetscape features contribute to a streets overall sense of safety and attractiveness while controlling for different age and gender groups. This study is described in Chapter 4 and addresses **RQ3**. It is based on a full paper published in the 26th AGILE Conference on Geographic Information Science (AGILE 2023) [54] (***V. Milias***, *S. Sharifi Noorian, , A. Bozzon, and A. Psyllidis*).
- A method for measuring natural surveillance as a proxy of perceived safety along city streets at scale using street-level images. This method is described in Chapter 5 and addresses **RQ3**. It is based on a book chapter published in Goodspeed, R., Sengupta, R., Kyttä, M., and Petit, C. (eds) Intelligence for Future Cities, CUPUM 2023 [55] (*T. van Asten**, ***V. Milias****, *A. Bozzon, and A. Psyllidis*).
- A study on the influence of physical features on the likely use of outdoor spaces among different (groups of) individuals. This study is described in Chapter 6 and addresses **RQ4**. It is based on a journal article currently under review in *Computational Urban Science* [56] (***V. Milias***, *R. Teeuwen, A. Bozzon, and A. Psyllidis*).

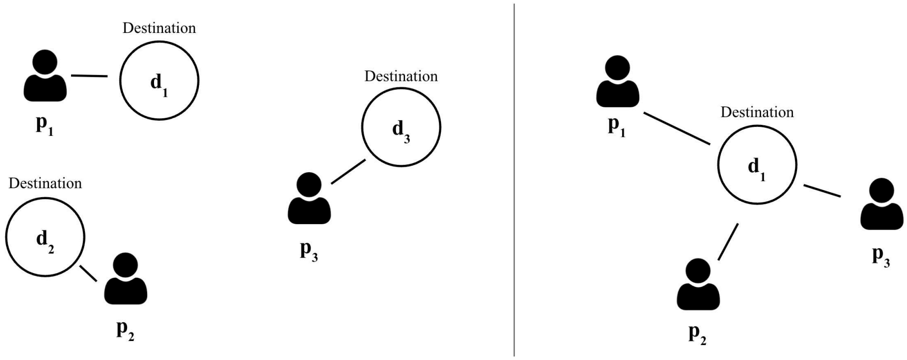
[2] (*) denotes equal contribution

2

URBAN CO-ACCESSIBILITY: CONCEPT AND FORMULATION

There is no such thing as a new idea. It is impossible. We simply take a lot of old ideas and put them into a sort of mental kaleidoscope

Mark Twain



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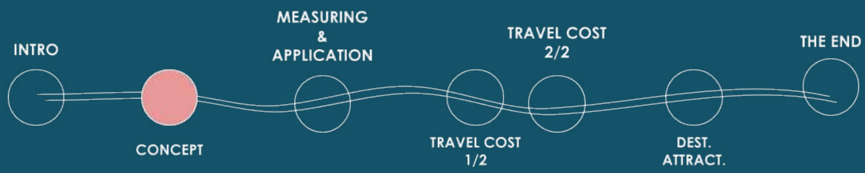
SUMMARY

In this chapter, we lay the groundwork for defining and measuring co-accessibility. First, we introduce the concept of co-accessibility and explain how measuring it can mitigate limitations of existing accessibility measures. Next, we describe its components and propose a mathematical formulation. Then, to highlight the complexities and challenges in measuring co-accessibility we apply a co-accessibility measure to a sample case study where we compare the accessibility and co-accessibility of various destinations in Amsterdam, The Netherlands. Building upon existing literature and the results of our analysis, we discuss the potential implications of co-accessibility, highlight the key challenges in assessing it, and recommend directions for future research.



*This chapter is based on a journal article currently under review in the *Journal of Transport Geography*

2.1. INTRODUCTION

While there are various approaches to measuring accessibility, one prevailing and widely accepted principle is that accessibility is determined by the attractiveness of a desired destination and the associated cost required to reach it [4, 7, 57]. The attractiveness of a destination encompasses a range of factors, such as the number and type of activities, amenities provided, or employment opportunities available at that location. In turn, travel cost refers to time, monetary expenditures, or other costs required for an individual to reach a desired location.

As explained in Chapter 1, accessibility can be specialized into *active* and *passive* accessibility. Active accessibility reflects the ease with which an individual can reach a destination or engage in activities at a specific location (e.g., work, education, leisure). It is the most commonly found interpretation of spatial accessibility and corresponds with the fundamental definition of Hansen [5]. In contrast, passive accessibility indicates the ease with which an opportunity can be reached by the population [6, 25, 26]. Although passive accessibility measures have significant potential and are increasingly being applied, they have received less attention than active accessibility measures[26–28].

In both cases, the optimization of accessibility entails maximizing the attractiveness of destinations while minimizing the costs for individuals to reach them. Nevertheless, this optimization goal exhibits certain limitations. For active accessibility, it cannot differentiate between various destinations being accessible to different individuals and the same destination being mutually accessible to multiple individuals. In contrast, passive accessibility measures can overcome this shortcoming by considering the number of people who have access to each destination. However, most passive accessibility measures have another limitation: they do not differentiate between destinations accessible to individuals from a single demographic group and those accessible to individuals from diverse demographic groups.

This Chapter addresses these limitations by laying the groundwork for defining and measuring co-accessibility: a measure for evaluating the extent to which a destination is mutually accessible to individuals from various demographic groups (e.g., age, ethnicity, income). The co-accessibility of a destination is measured as the degree to which a destination is accessible to different individuals or groups, taking into account the variations in factors influencing accessibility contingent on the demographic group to which each individual belongs. These factors include available travel modes, types of activities, and needs and preferences pertinent to different demographic groups or individuals.

In the following sections, we examine existing accessibility measures, highlight some of their inherent limitations, and illustrate how co-accessibility might transcend these constraints. We then define the fundamental constituents of co-accessibility and provide a mathematical formulation for quantifying it. In highlighting the intricacies and challenges involved in the measurement of co-accessibility, we use a sample case study to evaluate and compare pedestrian accessibility and co-accessibility across various destinations in Amsterdam, the Netherlands. Drawing upon the existing literature and the outcomes of our analysis, we investigate the potential implications of co-accessibility, underscore the main challenges in its measurement, and suggest avenues for future research.

2

2.2. FROM ACCESSIBILITY TO CO-ACCESSIBILITY

There are various approaches for conceptualizing and measuring accessibility. A common underlying principle guiding most approaches is that accessibility is determined by the distribution of potential destinations across space, the characteristics of these destinations, and the ease of reaching them [4]. The most common mathematical formulation of accessibility in the literature builds upon the seminal work of [5], and is defined by two main components: the attractiveness of destinations and the associated costs required to reach them. Following the notation of [57], its formulation is given by:

$$A_i^j = \sum_{j=1}^{J} O_j f(C_{ij}) \tag{2.1}$$

where A_i^j denotes the accessibility of origin location or zone i to destination or zone j; O_j is the destination attractiveness, often reflecting the number of opportunities available at destination j; and $f(C_{ij})$ is the cost or impedance to reach destination j from origin i. Equation 2.1, formally defines active accessibility but can be used for both active and passive accessibility depending on what zone i and j represent (i.e., location of individuals or opportunities) [57].

Over time, numerous metrics have been introduced in the literature to expand upon Hansen's formulation, with the aim of capturing the different components of accessibility [16]. Some of these extended metrics enrich the cost component (C_{ij}), considering different travel modes and traffic conditions [17], time schedules of individuals, [18–21], individual perceptions of travel costs [22], or how different population subgroups such as minorities or persons with disabilities experience access [23]. Additionally, the destination attractiveness (O_j), initially used to reflect the number of accessible destinations or jobs in area j [5, 7], has evolved to encompass a wider array of factors pertaining to why individuals are attracted to particular destinations. This includes considerations such as the type of activities at a destination, the size and quality of facilities, or individuals' lifestyle-based preferences [24].

To capture and differentiate the various perspectives within accessibility-related literature, existing measures have been classified in multiple ways. Both active and passive accessibility measures can be further divided into place-based and person-based categories [18, 29, 30]. Place-based measures evaluate the spatial separation between various locations, which often include individuals' anchor points such as home or work, and important destinations where activities take place. On the other hand, person-based measures consider the ease with which individuals or specific groups can access different destinations, taking into account each individual's spatial and temporal constraints.

Levinson and Wu [57], building on Hansen's formulation (equation 2.1), proposed a generalized measure of accessibility to encapsulate all the different considerations of spatial accessibility (equation 2.2). This formulation, while similar to Hansen's equation 2.1, allows a shift from partial to general access [57] by representing $\mathbf{A_i}$, $\mathbf{O_j}$, and $\mathbf{C_{ij}}$ as matrices. These matrices enable accounting for different types of destinations, times of day, time availability, travel modes, and all costs related to accessing a destination (e.g., money, noise, or congestion). In addition, function g is used to reflect the unequal value of destinations.

$$\mathbf{A_i} = \sum_{j=1}^{J} g(\mathbf{O_j}) f(\mathbf{C_{ij}}) \qquad \text{(active)}$$
$$\mathbf{A_i^{\circlearrowleft}} = \sum_{j=1}^{J} g(\mathbf{O_j}) f(\mathbf{C_{ji}}) \qquad \text{(passive)} \tag{2.2}$$

As explained in Chapter 1, based on the existing formulations and components of accessibility measures the optimization objective for accessibility concerns maximizing the destination attractiveness (i.e., what is offered at a destination) and minimizing the travel cost (i.e, the costs to reach a destination). However, such an optimization does not guarantee the existence of locations accessible to different individuals and population groups (e.g., ethnicity, age, or income-level groups). In practice, the accessibility of distinct destinations to different individuals is often mistakenly considered equal to the same destination being accessible to different individuals. We refer to this as *isolation accessibility bias*. Moreover, the accessibility of a destination to individuals from a homogeneous group is erroneously equated to a destination being accessible to individuals from different demographic groups. We refer to this as *homogeneity accessibility bias*. These biases are illustrated and explained in Chapter 1, through two examples depicted in Figs. 1.1 and 1.2.

A possible way to overcome these limitations is by employing a *time-geography* approach [18]. In time geography, which constitutes the primary theoretical framework for conceptualizing person-based accessibility [29], an individual's accessibility is modeled using a space-time prism [19]. The space-time prism represents the possible movements of an individual through both space and time, considering factors such as personal mobility constraints and time schedules [33]. The intersection of multiple individuals' space-time prisms across the continuous geographic space has been conceptualized through *joint accessibility* [20, 34, 36].

In this Chapter, we address the above-mentioned accessibility biases by defining and formulating *co-accessibility* as a place-based measure that assesses a destination's potential to bring together different individuals and individuals from diverse demographic groups by being accessible to them. Co-accessibility accounts for spatial constraints without considering individual time constraints. This enables its measurement without the need for detailed data on specific activity patterns and trips of individuals, thus avoiding associated privacy and ethical issues. [6, 27, 35]. To address the *isolation accessibility bias*, the co-accessibility of a destination is determined by the number of individuals who have access to that destination. To address the *homogeneity accessibility bias* we need to consider the individuals' demographic groups and the co-accessibility of a destination is determined by the number of individuals who have access to that destination and the number of demographic groups these individuals belong to.

In Fig. 2.1, we present six dummy examples to illustrate how measuring accessibility and co-accessibility could enable us to examine the degree to which various destinations are accessible to different individuals and demographic groups. In all our examples we consider five individuals ($P_n = \{p_1, p_2, p_3, p_4, p_5\}$) and three destinations ($D_n = \{d_1, d_2, d_3\}$). Furthermore, in these examples, in alignment with the commonly found formulation of accessibility, for a destination to be considered accessible by an individual two conditions must be met: the individual needs to be able to reach the destination (low travel cost) and to consider the destination attractive (high destination attractiveness). To depict the accessibility of a destination by an individual, meaning that the individual can reach the destination and considers it attractive, we utilize lines that connect the individual to the corresponding destination.

The co-accessibility of a destination is indicated based on two numbers: the number of individuals who have access to that destination, and the number of demographic groups to which the individuals with access to that destination belong. The purpose of these examples is to underscore the distinctions between the outcomes of (active or passive) accessibility and co-accessibility measures, and to demonstrate how co-accessibility could address the *isolation* and *homogeneity* accessibility biases presented in Figs. 1.1a and 1.2.

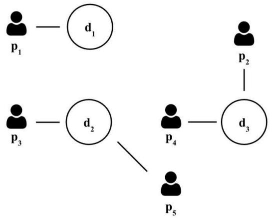
In examples (I) - (III) illustrated in Fig. 2.1, we examine the limitations of active and passive place-based accessibility measures towards indicating the degree to which destinations are accessible to different (groups of) individuals. In example (I), following an active accessibility approach, each individual has access to one destination and all three destinations d_1, d_2, and d_3 are considered to be equally accessible to different (groups of) individuals. In example (II), following a passive accessibility approach, destinations d_2 and d_3 are accessible to two individuals, while d_1 is accessible to only one individual. Moreover, destinations d_2 and d_3 are equally accessible to different individuals and groups. In example (III), we illustrate the proposed co-accessibility measure, by extending passive accessibility to account for the different demographic groups. In this case, d_2 and d_3 are accessible to two individuals while d_1 is accessible to only one individual. When we further look at the demographic group of each individual we also observe that only d_2 is accessible to individuals from different demographic groups (red and green) since d_1 and d_3 are accessible to only one group, red and blue respectively.

In examples (IV) — (VI) shown in Fig. 2.1, we demonstrate how further adjusting the co-accessibility measure could provide a more refined indication of the degree to which destinations are mutually accessible to different (groups of) individuals. Beginning with example (IV), similar to (III), destinations d_2 and d_3 are mutually accessible to two individuals while d_1 is accessible to only one individual. Looking at the number of groups who have access to each destination, we observe that d_2 is mutually accessible by two groups, while d_1 and d_3 are accessible by only one group. Thus, d_2 exhibits a higher degree of co-accessibility overall.

To measure the co-accessibility of a destination while considering the individuals' demographic groups, we also propose to account for the factors that impact the travel cost to reach it and are shared among the people of each demographic group (e.g., in the case of pedestrians belonging to different age groups we would need to consider the different walking speeds [58]). Certainly, within the same demographic group, individual differences still exist. Nonetheless, by tailoring the factors that impact accessibility by each population group, we gain a more nuanced understanding of co-accessibility compared to treating all groups as identical while avoiding the excessive complexity of considering each individuals unique preferences. In example (V), we adjust the travel cost per group to show how this consideration could alter co-accessibility. We illustrate the adjusted

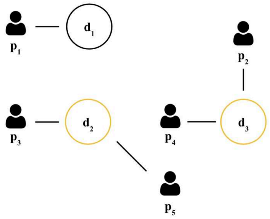
Accessibility & Co-accessibility

(I) **Place-based Active Accessibility**



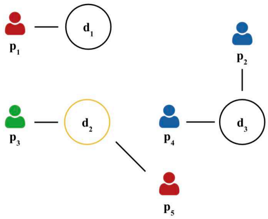
The distribution of destinations ensures that each individual has access to one destination. d_1, d_2, and d_3 are considered equally accessible to different (groups of) individuals (Isolation and Homogeneity accessibility biases).

(II) **Place-based Passive Accessibility**



Destinations d_2 and d_3 are equally accessible to different individuals and more accessible than d_1. Moreover, d_1, d_2, and d_3 are considered equally accessible to different demographic groups (Homogeneity accessibility bias).

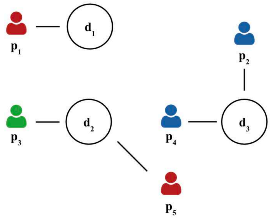
(III) **Co-accessibility**



Destinations d_2 and d_3 are equally accessible to different individuals. d_2 is also accessible to individuals belonging to different demographic groups (green and red in this example). d_1 and d_3 are not accessible to people from multiple demographic groups.

Adjusting Co-accessibility

(IV) **Individuals from different demographic groups**



C = [#individuals, #groups]

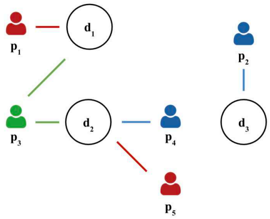
$\boldsymbol{d_1}$: C_{Pn}^{d1} = [1, 1]

$\boldsymbol{d_2}$: C_{Pn}^{d2} = [2, 2]

$\boldsymbol{d_3}$: C_{Pn}^{d3} = [2, 1]

Destination $\boldsymbol{d_1}$ is not accessible to different individuals. $\boldsymbol{d_2}$ is mutually accessible to two individuals and two demographic groups (green and red groups). $\boldsymbol{d_3}$ is mutually accessible by two individuals and one demographic group.

(V) Individuals from different demographic groups **(+) adjusting the travel cost per group**



C = [#individuals, #groups]

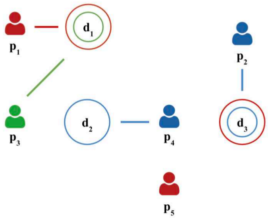
$\boldsymbol{d_1}$: C_{Pn}^{d1} = [2, 2]

$\boldsymbol{d_2}$: C_{Pn}^{d2} = [3, 3]

$\boldsymbol{d_3}$: C_{Pn}^{d3} = [1, 1]

This example demonstrates how adjusting the travel cost per group could alter the results of co-accessibility. In this case, $\boldsymbol{d_1}$ is accessible to two individuals and two groups (red and green). $\boldsymbol{d_2}$ shows the highest degree of accessibility since it is accessible to three individuals and all demographic groups under consideration (red, blue, and green). $\boldsymbol{d_3}$ is only accessible to a single individual.

(VI) Individuals from different demographic groups **(+) adjusting the destination attractiveness per group**



C = [#individuals, #groups]

$\boldsymbol{d_1}$: C_{Pn}^{d1} = [2, 2]

$\boldsymbol{d_2}$: C_{Pn}^{d2} = [1, 1]

$\boldsymbol{d_3}$: C_{Pn}^{d3} = [1, 1]

This example demonstrates how further adjusting the destination attractiveness per group could alter the results of co-accessibility. For $\boldsymbol{d_1}$, the results remain the same: $\boldsymbol{d_1}$ is accessible to two individuals and two groups. $\boldsymbol{d_2}$ and $\boldsymbol{d_3}$ are each accessible by only one individual and therefore exhibit a low degree of co-accessibility.

Figure 2.1.: Dummy examples illustrating how accessibility and co-accessibility measurements can indicate the degree to which different destinations are accessible to various individuals and demographic groups.

travel costs, using group-based colors for each line. In this case, the destination that shows the highest degree of co-accessibility is d_2. d_2 is mutually accessible by three individuals all belonging to different groups. Then, d_1 follows, which is mutually accessible by two individuals, also belonging to different groups (red and green). Last is d_3, a destination only accessible by a single individual.

Finally, we also account for the factors that impact the attractiveness of each destination and are shared among the people of each demographic group [24] (e.g., playgrounds are more attractive to children than to the elderly). In example (VI), we further adjust the destination attractiveness per group to show how this consideration could alter co-accessibility. We illustrate the adjusted destination attractiveness, using group-based colors for each destination. In this case, d_1 is mutually accessible by two individuals, also belonging to two different groups, and it is the destination with the highest degree of co-accessibility. Then, destinations d_2 and d_3 follow, each being accessible by only one individual.

2.3. MATHEMATICAL FORMULATION OF CO-ACCESSIBILITY

In this section, we propose a mathematical formulation of co-accessibility. To measure the co-accessibility of a destination d for individuals from different demographic groups, we first need to measure the accessibility of d for each demographic group g. As illustrated in Fig. 2.1, this involves considering factors that influence the attractiveness of d and the travel costs associated with reaching it, which are assumed to be shared among members of each demographic group g. As mentioned in the previous section, individual distinctions persist even within the same demographic group. However, by adjusting the factors influencing accessibility for each group, we obtain a more nuanced understanding of co-accessibility compared to treating all groups as identical, while avoiding the excessive complexity associated with considering the unique needs and preferences of each individual. Thus, within the formulation of co-accessibility, the travel cost depends on the location of the person $p_j \in g$ in relation to the destination d and on factors that impact traveling and are shared among the people who belong in group g (e.g., income level, available travel modes, walking speed, etc). Similarly, the attractiveness of a destination depends on factors that impact how attractive destination d is considered and are shared among the members of group g.

The passive accessibility of a destination d to n individuals who belong to the same demographic group g, allows us to address the *isolation accessibility bias* presented in Fig. 1.1 by expressing the degree to which d is mutually accessible by members of g and is formulated as:

$$c_g^d = h\left(A_{p_1}^d, A_{p_2}^d, \ldots, A_{p_n}^d\right), \forall p_j \in g \tag{2.3}$$

where c_g^d denotes the (passive) accessibility of destination d to individuals from group g. $A_{p_j}^d$ is the accessibility of destination d to a person p_j from group g (equation 2.2). $A_{p_j}^d$ is determined by factors that impact how attractive a destination is considered and are shared among the people from group g, the location of the person in relation to the destination and factors that impact traveling and are shared among the people from group

g. $A^d_{p_j}$ can adopt various types of accessibility measures depending on the underlying assumptions made, as explained by [57]. h represents a function that is used to aggregate the accessibility of destination d by each $p_j \in g$ and provides the co-accessibility of destination d by all individuals. We purposefully permit h to be non-linear and output different types of results such as single values (e.g., from summation) or distributions (e.g., from probability distribution functions). By embracing non-linearity in our approach, we aim to provide a versatile formulation that can yield a spectrum of results, catering to the demands of analyzing co-accessibility across different scenarios and contexts. For instance, h could be a summation and provide the total number of people who have access to a destination.

This approach is commonly seen in passive accessibility measures [27, 28]. When developing a co-accessibility measure, h can be tailored to account only for individuals belonging to a specific demographic group (e.g., the number of children with mutual access to a park). In that case, equation 2.2 can also be adjusted to the group under study. Alternatively, h could represent a probability distribution function, providing insights into the likelihood that individuals from demographic group g will access a destination, We refer to equation 2.3 as group-based co-accessibility, which essentially serves as a specialized passive accessibility measure.

Finally, the co-accessibility of a destination d to individuals belonging to a set of n mutually exclusive demographic groups G (e.g., [children, adults, older persons] or [low income, medium income, high income]), C^d_G, allows us to address the *homogeneity accessibility bias* presented in Fig. 1.2 and can be formulated as:

$$C^d_G = H\left(c^d_{g1}, c^d_{g2}, .., c^d_{gn}\right), \forall g_i \in G \tag{2.4}$$

where H is the function used to aggregate the co-accessibility values of destination d for each group in G, resulting in the overall co-accessibility of the destination for all groups in G. Like h, the selection of H depends on the context of the problem being studied. H aims to address the homogeneity bias and allows for the differentiation of destinations based on their accessibility to individuals from different demographic groups. Therefore, H can be chosen to reflect the diversity of the people who have access to a destination according to their demographic group. Examples of widely known diversity indices that can be used include Shannon's Equitability Index [59], Simpson's Diversity Index [60], and the Gini Index [61]. Alternatively, for simplicity, H could be a summation reflecting the number of different demographic groups with access to d.

2.4. SAMPLE CASE STUDY

We employ a representative case study to demonstrate how the proposed co-accessibility measure can be compared with and complement the more commonly used active accessibility measures. The simplified co-accessibility measure we use does not encompass all the factors influencing co-accessibility as discussed in earlier sections. Its aim is to facilitate a discussion on the applicability of co-accessibility and to highlight the intricacies and challenges involved in its measurement.

Our case study is defined by four key aspects: the area of analysis, the travel mode, the demographic attributes, and the type of destinations involved. The area of analysis is the city of Amsterdam in the Netherlands. We chose Amsterdam due to its diverse array of neighborhoods, which include both historic and more recently developed areas. Additionally, Amsterdam features a mix of pedestrian-friendly streets and barriers, such as canals and high-traffic roads. As for the travel mode, our focus is on pedestrians. Walking is chosen as it is the most affordable and accessible travel mode for individuals of virtually every population group, it is a sustainable means of transport, and it has been shown to positively contribute to people's well-being. The demographic characteristic we examine is age. The need for urban spaces that bring people of different ages together and encourage intergenerational encounters is universal and relevant to most countries and cities, as underscored by the United Nations' Sustainable Development Goal 11.7 [40]. The selection of destinations is guided by the concept of *third places* introduced by [62], encompassing venues where individuals of different ages can encounter each other beyond the realms of home and work. Specifically, we selected destinations that are accessible to individuals of all ages, such as parks, playgrounds, and museums while deliberately excluding venues that impose age restrictions to access, such as casinos or nightclubs.

2.4.1. MEASURING ACCESSIBILITY & CO-ACCESSIBILITY

To assess accessibility and co-accessibility, we employ an isochrone-based measure. Isochrones show what destinations can be reached from an origin location within a given travel cost threshold [57, 63]. Isochrones are selected because of their simplicity and ease of interpretation, characteristics that also contribute to their widespread adoption by practitioners [64].

We make three main *assumptions*. First, we consider all destinations in our analysis equally attractive to all groups. Second, we assume all people walk at the same speed: 1.26 m/s (i.e., the average of different age groups, as measured by [58]). The reason for not adjusting the walking speed per age group is that considering the lowest ($1.2m/s$) and highest ($1.29m/s$) average walking speeds found by [58] would only result in a difference of 81m within a 15-minute walk. This difference cannot be reflected in our estimations due to the spatial resolution of the employed population data ($100 \times 100m$ grid cells). Third, regarding the travel cost we only account for the walking time and consider accessible every location a person can reach within a 15-minute walk from their home. We opted for the 15-minute walking distance threshold because it is increasingly utilized both in research and in practice, with several cities integrating it into their urban planning strategies in recent years [65–69]. However, we acknowledge that assigning any time threshold is somewhat arbitrary in nature. Based on these three assumptions, the accessibility of a destination d by an individual $p_j \in g$ is formulated as:

$$A^d_{p_j} = \begin{cases} 1 & \text{if walking-time between } d \text{ and } p_j \leq 15 \text{ minutes} \\ 0 & \text{if walking-time between } d \text{ and } p_j > 15 \text{ minutes} \end{cases} \tag{2.5}$$

To identify which destinations are accessible to each individual, we model the pedestrian street network as a graph, with nodes representing street intersections and edges representing street segments. We then overlay a grid layer ($100x100m$) indicating residential areas and determine the closest intersection to the center of each grid cell. These intersections represent individuals' home locations. Next, we calculate 15-minute walking trips from these home locations, considering the length of each street segment and the average walking speed defined earlier. This process allows us to measure all destinations within the reach of these walking trips for each individual.

To measure the co-accessibility of a destination by a particular group we need to define the function h as shown in equation 2.3. In our analysis, we define h as a summation to align with the aforementioned isochrone-based measurement of accessibility. Thus, the group-based co-accessibility of a destination by the n individuals from group g is formulated as:

$$c_g^d = \sum_{j=1}^{n} A_{p_j}^d, \forall p_j \in g \tag{2.6}$$

After having calculated the co-accessibility of destinations per group we can calculate the co-accessibility of each destination by all groups. To do so, we need to define the function denoted as H in equation 2.4. In our case, we are interested in the degree to which a destination is mutually accessible by a set G of n different age groups (g_1 is children, g_2 is adults, g_3 is elderly). Therefore, H is chosen to represent the age diversity of the people who can access each destination by means of Shannon's Equitability Index [59]. Shannon's Index is selected as it is among the most commonly used diversity indices and summarizes in a single number a partial description of species richness and evenness [70, 71]. Thus, equation 2.4 is now:

$$C_G^d = \frac{-\sum_{i=1}^{n}(P_{g_i}^d \times lnP_{g_i}^d)}{ln(n)}, \forall g_i \in G \tag{2.7}$$

where $P_{g_i}^d$ is the ratio of the co-accessibility of d by each age group ($c_{g_i}^d$) over the total number of individuals with access to d ($\sum_{i=1}^{n} c_{g_i}^d$); n is the count of age categories. The C_G^d values range from 0 to 1, with 1 indicating a perfect balance in the proportions of each age category.

2.4.2. DATA

We use three different types of data: population demographics, pedestrian street network data, and location-based data. Starting with the population demographics, to collect information reflecting peoples' residence location and age we use the Dutch [38] (spatial resolution of $100 \times 100m$). The collected data pertain to the year 2020. In total, the population demographics data include 6,949 grid cells reflecting the entire Amsterdam. We group residents into three population age categories: *children* (0-15 years old), *adolescents and adults* (16-64 years old), and the *elderly* (equal or above 65 years of age).

The data related to the pedestrian network reflect streets that are considered for pedestrians such as sidewalks and pedestrianized streets. We obtain this information from [37], by collecting the streets for which the `network_type` is set to walk using the *OSMNX package* [72]. Thus, we only collect streets for pedestrians and exclude streets such as motorways, bike lanes, or service roads. The street network of OpenStreetMap has been determined to be approximately 83% complete in over 40% of countries worldwide [73].

When focusing on the pedestrian street network studies have suggested that OpenStreetMap data provide a free and adequate alternative in situations where commercial pedestrian data sets are not available [74]. The data collection was realized in November 2021. The collected street segments lie within the administrative boundaries of Amsterdam, as delineated from the open Dutch land use dataset Basisregistratie Grootschalige Topografie (BGT) [75], extended by a buffer of 1km to minimize potential boundary effects [76].

Lastly, the locations are also collected from OpenStreetMap. In particular, we select and collect locations that lie within the administrative city boundaries of Amsterdam extended by a buffer of 1 km and come from the following primary feature groups: *Amenity*, *Entertainment, Arts & Culture*, *Leisure*, or *Shop*. OpenStreetMap has been considered a valid source for such data with an acceptable level of completeness [77–79]. The data collection process was realized in September 2021. In total, we collected 10,483 locations.

2.4.3. RESULTS

The results of the measurements of pedestrian accessibility and co-accessibility are illustrated over three types of maps. First, the maps of pedestrian (active) accessibility highlight the number of destinations accessible from each grid cell within a 15-minute walk. According to equation 2.5, these maps show the total number of accessible destinations for each grid cell included in our analysis. Second, the maps of pedestrian co-accessibility per group (c_g^d) (passive accessibility) display the total number of people within a specific age group who can access a destination, estimated using equation 2.6. Third, the maps of the co-accessibility of each destination from all groups (C_G^d) reflect the age diversity of the people with access to each destination, as calculated through equation 2.7.

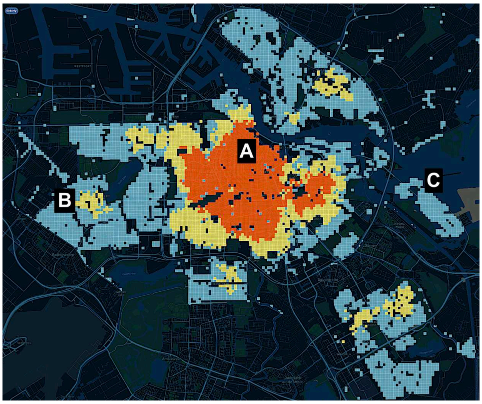
For the visualizations, we first calculate the average accessibility of all grid cells and the average co-accessibility of all destinations. Then we cluster our values in three groups and color them accordingly: *Higher than average* , *Near-average*, and *Lower than average*. To identify the statistically significant clusters of high and low values we further create a connectivity matrix using queen contiguity-based spatial weights and measure the spatial autocorrelation using Moran's I correlation coefficient.

2.4.4. COMPARISON OF ACCESSIBILITY AND CO-ACCESSIBILITY

We display our area-based results through Figs. 2.2 and 2.3. Panels 2.2a and 2.2b highlight the spatial inequities in accessibility. In particular, panel 2.2a shows the number of accessible destinations within a 15-minute walk from each grid cell and 2.2b further underpins the spatial clusters of grid cells with a significantly high (or low) number of accessible destinations, compared to the mean. Then, panels 2.2c and 2.2d present the destinations' co-accessibility in terms of how age-diverse is the set of people who have access to each destination. Fig. 2.3 follows the same structure while focusing on the accessibility and co-accessibility of different areas per age group (i.e., children and elderly).

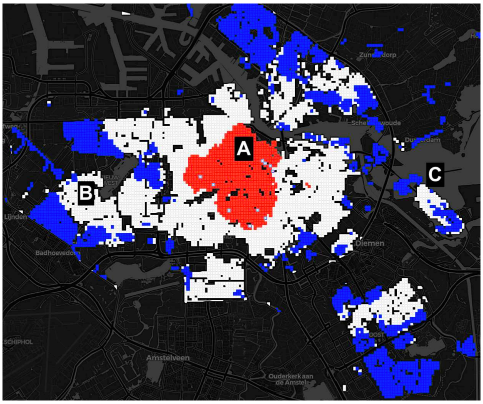
As indicative examples, we consider three areas denoted as *A*, *B*, and *C*. People residing in area *A* have access to the highest number of destinations in comparison to any other area. Indicatively, people in the vicinity of *A* have access to a significantly high number

(a) Accessibility of destinations from each grid cell within a 15-minute walk.



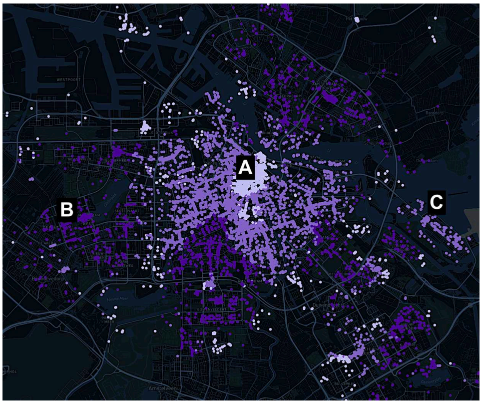
Number of accessible destinations within a 15-minute walk from each grid cell.
- Higher than average (> 340)
- Near-average (240 ± 100)
- Lower than average (< 140)

(b) Local spatial autocorrelation (Moran's I) of the number of accessible destinations from each grid cell within a 15-minute walk.



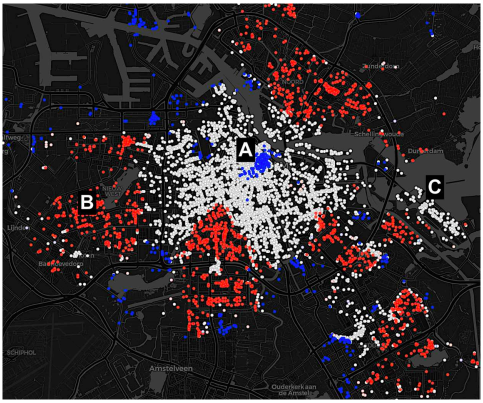
Number of accessible destinations within a 15-minute walk from each grid cell.
- High values
- Not significant
- Low values

(c) Co-accessibility of each destination based on the age diversity of the people who have access to it within a 15-minute walk.



Destinations' age diversity based on the individuals who have access to them within a 15-minute walk.
- Higher than average (> 0.66)
- Near-average (0.61 ± 0.05)
- Lower than average (< 0.56)

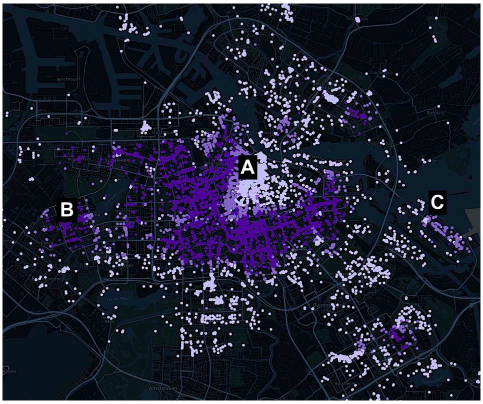
(d) Local spatial autocorrelation of the age diversity of the people who have access to each destination within a 15-minute walk (Moran's I).



Destinations' age diversity based on the individuals who have access to them within a 15-minute walk.
- High values
- Not significant
- Low values

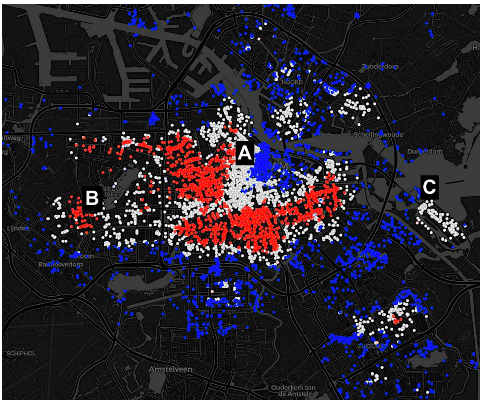
Figure 2.2.: Accessibility and co-accessibility (based on age diversity) of different areas in Amsterdam.

(a) Co-accessibility of each destination based on the number of children who have access to it within a 15-minute walk.



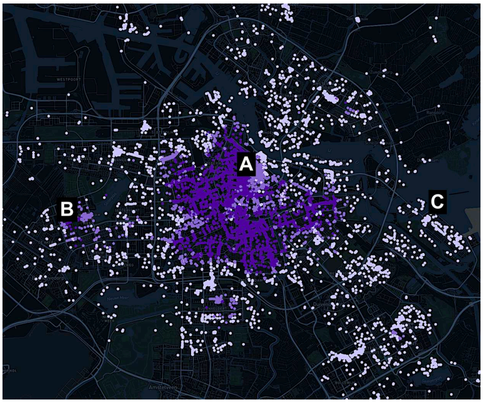
Number of children who have access to each destination within a 15-minute walk.
- Higher than average (> 2865)
- Near-average (2365 ± 500)
- Lower than average (< 1865)

(b) Local spatial autocorrelation of the number of children who have access to each destination within a 15-minute walk (Moran's I).



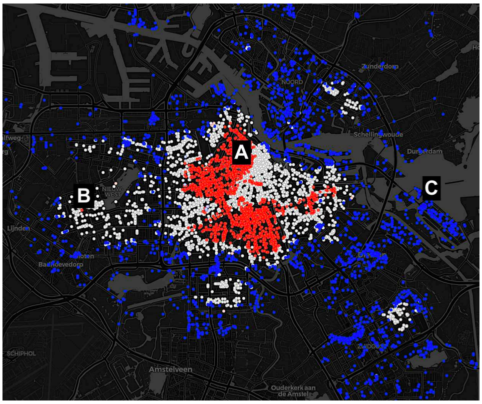
Number of children who have access to each destination within a 15-minute walk.
- High values
- Not significant
- Low values

(c) Co-accessibility of each destination based on the number of elderly people who have access to it within a 15-minute walk.



Number of elderly people who have access to each destination within a 15-minute walk.
- Higher than average (> 3378)
- Near-average (2878 ± 500)
- Lower than average (< 2378)

(d) Local spatial autocorrelation of the number of elderly people who have access to each destination within a 15-minute walk (Moran's I).



Number of elderly people who have access to each destination within a 15-minute walk.
- High values
- Not significant
- Low values

Figure 2.3.: Accessibility and co-accessibility (based on children and elderly) of different areas in Amsterdam.

of destinations compared to other areas, as can be seen from panel 2.2b, ranging from around 2250 to 400.

Regarding co-accessibility, the destinations located in area *A* are accessible within a 15-minute walk by a significantly low or near average in terms of age-diversity set of people compared to other destinations as depicted in panels 2.2c and 2.2d. These results are also supported when looking at the group-based co-accessibility (panels 2.3a—d): the destinations within the *A* area are accessible by a significantly lower number of children, compared to the mean. Thus, by comparing the results of accessibility and co-accessibility for the area *A* we see that a higher number of accessible destinations does not directly translate to a higher number of destinations that are simultaneously accessible by multiple age groups.

The people residing within the *B* area, have access to a more limited range of destinations typically varying between 10 and 180. In certain cases, the number of accessible destinations is statistically significantly lower than the mean, as indicated by panel 2.2b. Regarding co-accessibility, the destinations within area *B* are mutually accessible by a significantly broader age range of people compared to other destinations. Regarding the number of children who have access to the destinations in that area, we can observe diverse results with small clusters of destinations that are accessible to either a near-average or significantly higher number of children. When looking at the elderly, we see results that are closer to the mean.

Similarly to the *B* area, the people residing within the *C* area have access to a statistically significantly lower number of destinations, compared to the mean, as shown in panel 2.2b. When looking at co-accessibility, the estimated age diversity values of the destinations within area *C* are not significantly higher or lower than those of other destinations. However, when focusing on specific groups we observe that the destinations within the *C* area, are found to be accessible by a significantly low number of elderly.

In summary, the results of accessibility and co-accessibility provide complementary insights. While accessibility provides information regarding the extent to which destinations are accessible to people, co-accessibility indicates the degree to which the destinations of each area promote encounters among individuals belonging to the same age group (tackling the *isolation accessibility bias*) or different age groups (tackling the *homogeneity accessibility bias*) by being accessible to them.

2.5. DISCUSSION AND CONCLUSION

This Chapter lays the groundwork for a methodological framework for measuring co-accessibility, which assesses the degree to which various destinations are mutually accessible to individuals from different demographic groups. We demonstrated how a measure of co-accessibility could enhance traditional accessibility metrics and alleviate inherent biases such as the *isolation* and *homogeneity* bias. We also outlined the components of co-accessibility and proposed a mathematical formulation for its measurement. In the following paragraphs, we highlight potential opportunities and prospective measurement challenges to support future research endeavors in related fields.

Co-accessibility is a place-based measure that shares some conceptual similarities with passive accessibility and other person-based measures such as joint accessibility. The advantage of person-based measures is that they consider both spatial and time constraints. However, their implementation in real-world case studies can be challenging due to the need for detailed data on individual spatiotemporal activity patterns. Additionally, it is cumbersome to apply such measures when evaluating future spatial planning interventions since they rely on data from past activities and trips. These challenges have been well-documented in the literature [6, 80]. Co-accessibility offers an alternative for examining how mutually accessible destinations are to different individuals and demographic groups when detailed data cannot be collected due to time or monetary costs or should not be collected because of ethical concerns.

We introduced co-accessibility as a broad concept but subsequently narrowed our focus to measure and apply it in a sample case study. Specifically, we measured co-accessibility by focusing on a single mode of travel, namely walking, and a given demographic, namely age. Nevertheless, co-accessibility can be applied across any mode of travel or demographic group. For instance, when considering other demographic groups, co-accessibility could be valuable for studying segregation phenomena, typically centered on ethnicity [81], income [82], or education level [83] by enabling to go beyond the commonly studied domains of residential [84], workplace [85], and educational settings [86].

Similarly, measures of co-accessibility could be employed to compare the effectiveness of public transportation systems in fostering place-based encounters. Such an examination could delve into understanding how considering different modes of travel, such as public transportation, private vehicles, or cycling impacts co-accessibility. This approach could provide insights into the social dynamics facilitated by different transportation modes and expand existing research on the impact of public transport on social encounters [87, 88].

Moreover, measures of co-accessibility can be leveraged to guide the design of destinations to better meet the wants and needs of those who can reach them. This approach can help to address issues of spatial inequality and spatial justice by ensuring equitable access to essential services and opportunities for all demographic groups. Studying the co-accessibility across different destinations might also provide a nuanced understanding not only of the capacity of destinations to facilitate encounters among diverse individuals but also of the intrinsic characteristics of areas that nurture this potential. These characteristics extend to the surroundings of the destinations which, as Jane Jacobs argued, can generate mutual support and “complex pools of use" that encourage people to use destinations at different times of the day [89, 90]. Additionally, prospective interventions or urban design scenarios can be converted into input data for the proposed measure to assess their impacts on co-accessibility. However, this undertaking must be approached with caution, as there is a risk of developing urban destinations tailored to the predominant population groups that have access to them, inadvertently marginalizing other population subgroups [91].

Lastly, our sample case study highlighted the complexities associated with the measurement of co-accessibility, revealing inherent challenges that should be addressed. We identify three main challenges for measuring co-accessibility. The first challenge stems from the necessity to identify and measure the factors influencing accessibility for various demographic groups. This is illustrated through examples (IV)-(VI) in Fig. 2.1, where we adjust the travel cost and destination attractiveness per group. While it is important to account for demographic disparities, it is challenging to simultaneously identify and measure such differences in a time and cost-effective manner. The factors that influence accessibility are group-specific, many, and intertwined [92, 93]. As a result, there is the challenging task of disentangling the impact of each factor and prioritizing them for the different groups. Moreover, some factors can be very subjective and thus difficult to capture, particularly when adjusting for the different demographic groups. For instance, when considering pedestrian co-accessibility, such factors can be the perceived safety or the attractiveness of a street which can influence whether a person can walk to a destination [54, 94].

Second, the proposed mathematical formulation of co-accessibility (expressed through equation 2.3 and 2.4) is purposefully quite broad, encompassing more of a conceptual formulation, aiming to guide and inspire the development of new context-specific co-accessibility measures, rather than a "ready-to-follow" recipe one can use to measure co-accessibility. To apply a co-accessibility measure three main questions need to be answered first: How to measure accessibility (equation 2.2)? How to aggregate the accessibility of a destination to different individuals belonging to the same group (equation 2.3)? How to aggregate the co-accessibility of a destination to multiple groups (equation 2.4)? Establishing a consistent selection process protocol for defining these functions proves challenging, as this decision is influenced by a variety of factors such as the context (e.g., demographics), the data availability, and the specific aspect of the problem under investigation (e.g., assessing co-accessibility statically or dynamically based on time, season, or weather). In this quest, other scientific fields can provide valuable insights. For instance, the plethora of accessibility studies can aid the selection of the most relevant accessibility measure to the problem under study. In another example, when selecting aggregation functions to measure the diversity of individuals with respect to their demographic traits, one can draw insights from existing studies on the potential and limitations of different diversity indices [95].

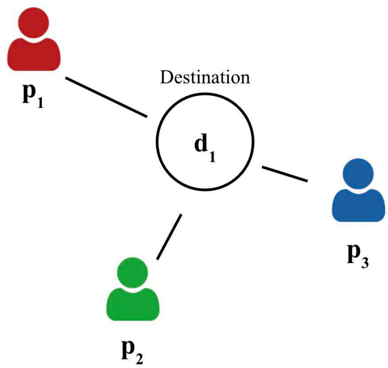
Third, when measuring co-accessibility it is important to consider the interplay between a destination's co-accessibility and visitation patterns. This relationship may indicate how to assess co-accessibility to better reflect its impact on real visitation patterns. The influence of co-accessibility on visitation patterns can be complex and may exhibit variations based on demographics, cultural nuances, time, or season. Relevant literature on visitation patterns can provide valuable guidance on how to approach this relationship [96, 97]. The aforementioned opportunities and challenges serve as avenues for additional investigation and hold the potential to shape the trajectory of future research endeavors that expand upon the concept of co-accessibility.

3

MEASURING CO-ACCESSIBILITY TO ASSESS SPATIAL AGE SEGREGATION

All places are accessible but some places are more accessible than others.

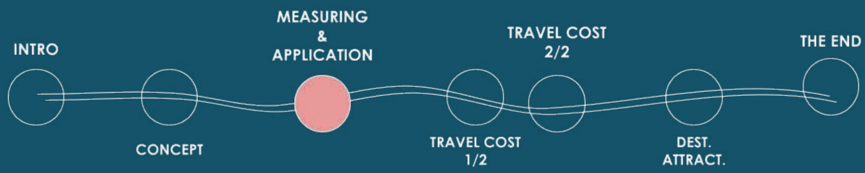
modified from George Orwells Animal Farm



3

SUMMARY

Building on the definition and formulation of co-accessibility established in the previous chapter, we propose a method to measure co-accessibility and apply it for the assessment of spatial age segregation, meaning the degree to which different age groups occupy the same space. In particular, we use spatially disaggregated data about urban destinations across the cities of Amsterdam, Rotterdam, The Hague, Utrecht, and Eindhoven in the Netherlands to calculate several spatial accessibility metrics and to estimate co-accessibility scores for each destination. This chapter's analysis results demonstrate how the proposed co-accessibility measure can provide new insight into the potential moderating effect that exposure to other age groups in places outside of the home can bring to the level of spatial age segregation.



*This chapter is based on a journal article published in *Computers, Environment, and Urban Systems* [51]

3.1. INTRODUCTION

In this chapter, we demonstrate how co-accessibility can be utilized to assess spatial age segregation. Spatial age segregation occurs when individuals of different ages do not occupy the same space and, thereby, lack mutual interactions [98]. Evidence suggests that bringing different age groups together could have a number of societal benefits that range from the reduction of ageism and the risk of isolation in later life to the promotion of socialization between the young and the old [99–102].

Common indicators of spatial age segregation that have extensively been used in literature are the concentration and distribution of different population age groups residing within a neighborhood [103–109]. Even though this is important to consider when aiming to identify the existence of segregation, in reality people may further experience age segregation in places outside of the residential space. This implies that the location and distribution of different daily activity spaces (e.g. parks, restaurants, supermarkets, workplaces) across the urban fabric may either promote or obstruct encounters with people from different age groups [62, 110–113]. For instance, a park that is accessible to and visited by children, adults, and the elderly promotes mutual exposure and could induce interactions between these age groups. Subsequently, determining spatial age segregation solely on the basis of population distribution in the residential space may lead to partial or biased insights into this phenomenon.

Access to different activity locations is rarely considered in studies of spatial age segregation. Only a limited number of studies of general spatial segregation have accounted for locations beyond the residential space [81, 110, 114–116]. However, accounting for how accessible various activity locations are to different age groups merits attention as a key component of spatial age segregation, in addition to the commonly considered factor of age structure (i.e. the presence and concentration of different age groups). Three reasons underscore the necessity for considering access to activity locations in a spatial age segregation context: (1) social encounters and interactions primarily occur in places outside of home [110, 117], (2) easy access to facilities has been shown to encourage their use [1], and (3) differences in access capacity (e.g. between younger and older people) substantially influence the chance for encounters between age groups. To enable the integration of accessibility in spatial age segregation research and policy, there is a need for methods that do not only capture how accessible activity locations are to different people, but can also assess the possibility of different age groups sharing the same space.

Despite the growing body of accessibility studies, existing metrics fall short in capturing both who can access different destinations and how likely it is that people from different groups meet in these places. Generally, accessibility metrics fall into two categories: (a) place-based (or location specific), and (b) people-centered measures [29, 30]. The former capture access according to the number, density, and diversity of activity locations in a neighborhood, whereas the latter measure the degree to which individuals or groups have access to a given set of destinations [118, 119]. Typical determinants are space (i.e. the distance between a destination and an origin — usually, the home location of an individual), time (e.g. business or office hours), and cost (i.e. travel time and related costs to reach a destination) [4, 120]. Regardless of the general category, these metrics often fail to distinguish between a facility that is accessible to a large, yet homogeneous, population age group and one that brings people of different ages together. In other words, there is a need for methods that can capture the degree of *co-accessibility* (i.e. how accessible a given destination is to individuals from different population groups) of activity locations.

In this chapter, we aim to fill this gap by proposing a new methodology for measuring spatial age segregation at a granular level (i.e., at the level of individual activity locations) that considers both age structure and the degree of co-accessibility to different activity locations. To that end, we account for factors pertaining to the spatial distribution of different destinations and the age diversity of people who potentially occupy these places at the same time. First, we calculate several accessibility metrics to measure how accessible different activity locations are to various age groups relative to other places within different walking distances. Second, we estimate the age diversity of the people who potentially access each activity location. These estimates are used to capture the possibility of different age groups occupying the same space and, therefore, serve as proxies of potential encounters and intergenerational interactions.

We use the five most populated cities in the Netherlands — namely, Amsterdam, Rotterdam, The Hague, Utrecht, and Eindhoven — as case studies to demonstrate the utility of our methodology. Even though quite similar in terms of population size, the cities are characterized by different densities, distributions of activity locations, and age structures. We collect spatially disaggregated data about the road and pedestrian network, population demographics, and the distribution of land uses across the five case studies to explore the role of activity (co)accessibility in spatial age segregation. We further compare our methodology to existing approaches to measuring the spatial age segregation, by contrasting age diversity scores at activity locations to those derived from age structure in residential space. What sets our approach apart is the simultaneous consideration of factors that do not only pertain to how age populations are distributed at the neighborhood level (i.e. the age structure used exclusively in existing approaches), but also reflect the degree of potential encounters between age groups at the level of individual activity locations. Our results highlight the importance of considering both the population distribution and the (co)accessibility of activity locations, especially in neighborhoods with different age structures that are adjacent to each other, and in neighborhoods with a limited number of activity locations. Our work complements the existing literature by providing an additional avenue to assess spatial age segregation at a granular level, considering how exposures to different age groups at activity locations beyond home might bring a moderating effect to the way people experience segregation.

The remainder of this chapter is structured as follows. First, we review the related research on spatial age segregation and different approaches to measuring accessibility. Second, we explain how we calculate spatial accessibility and estimate age-adjusted co-accessibility scores for each activity location. We then detail the data sources and explain how we extract information pertaining to population demographics, the pedestrian network, and distribution of activities. Next, we present the outcomes of our analyses. We then discuss the obtained results, demonstrate how our methodology complements existing approaches, and outline the limitations of our approach. Finally, we summarize the conclusions and suggest future lines of research.

3.2. RELATED WORK

3.2.1. SPATIAL AGE SEGREGATION

Spatial age segregation, as defined by Hagestad and Uhlenberg in [98], is determined by the extent to which people of different ages occupy the same space. A large body of literature primarily focuses on residential age segregation. That is, areas are considered age segregated if people belonging to different age groups do not reside in the same city, neighborhood, urban block or building unit [108, 121]. Evidence has demonstrated that the societal effects of spatial age segregation may include ageism, weaker social ties among different ages, and could lead to a society that is less generative (i.e. a society that cares less for future generations) [99–101]. Similar concerns have been raised by the World Health Organization (WHO), leading to the emergence of the "age-friendly city" concept as a response to the converging trends of ageing. WHO has specifically stressed that older people need more activities that can foster integration within the community and with other age groups and cultures, in proximity to the places they live in [102].

3

Empirical studies on age segregation suggest that the degree of segregation varies significantly across different counties in the United States [121], whereas [108] show an increase of this phenomenon in the urban areas of England and Wales throughout the years. Other empirical studies focus on measuring the potential effects that residential age segregation could have on the society or on people's health. For instance, [109] developed new age segregation metrics towards an improved understanding of its effects on older adults' self-rated health. Similarly, [122] examined the relation between a neighborhood's age structure and people's self-rated health. Their findings support that people living in neighborhoods with an increasing percentage of older adults rated their health lower compared to people who live in areas with more mixed age groups.

Despite the growing body of literature on the effects of spatial age segregation on health outcomes, the primary focus has hitherto been on neighborhood age structure. However, WHO has recently emphasized that strategies towards age-friendly cities should rather adapt neighborhood *structures* and *services* so as *"...to be accessible to and inclusive of older people with varying needs and capacities."* [102, 123]. This implies that, besides neighborhood age structure, the consideration of accessibility to services and activity locations could add meaningful insights into the level of spatial age segregation. This is lacking in existing related studies. This chapter aims to fill this gap by considering the role of accessibility to activity locations beyond the residential space as an important complementary indicator of spatial age segregation.

3.2.2. MEASURING ACCESSIBILITY

A variety of methods have been introduced for measuring accessibility to various destinations in cities. These methods can be categorized into two main categories: *place-based* (or locational) and *people-centered* [118, 119]. Place-based approaches to measuring accessibility aim to determine how accessible different destinations are (e.g. retail establishments, greenspaces, hospitals) from a given set of origins (e.g. home locations) [124]. Conversely, people-centered approaches aim to assess how accessible different locations are to a given group of people or individuals, with particular emphasis on equitable access [79, 125]. An example of the latter approach is [3], in which it is suggested that ethical theories, such as egalitarianism and sufficientarianism, should be combined to evaluate how equitably accessible different facilities are to people. Other people-centered approaches revolve around Hägerstrand's time geography concept [18] and focus on the spatiotemporal settings of individuals. Both approaches determine accessibility in relation to the spatial distribution of destinations in a given area (e.g. a neighborhood or other administrative units), their characteristics (e.g. type, price range, quality) or the ease of reaching them (e.g. in terms of distance, time or cost) [4].

However, the demographic characteristics of the people who have access to the same destinations are rarely considered. Kelobonye et al. [126] proposed the addition of a competition component when measuring accessibility to urban services, and further supported that it can be misleading to consider a large number of accessible urban services as an indicator of increased choices, if the competition or demand for these services is not considered. To demonstrate this, three groups of people were considered, namely the labor force, school-age children, and the population as a whole. The main assumption is that people belonging to each group compete each other for accessible job, education, and shop opportunities, respectively. Related studies that account for people's characteristics focus either on where people reside (and not necessarily on what is accessible to them) or on visitation patterns. For instance, [127] explore income segregation in US cities using Global Positioning System (GPS) and Foursquare data to classify places according to the time different income groups spend at each place. Similarly, [106] use GPS data to estimate experienced racial segregation, and highlight that policies concerning the spatial distribution of commercial facilities could largely influence the degree of facility occupation by people belonging to different races.

This chapter builds on existing methods to measuring spatial accessibility, with the aim to explore its meaningfulness in assessing spatial age segregation. It further complements existing literature by considering the extent to which people belonging to different age groups have access to the same activity locations beyond the residential space (i.e. the degree of *co-accessibility* of activity locations).

3.3. MEASURING AGE-ADJUSTED CO-ACCESSIBILITY SCORES

This section outlines the proposed methodology, in which people's residences (origins) together with activity locations (destinations) are received as input, a set of spatial accessibility measures are then calculated, giving as output a set of age-adjusted co-accessibility scores for each activity location.

In the following paragraphs, we first explain the spatial accessibility measures we use to determine which locations are accessible to different people. Then, we look beyond accessibility and describe how we enrich these measures with age-adjusted variables that are based on the co-accessibility of these locations. The measures of co-accessibility are aligned with the ones described in the empirical analysis of Chapter 2.

3.3.1. SPATIAL ACCESSIBILITY MEASURES

We measure accessibility according to which activity location is accessible to different people within walking distance. This choice is made for two reasons. First, drawing on related literature, places that lie within walking distance (walkable distances vary between

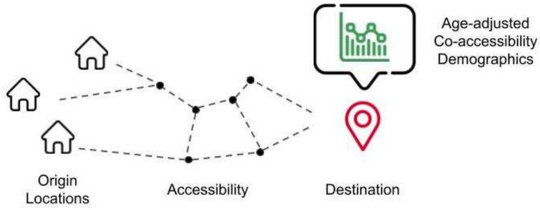


Figure 3.1.: Simplified graphical overview of the proposed method

300m and 800m of a person's — usually home — location) may have an effect on people's health and habits. For instance, food stores of either high or low quality in proximity to someones home have been shown to, respectively, promote or obstruct healthier eating habits and, subsequently, people's health [128, 129]. In addition, activity locations within walking distance of individuals belonging to different age groups may encourage encounters and social interaction. Second, by conducting an analysis on the Netherlands Mobility Panel (MPN) data [130] we discovered that walking is the third most frequent (i.e., 15%) travel mode in the Netherlands (after car with 29%] and bike with 28%) for shopping and social recreational trips, and the second most frequent (i.e., 25%) travel mode for short trips (i.e., less than 5km from home, with car and bike representing 23% and 40% of trips, respectively). Besides, walking is the most affordable and accessible travel mode to people of virtually any age and income level, compared to cars and bikes. Given these two reasons, the use of walking distance to an activity location as a determinant of accessibility better fits the context of this chapter.

To determine which activity locations are reachable within walking distance around each residence we use different pedestrian sheds. Specifically, we use buffers that correspond to 5, 10, and 15-minute walksheds. Generally, there is no consensus in the literature on which (travel time) distance optimally captures pedestrian trips. Moreover, the distance covered on foot may vary substantially across different population age groups. However, evidence suggests that the three aforementioned walksheds capture the majority of pedestrian trips [4, 131–133]. The corresponding radii that determine the buffer size can be defined in two ways. According to [134], a 5, 10 or 15-minute walk would, respectively, correspond to a 300m, 500m or 800m network radius distance. Another way to determine the radius is by means of average walking speed. Even though this varies across population age groups, [58] suggest that the lowest average walking speed is found to be 1.2m/sec (for people above 60 years of age), whereas the highest is 1.29m/sec (for people between 40 and 49 years of age). For the longest considered walking trip in our case (i.e. a 15-minute walk or 900sec), this would correspond to an $1.29m/sec \times 900sec - 1.2m/sec \times 900sec = 81m$ difference in network radius distance among the different age groups. This difference cannot be reflected in our estimates, given that the resolution of population demographics used in our study is available at $100 \times 100m$ grid cells. For this reason, we use the average walking speed of 1.26m/sec (i.e. average of all age groups, as defined by [58]) throughout, to calculate walking trips to different activity locations.

In order to capture the spatial accessibility of each activity location, we represent the case-study environments as a graph. The edges of the graph represent the streets, whereas the nodes represent the street intersections. We then calculate the centroid (i.e. the geometrical center) of each grid cell and identify the closest graph node to this centroid. The resulting node represents the estimated home location of a person, and is used as the origin point in our analyses. We estimate the potential accessibility to different destinations (i.e. activity locations) by calculating walking trips from these origin points, weighed by the length of each street segment and considering the average walking speed defined above. In this way, we calculate the areas accessed on foot within 5, 10, and 15-minute trips, and identify the activity locations that lie within these areas. We should emphasize that these denote potentially accessible locations around people's residences and are not based on observed walking trips.

3.3.2. AGE-ADJUSTED CO-ACCESSIBILITY

To assess spatial age segregation, we need to look beyond general accessibility to activity locations. For this, we enrich our estimated accessibility measures with a number of age-related variables. Similarly to our approach in Chapter 2, we first calculate the total number of people who have access to each facility within the three considered walksheds. Second, we calculate how many (number and percentage) of these people belong to each age group. As suggested in [98], instead of accounting for a single age group (e.g. elderly) relative to all others, we consider three main age categories that represent the different walks of life (i.e. children, adolescents and adults, and the elderly). Lastly, within the context of spatial age segregation, it is important to determine not only which age groups have access to each activity location but also to what extent the different age groups have access to the same activity location. To do so, for each activity location we calculate the age diversity of all the people who have access to it by means of Shannon's Equitability Index (EI) [59, 135, 136] using the following formula:

$$EI = \frac{-\sum (P_i \times lnP_i)}{ln(k)} \tag{3.1}$$

where P_i denotes the proportion of each age category i relative to the total number of people who have access to a given activity, and k is the number of age categories. Index values range between 0 and 1, with 1 denoting complete evenness of each age category's proportions. Shannon's Equitability Index can be applied to any number of age groups, and is influenced only by the age diversity of the people who have access to a given location, rather than by the age structure of the overall urban population.

3.4. DATA & CASE STUDIES

EMPIRICAL CASE STUDIES

To demonstrate the utility of our methodology, we use the five most populated Dutch cities, namely Amsterdam, Rotterdam, The Hague, Utrecht, and Eindhoven. Even though they are quite similar in terms of population size, they are characterized by different densities, distributions of activity locations, and age structures. Moreover, within their administrative boundaries, there is a combination of historical city centers alongside new housing developments, especially in the outskirts, which has led to a change in the distribution of population age groups over the past three decades (e.g. increased concentration of children in the outskirts relative to the city center, which are predominantly populated by adults).

POPULATION DEMOGRAPHICS

We use the Dutch Central Bureau of Statistics [38] to collect granular data on population demographics (including household location and age) at a $100 \times 100m$ grid level. Our population demographics concern the year 2020. In total, the population demographics data include 6,949 grid cells for Amsterdam, 5,490 grid cells for Rotterdam, 5,076 grid cells for The Hague, 3,725 grid cells for Eindhoven, and 2,988 grid cells for Utrecht. We group residents into three population age categories: *children* (0-15 years old), *adolescents and adults* (16-64 years old), and the *elderly* (equal or above 65 years of age).

PEDESTRIAN NETWORK

We use OpenStreetMap (OSM), an open-source mapping platform containing worldwide geographical data, to collect data on the pedestrian network in the five case-study cities [37]. The OSM street network has been found to be complete in more than 40% of all countries worldwide [73], thereby allowing for replicability of our approach to other cities beyond the ones included in this study. More specifically, we use the *OSMnx* package [72] to extract walkable streets, by setting the `network_type` to walk. In this way, we exclude from the analysis streets categorized as motorways, service roads and cycleways, among other categories unrelated to pedestrian movement. OSM data were collected in November, 2021. In total, our resulting sample includes 540,896 street segments usable by pedestrians in the five cities. The collected pedestrian street segments lie within the administrative boundaries of the five cities, extended by a buffer of 1km to avoid potential boundary effects [76].

ACTIVITY LOCATIONS

We use the *Overpass* Application Programming Interface (API) to collect OSM land use data about urban activities. The selection of the activity locations to be included is influenced by Ray Oldenburgs definition of the third places (i.e. *public places that host the regular, voluntary, informal, and happily anticipated gatherings of individuals beyond the realms of home and work*) [62]. We, specifically, extract activity locations where people of different ages perform activities and can socially interact with each other. Subsequently, we exclude land use types that are restricted to a specific population age group (e.g. nightclubs). Similar to the pedestrian network data, we collect activity locations that lie within the administrative city boundaries, extended by a buffer of 1km. We collected the following activity location types, using the corresponding land use categories: `square`, `park`, `playground`, `library`, `dog_park`, `beach_resort`, `swimming_area`, `cafe`, `fast_food`, `food_court`, `pub`, `restaurant`, `marketplace`, `shop`, `social_facility`, `arts_centre`, `cinema`, `community_centre`, `social_centre`, `theatre`, `gallery`, `museum`. In total, we collected 30,420 activity locations in September, 2021 across the five cities, and more specifically: 10,483 activity locations in Amsterdam, 5,226 in Rotterdam, 8,118 in The Hague, 4,190 in Utrecht, and 2,403 in Eindhoven.

3.5. RESULTS

This section provides an overview of the application of our proposed methodology in the five largest cities in the Netherlands. Specifically, we aim to explore spatial age segregation from the perspective of age-adjusted co-accessibility: how accessible activity locations (i.e. our spatial units of analysis) are to different population age groups (categorized in our study into children, adolescents and adults, and elderly). We look at the distribution of activities (destinations) over the geographical space of each city and how this influences the time required to reach them from people's residences (origins). Subsequently, we explore how this impacts the degree of age diversity at the different activity locations and use this as a measure of spatial age segregation.

3.5.1. CO-ACCESSIBILITY OF ACTIVITY LOCATIONS — AGE GROUPS

We start by exploring how accessible the different activity locations in each city are to the three population age groups under study. To do so, we calculate an estimate of the total number of each age group that has access to any given destination within five, ten, and fifteen-minute walking radii from people's residences. We then assign percentages to each destination that reflect the potential age structure of people who might perform activities at that location. These percentages are used as proxies of potential exposure of an individual to a specific age group (e.g. children).

Fig. 3.2 illustrates the various activity locations across the five case-study cities, classified according to the percentage of a given age group that can access each location relative to all the other groups. In other words, a location yielding a 10% accessibility score in the children's age group would indicate that only 10% of the people who overall have access to it would be children between the ages of 0 and 15. Fig. 3.2 specifically presents the co-accessibility results pertaining to children (0-15 years of age) and the elderly (65+). The majority of activity locations considered in this chapter appear to be easily accessible by adolescents and adults (between 16-64 years) relative to children and elderly people. For this, we illustrate the percentages of the two latter age groups, as they primarily determine the degree of age diversity at a given destination. Fig. 3.2 further shows how the different walking radii (five and fifteen-minute walksheds are illustrated in columns) affect the corresponding degree of accessibility across the five case-study cities (rows). We organize the resulting percentages into five classes. The fifth class (i.e. 20% – 100%) has a larger increment relative to all others, and corresponds to a relatively small number of locations, where the percentage of either the children or elderly populations — of those accessing the same location — is larger than 20%.

Depending on the city, the largest differences between the percentages of the children and the elderly — of those accessing the same activity location — range between approximately 10% and 50%. An indicative example of this is observed in Amsterdam Center (AC in Fig. 3.2), where approximately 14% of the total number of people who have access to the activity locations in that area within a 15-minute walk from their residence are elderly, and only about 5% are children. Our analysis yields similar results in the

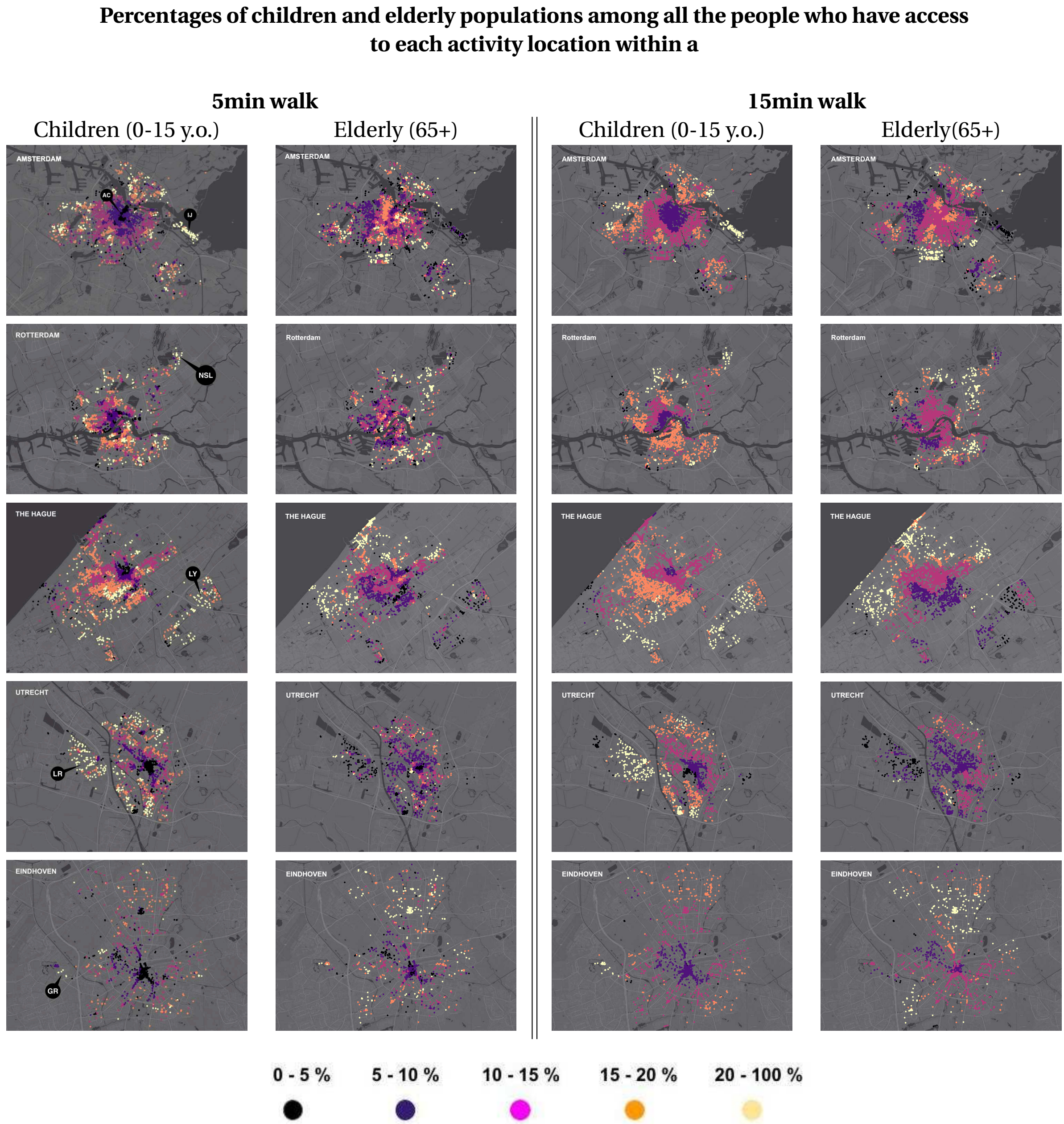


Figure 3.2.: Activity locations across the five case-study cities, classified according to the percentage of children and the elderly that can access each location relative to all the other groups within two different walking distances (5 and 10-minute walksheds).

Nieuwe Werk (NW) neighborhood of Rotterdam. A notable example of the opposite case is the IJburg (IJ) neighborhood of Amsterdam, where there is a concentration of activities that are predominantly accessible to children relative to elderly populations. Specifically, we estimate that approximately 20-30% of the total number of people who have access to various destinations in IJburg are children and only 2-6% are elderly people. This may further be associated with the age structure of IJburg, where children comprise 23-30% of the total population, whereas only 3-5% are elderly people.

A notable case of co-accessibility score discrepancy among the considered pedestrian walksheds emerges when comparing the scores pertaining to children and the elderly across the case-study cities. Specifically, when looking at destinations accessible within a five-minute walk, the resulting accessibility scores of either children or the elderly are relatively low for a large number of activity locations. On the contrary, this case is reversed when looking at destinations accessible within a fifteen-minute walk, regardless of the city. This discrepancy is associated with the spatial distribution of the places where either children or the elderly live. In fact, the residencies of these two age groups are more sparsely distributed over space, relative to the home locations of adolescent and adult populations. This, subsequently, impacts the co-accessibility scores. Correspondingly, destinations that are located within a five-minute walk from people residencies are often accessible to a low percentage of either children or the elderly. In contrast, considering destinations within a larger distance from people's residencies (e.g. within a 15-minute walk) result in higher co-accessibility scores.

3.5.2. CO-ACCESSIBILITY OF ACTIVITY LOCATIONS — AGE DIVERSITY

In investigating spatial age segregation from the perspective of accessibility, it is important to not only determine whether activity locations are accessible to specific age groups, but to also explore the degree to which they are accessible to a diverse set of age groups. This section focuses specifically on the second aspect. In particular, we look at the spatial distribution of activities in each city and explore how this influences the degree to which they are accessible to an age-diverse set of people, by calculating Shannon's Equitability Index (EI).

Fig. 3.3 maps the spatial distribution of activity locations in the five cities with the resulting age diversity scores, considering 5, 10, and 15-minute walks from people's residences. The age diversity values are categorized into four classes: low (0-25%), low-to-medium (25-50%), medium-to-high (50-75%), and high (75-100%). Rows represent each of the five cities under study, whereas columns represent the walking trip distances used to determine the accessibility of different destinations.

Across all cities and walking trip distances, the age diversity scores of most areas range from medium-to-high (i.e. 50% < EI < 75%) to high (EI > 75%). An emerging pattern, visible across all the cities under study, is that activity locations with higher age diversity

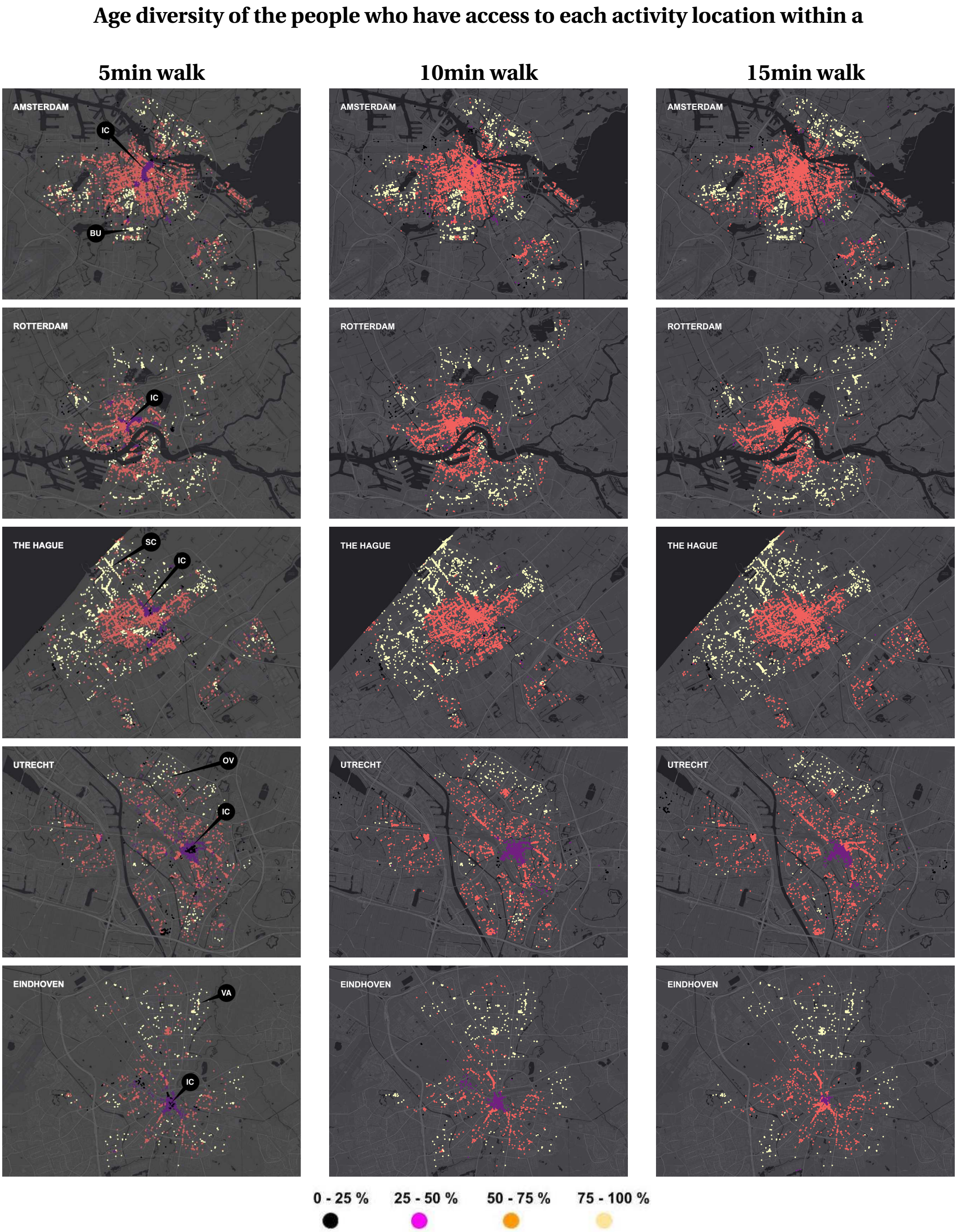


Figure 3.3.: Activity locations based on the age diversity of the people who have access to them within a 5, 10, or 15-minute walk

scores tend to be located in the city outskirts. Examples of such areas include Buitenveldert (BU) in Amsterdam, Scheveningen (SC) in The Hague, Overvecht (OV) in Utrecht, Vaartbroek (VA) in Eindhoven and the northern and southern precincts of Rotterdam. In contrast, across all cities, activity locations with low age diversity scores (i.e. EI < 25%) tend to be located in the Inner City (IC) neighborhoods. This, is mostly visible when considering activities accessible within a five-minute walk distance from people's residencies. Overall, activities within a 10 or 15-minute walk from people's residencies yield higher age diversity scores.

Fig. 3.4 provides further insight into the distribution frequency of the various destinations relative to their age diversity scores for the three walking trip distances. The width of each plot is scaled by the number of activity locations with a given age diversity score, whereas the centerline illustrates the value distribution and the median (denoted with a white dot).

The plots illustrated in Fig. 3.4 highlight two distinctive cases. On the one hand, the majority of activity locations in Amsterdam, Rotterdam, and The Hague appear to have relatively similar and high age diversity scores (i.e. EI > 60%, with most values revolving around the median). On the other hand, the age diversity values of activity locations in both Utrecht and Eindhoven are more evenly distributed. These results suggest that individuals who perform activities within Amsterdam, Rotterdam, and The Hague are, overall, more likely to encounter people of different ages than individuals who perform activities in Utrecht and Eindhoven. However across all the cities under study, while this is not clearly visible in Fig. 3.4, there are several activity locations with relatively low age diversity scores. For example, there are 314 and 78 activities in Utrecht accessible within a 5 and 15 minutes walk, respectively, by sets of people of age diversity lower than 20%. People who perform activities in these locations are less likely to be exposed to an age diverse set of people.

Moreover, the diagrams of Fig. 3.4 further support the previously mentioned observations regarding the effect of walking distance on the resulting age diversity scores. In particular, destinations that lie within a 10 or 15-minute walking distance tend to yield higher age diversity scores, relative to those that lie within a 5-minute walk. This is particularly evident in the cases of Utrecht and Eindhoven.

3.6. DISCUSSION

This section first discusses the results of our analysis, followed by a comparison of our methodology with existing approaches to measuring spatial age segregation, and concluding with an outline of the limitations of our approach.

The application of our methodology in the five most populated cities in the Netherlands demonstrated how the spatial distribution of activities influences the degree to which the same activity locations are accessible to different age groups. We further calculated an age diversity score and assigned it to each destination. This score can be used as a proxy of an individual's potential exposure to people of other age groups and, subsequently, as a measure of spatial age segregation.

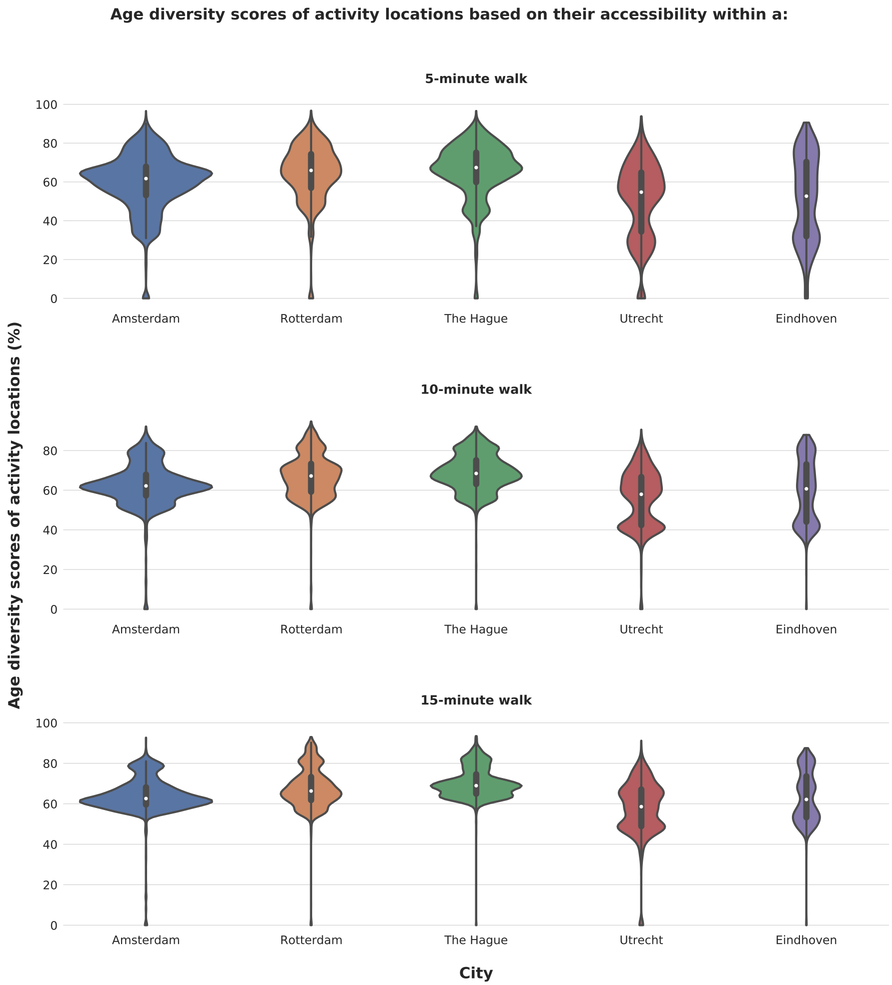


Figure 3.4.: Frequency distribution of all activity locations by the age diversity of the people who have access to them. The y axis shows the age diversity. The width of each plot reflects the number of activity locations.

Our results suggest that the likelihood of an individual to be exposed to people from different age groups when visiting various destinations is influenced by the location of these destinations. For instance, as shown in Fig. 3.3, individuals who perform activities within the IJburg (IJ) neighborhood of Amsterdam are less likely to encounter elderly people. Specifically, among all the people who have access to activities located in this neighborhood, only 2-6% appear to be elderly (i.e., 65+ years of age). IJburg is a relatively new neighborhood (first residents moved in there in 2002) and one of the most child-rich neighborhoods of Amsterdam. Our results suggest that, similar to IJburg, other neighborhoods under the so-called "Vinex" policy [1], tend to contain activity locations that are more accessible to children relative to elderly populations. Examples of such neighborhoods include Nesselande (NSL) in Rotterdam, Leidsche Rijn (LR) in Utrecht, Leidschenveen-Ypenburg (LY) in The Hague, and Grasrijk (GR) in Eindhoven.

Contrariwise, individuals who visit destinations within the Center of Amsterdam (AC) are less likely to encounter children. In this case, among all the people who have access to activities located there, only 5% appear to be children. Moreover, across all cities under study a similar pattern emerges; that is, the activities located in the outskirts of each city tend to have higher age diversity values. These values are strongly affected by the population distribution in the Netherlands, where children and elderly populations reside primarily in the outskirts of the cities, contrary to adolescent and adult populations that are more dispersed across the urban fabric. Thereby, local age structure should be considered in tandem with the distribution of activities when assessing spatial age segregation from the lens of accessibility.

The effect that the spatial distribution of activities has on the co-accessibility and age diversity scores is further supported by the results of the distribution frequency analysis, illustrated in Fig. 3.4. In particular, our results suggest that the majority of activity locations are accessible to a set of people that is characterized by a medium-to-high age diversity (i.e., 50% < EI < 75%) in Amsterdam, Rotterdam, and The Hague, and by a low-to-medium age diversity (i.e., EI < 50%) in Utrecht and Eindhoven. A potential explanation of this discrepancy could be that in the case of Utrecht and Eindhoven both population density and the density of activity locations are the lowest among the five cities under study. Subsequently, the various destinations appear to be accessible to a lower number of people with a rather unequal representation of the three age categories at hand. Lastly, our results suggest that the time required to reach a destination also influences the co-accessibility and age diversity scores. In particular, destinations that lie within a 10 or 15-minute walk yield higher age diversity scores, relative to destinations within a 5-minute walk from people's residences (accessible to a lower number of people). This further indicates that promoting people to perform activities only within a 5-minute walking radius potentially decreases the likelihood of encountering people from different age groups.

3.6.1. COMPARISON OF AGE DIVERSITY SCORES — ACTIVITY VERSUS RESIDENTIAL SPACE

Existing approaches to measuring spatial age segregation make almost exclusive use of spatially aggregated data (e.g., at the neighborhood or city level) about the distribution of age groups in the residential space to evaluate the level of age segregation. This section discusses how the co-accessibility score at the activity location level proposed by our methodology could further complement and enrich the existing approaches. To do so, we compare two different types of age-diversity estimates of activity locations: one

[1] Vinex stands for "Fourth Memorandum on Extra Spatial Planning" in Dutch) neighborhoods were created based on a 1991 policy briefing note from the Dutch Ministry of Housing, Spatial Planning and the Environment. Based on this note, large outer city areas were designated for new housing development. Vinex neighborhoods led to an overall increase of the number of young children who grow up in an urban environment [137].

based on the age structure of people who have access to each activity location within a 15-minute walk from their residence (similar to what is presented in Section 3.5.2), and another one based on the age structure of people who reside within the same neighborhood where the various activities are located, assuming equal distribution of age structure over each neighborhood's geographic space. Fig. 3.5 illustrates the differences between these two approaches.

Activity locations colored in blue indicate that the overall age diversity deriving from the people residing in the neighborhood where these activities are located is higher (i.e., more than 5%) relative to the age diversity deriving from the people who have access to these activity locations. Such activity locations are often found in neighborhoods that are populated by residents with a higher age diversity relative to adjacent neighborhoods. Notably, individuals performing activities in these neighborhoods appear to be less likely exposed to people from other age groups compared to what the age composition of these neighborhoods suggests. Indicative examples include the Westerdokseiland (WE) neighborhood in Amsterdam, Oude Western (OW) in Rotterdam, Schildersbuurt-Noord (SN) in The Hague, Langerak (LA) in Utrecht, and Schrijversbuurt (SC) in Eindhoven.

Contrariwise, activity locations colored in red indicate that the overall age diversity deriving from the people residing in the neighborhood where these activities are located is lower relative to the age diversity deriving from the people who have access to these activity locations. Such activity locations are often found in neighborhoods that are populated by residents with a lower age diversity score relative to their adjacent neighborhoods. Individuals visiting destinations within these relatively age segregated neighborhoods appear to be more likely to encounter people from other age groups. Notable examples include Zuidas (ZU) in Amsterdam,Blijdorpsepolder (BLI) in Rotterdam, Kerketuinen en Zichtenburg (KEZ) in The Hague, Bedrijvengebied Kanaleneiland (BK) in Utrecht, and Strijp S (STS) in Eindhoven.

As shown in Fig. 3.5, the majority of destinations are colored gray. These, in fact, refer to activity locations for which the two types of estimates yield similar results (i.e., a difference smaller than 5%). This is not surprising, given that the spatial distribution of activity locations and age structure of the different neighborhoods are, overall, relatively uniform over space across all the cities under study.

There is one more notable insight emerging from the comparison of the two measurement approaches. This primarily concerns neighborhoods that are often located in the outskirts of each city, are large in size, are populated by a relatively age diverse set of residents, and include a limited number of activity locations (e.g., less than 4 activities/km^2). Conventionally, judging only on the basis of age structure in the residential space, these neighborhoods would not be considered age segregated. However, the scarcity of accessible activity locations within these neighborhoods could have a substantial effect on the likelihood of people from different age groups encountering each other. This, for instance, might occur either when the portion of residents who have access to the same activity location are not as age-diverse as the overall neighborhood population, or when a portion of the residents have no access to any activity location and it is, therefore, unlikely to encounter other people. In other words, the sole consideration of a neighborhood's overall age structure could often result in an overestimation of the degree to which different age groups are exposed to each other.

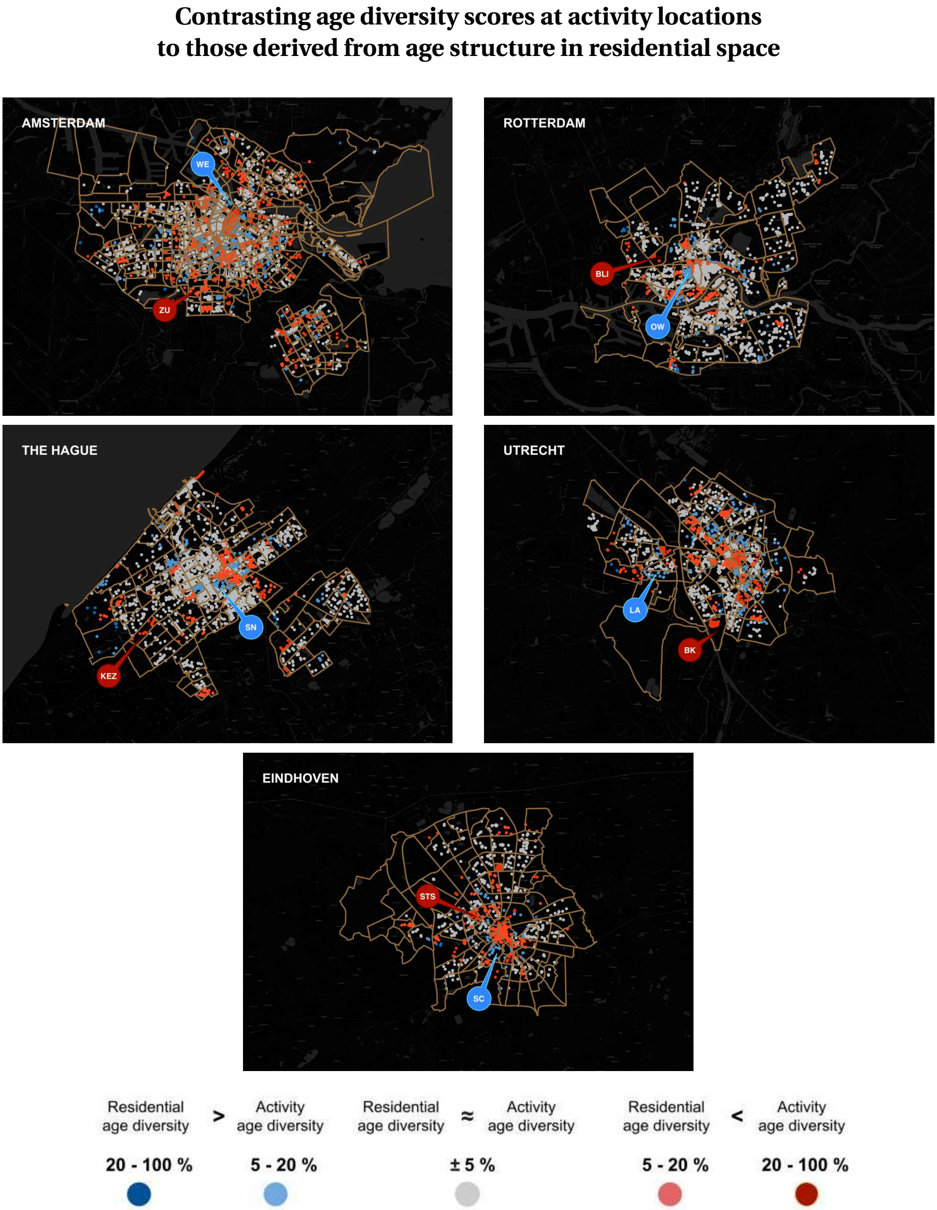


Figure 3.5.: Points represent the various activity locations within each neighborhood (delineated by its administrative boundary). We compare the age diversity scores of each activity location if calculated according to (1) the set of people who have access to it within a 15-minute walk from their residence (i.e., our approach), and (2) the set of people who reside in the same neighborhood where each activity is located, assuming equal distribution of age structure over geographic space (i.e., existing approaches). Differences between the two measurements are indicated by different colors. Specifically, blue indicates that the scores resulting from existing approaches are higher than those estimated with our approach. Red colors indicate the opposite. Gray colors indicate activity locations where both approaches yield similar results.

Overall, the results of this comparative analysis suggest that, in several cases, the age diversity of the people who have access to destinations (beyond the residential space) located within a neighborhood (e.g., within a 15-minute walk from people's residences) often diverges from the score that would derive from the sole consideration of the aggregated age structure in that neighborhood. These differences are consistently found in cases where neighborhoods with different age structures are adjacent to each other (i.e., share a common administrative boundary), and in neighborhoods with a limited number of activity locations (e.g., less than 4 activities/km^2). These differences further suggest that the two approaches could complement each other and lead to an improved understanding of the level of spatial age segregation. Moreover, they indicate that besides the concentration and level of mixture of different age groups in residential spaces, the density and distribution of activity spaces can play an important role in how people experience age segregation in their daily encounters.

3.6.2. LIMITATIONS

There are several limitations in this study that could be addressed in future research. First, we chose to focus our analyses only on one mode of travel, namely walking. Thereby, the results of our analyses reflect pedestrian access measured from people's residencies. Our work can be extended to further account for biking trips and other modes of transport, such as public transportation. Second, our calculations are not based on actual walking trips, but are rather based on the assumption that people tend to perform activities at destinations close to their place of residence. As such, they in fact reflect potential access to different activity locations within different walking distances (i.e., 5, 10, or 15-minute walking trips) from home. Data on actual walking trips and visiting patterns (i.e., indicating when and for how long people visit given places), if available, can be easily integrated in our methodology and would provide more accurate estimates of the level of potential encounters. Third, pedestrian mobility behavior may further vary across cities, countries, cultures, or by the type of destination (e.g., people generally tend to visit the closest retail or grocery store to their home, as opposed to more specialized activities for which they might travel longer distances). Fourth, drawing on insights from related work on pedestrian mobility, the characteristics and quality of the routes may substantially influence the routing choices of pedestrians. Examples include scenic environments, differences in the quality of sidewalks, and the mixture of land uses along streets, among others [138, 139]. Our methodology could be extended to further consider these variations in qualitative characteristics and attractiveness scores. Lastly, our analyses use people's residences as origins. In future work, we could consider additional daily activity locations (e.g., schools, workplaces) as origins in our accessibility analyses.

3.7. CONCLUSION

In this chapter, we proposed a novel methodology to assess the degree of an area's spatial age segregation through the lens of co-accessibility to different activity locations. Our methodology receives as inputs the locations of people's residences (origins) and a set of activity locations (destinations), calculates a set of spatial accessibility measures, and estimates an age-adjusted co-accessibility score for each activity location. These estimates are used as proxies of an individual's potential exposure to people from different age groups. Our results suggest that the spatial distribution of activities, in combination with an area's age structure, affect the degree to which the same activity locations are accessible to different age groups. We further highlighted how our methodology can provide an additional avenue to assess spatial age segregation relative to existing approaches that are exclusively based on population distribution in the residential space. We have shown that accounting for access to places outside of the residential space, in addition to the age structure of a neighborhood, can provide new insight into the potential dampening effect that exposure to other age groups at activity locations outside of home can bring to the level of spatial age segregation. In particular, our comparative analysis suggested that an exclusive focus on the age structure at the neighborhood level can lead to over-estimations of the level of age segregation, especially in adjacent areas with different age structures or areas with a limited number of activity locations (e.g. less than 4 activities/km^2).

To the best of our knowledge, this work is the first to account for the degree of co-accessibility of activity locations as an important indicator of spatial age segregation, complementary to an area's age structure. Our methodology has practical value for urban planners, policy makers, and public health officials who can use it as a tool to assess how the location, density, and distribution of places outside of the residential space can either promote or obstruct encounters with people from different age groups. Specifically, instead of exclusively focusing on the mixture and concentration of different age groups within neighborhoods, age segregation policies could further account for the density and distribution of activity locations to promote access and facilitate interactions between different population age groups.

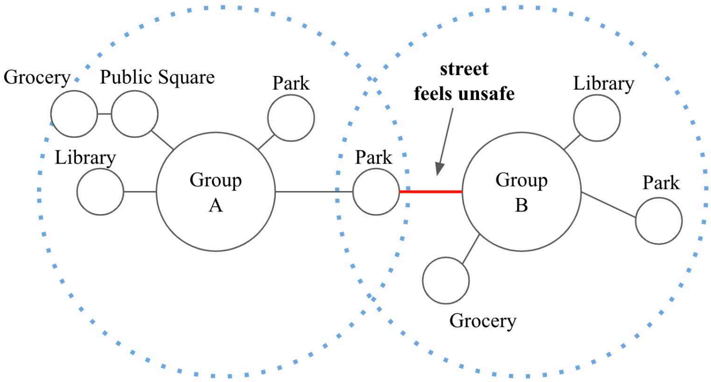
Future research could extend the proposed methodology by accounting for different travel modalities such as biking or public transportation. It could further be refined by data on actual walking trips and relevant information about the characteristics and quality of the chosen routes. Moreover, it can be extended to consider other socioeconomic characteristics such as income, ethnicity, and education level. Data on actual human interactions at different locations and over different time periods, where available, would help elicit the likelihood of meaningful interactions emerging from the now-estimated inter-generational encounters. Our methodology can be replicated in other cities to strengthen the generalizability of our approach.

4

DETERMINING THE IMPACT OF STREETSCAPE CHARACTERISTICS ON THE PERCEIVED SAFETY AND ATTRACTIVENESS

Beauty is in the eye of the beholder.

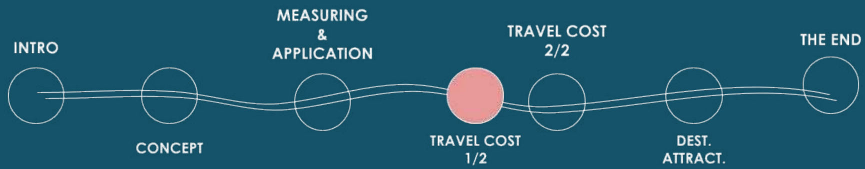
Margaret Wolfe Hungerford



SUMMARY

4

In the previous chapter, we demonstrated the application of a pedestrian co-accessibility measure. To measure co-accessibility we made the assumption that the travel cost component in its formulation is only related to the walking time. In this chapter, we dive deeper into the travel cost component by studying how streetscape characteristics influence the perceived safety and attractiveness of city streets, perceptions that have been found to highly impact different (groups of) individuals from walking. To do so, we developed a crowdsourcing tool and conducted a study with 403 participants, who were asked to virtually navigate city streets through a sequence of street-level images, rate locations based on perceived safety and attractiveness, and explain their ratings, while controlling for different age and gender groups. Ultimately, the findings of our study are used to make evidence-informed recommendations for designing safer and more attractive streets that promote pedestrian co-accessibility.



*This chapter is based on a full paper published at the 26th AGILE Conference on Geographic Information Science (AGILE 2023) [54]

4.1. INTRODUCTION

Safe and attractive public spaces are essential to a city's vibrancy, as they encourage social interaction and physical activity through walking and cycling [41, 140–142]. Since streets account for the majority of public space in cities, a growing body of literature focuses on identifying street design features that encourage active travel while also improving people's experiences and well-being [94, 143–146]. Greenery, the density and mix of land uses along streets, the morphology and aesthetics of buildings, intersection density, good visibility and street lighting, and the quality and maintenance of sidewalks have been identified as essential characteristics of safe and walkable streets [94, 147–151].

Aside from general streetscape characteristics, it is less clear how much each feature contributes to an overall sense of safety and attractiveness, and whether similar features have an equal influence on these perceived qualities. The subjective nature of perception, as well as the variety of conditions that influence it, makes determining these issues particularly difficult. Place perceptions vary among people of different ages, income levels, ethnic backgrounds, physical abilities, or past experiences [142, 152–156], and getting a representative sample of people to participate in city-scale studies takes time and effort.

Ewing and Handy [94] developed a conceptual framework that connects streetscape characteristics like sidewalk width and the number of trees to individual perceptions such as safety, comfort, and level of interest. Other empirical studies involving a small number of streets observed how people traversed and used the streets to identify characteristics such as street furniture and local stores that influence how people experience the urban environment and interact with other individuals [144, 146, 157]. More recently, a growing body of literature has investigated the relationship between urban characteristics and the perception of safety or attractiveness at the city scale using crowdsourcing and leveraging the availability of street-level imagery [142, 153, 158–162].

Typically, the streetscape features associated with perceived safety and attractiveness of city streets have been studied separately or assumed to be identical for both of these perceived qualities [15, 145, 163, 164]. But, do streetscape features that promote safety impact a street's attractiveness, and vice versa? And how much influence does each feature have? What factors should be considered when designing streets to make them feel safer and more attractive? Disentangling the factors influencing how people perceive city streets as attractive and safe may help to inform design interventions that contribute to healthier, more walkable, and accessible cities.

In this chapter, we adopt a crowdsourcing approach to determining how different design features contribute to a street's overall sense of safety and attractiveness. We develop a crowdsourcing tool that allows participants to virtually navigate a set of city streets represented by panoramic street-level images. We use Frankfurt in Germany as a case-study city. Participants in the study are asked to rate the locations they visit along each street on a 5-point Likert scale based on how safe and attractive they appear. To compare the factors influencing participants' perceptions, we ask them to explain their ratings. Then we investigate which features, and to what extent, influence the perceived safety and attractiveness of city streets, while controlling for age and gender.

Our findings show that streetscape features that influence perceived safety and attractiveness have a high degree of overlap, highlighting key differences. Overall, perceived safety along city streets was found to be strongly related to human activity characteristics such as traffic and crowdedness, whereas attractiveness is primarily influenced by building aesthetics and the amenities and services offered along a street. We show that construction sites along a street or underpasses, more than any other feature, have a significant negative impact on a street's sense of safety and attractiveness. We also discuss the practical value of our tool and empirical findings for urban design.

The remainder of this chapter is structured as follows. First, we present our research methodology and describe the data sources, as well as the demographics of the recruited participants. We then report the results of our analysis, followed by a discussion of the empirical findings and the practical value of our approach to urban design. The chapter concludes with a summary of the main findings, an outline of the limitations, and suggestions for future lines of research.

4.2. Capturing streetscape characteristics that influence perceived safety and attractiveness

4.2.1. Collection of perceptions of safety and attractiveness along city streets

To collect data that capture how people perceive city streets, we use crowdsourcing and street-level imagery. Crowdsourcing is selected as a time- and labour-efficient practice that allows us to recruit participants at scale while controlling for an overall representative sample of participants in terms of demographic characteristics such as age, gender, or country of residence. Street-level images are selected since most streetscape characteristics could be visually observed and are, therefore, depicted in such images (e.g., the number of shops and trees, the width of the street, and the number of cars).

In particular, we developed a crowdsourcing tool in *AngularJS* that integrates three key characteristics. *(1)* City streets are depicted as a sequence of panoramic (360) street-level images. The distance between consecutive locations ranges from 20 to 25 meters (depending on the availability of the images) and, therefore, the images practically cover every part of the selected streets. In this way, we can study how participants' perceptions develop along the street and investigate to what degree the characteristics participants encounter along a street influence how they perceive it. *(2)* Participants have complete control over their experience and can explore the streets at their own pace. They can digitally traverse the streets (by moving from one image to another), turn their view, and zoom in and out. *(3)* The tool asks the participants to traverse a path (consisting of multiple streets) and to rate at least four locations along the path according to two questions: "how safe is this place in your opinion?" and "how attractive is this place in your opinion?". The provided ratings are based on a 5-point Likert scale (1 corresponding to very unsafe/unattractive and 5 to very safe/attractive). For a task to be completed, participants must visit each location on the entire path at least once. Moreover, the tool prompts the participants to explain their ratings further. To make each task time and labour efficient, the participants' input is asked every other time they provide a rating or when their ratings are at the extreme points of the rating scale (i.e., 1/5 or 5/5). This input can be used to capture what are the main characteristics that influence the participants'

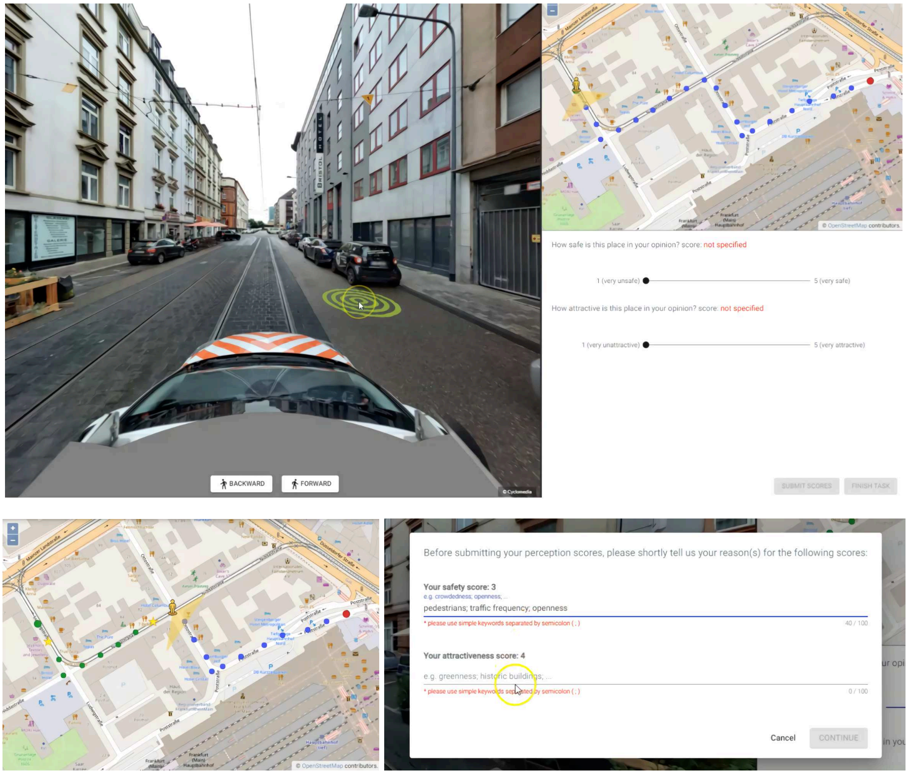


Figure 4.1.: *Top*: The user interface of the crowdsourcing tool developed to capture how safe and attractive city streets are perceived. *Bottom left*: Example of the birdview map after 2 locations have been rated (marked with a star) and 9 locations have been visited (green points). *Bottom right*: Example of the panel in which participants provide their input to explain their ratings.

rating process.

The user interface we used to collect participants' input is shown in the upper part of Fig. 4.1. On the left side of the screen, participants see a street-level image and can turn their view and zoom in and out. Whenever they want to move to the following location, they can either click within the picture towards the direction they want to move or click on one of the two buttons named “BACKWARD" and “FORWARD" located at the bottom of the screen. Alternatively, they could also select to visit a specific location through the *birdview map*, located on the upper right side of the screen (Fig. 4.1). To provide a rating for a location, participants can adjust the sliders accordingly and then click on “SUBMIT SCORES". The locations for which they have already provided a rating will appear as a star on the birdview map (Fig. 4.1, bottom left). Fig. 4.1 (bottom right), also depicts the pop-up window that enables participants to provide an explanation of their ratings.

4.2.2. Identification of characteristics that influence the perceived safety and attractiveness of city streets

To identify the characteristics that influence how safe or attractive city streets are perceived, we first average the participants' ratings per location and then group the locations based on their average rating. In particular, according to our 5-Point Likert scale, each location has been rated by each participant as very unsafe/unattractive ($r = 1$), unsafe/unattractive ($r = 2$), neutral ($r = 3$), safe/attractive ($r = 4$), or very safe/attractive ($r = 5$). We calculate the rounded average of the participants' ratings per each location and group them accordingly as unsafe/unattractive ($r_{avg} \leq 2.5$), neutral ($2.5 < r_{avg} < 3.5$), or safe/attractive ($r_{avg} \geq 3.5$). Then, we process the text that accompanied the participants' ratings by first manually correcting spelling mistakes and merging closely related words (e.g., "road" and "street"). After that, we use the *NLTK* Python package[1] to remove stop-words, perform lemmatization, and look at the most frequently used words. In this way, we identify the characteristics participants most frequently describe when rating the perceived safety and attractiveness of city streets.

4

To further investigate how participants describe the characteristics that most frequently influence their perceptions, we convert the participants' input into a graph, similar to previous work that follows graph-based approaches to analyse textual data [165, 166]. First, for each word in each sentence we determine its *head* using *spaCy*[2], a Python Library that relies on dependency parsing [167]. The head of a word determines the word's syntactic category [168]. As an indicative example, in the sentence "*Nice urban street with many cool shops and beautiful buildings*", the heads of "*urban*" and "*cool*" are the words "*street*" and "*shops*", respectively. Next, based on the *word-head* pairs, we construct a weighted graph where each word is represented by a node, and each *word-head* relationship is represented by an edge. The edges' weight reflects how often this pair occurs in our data. Then, we calculate the degree centrality of each node (i.e., how many other words it is connected to) to identify the characteristics that participants tend to describe most often. We examine the five nodes with the highest degree centrality scores, representing the five most discussed characteristics, and look at the 10 most frequent neighbours of those, representing the words most commonly used to describe these characteristics. In this way, we identify the words participants use to describe the characteristics they most frequently focus on when providing their ratings.

Furthermore, to investigate the degree to which streetscape characteristics influence the perception of safety and attractiveness, we look at the rate of change of the ratings along the streets. Particularly, we list all pairs of consecutive locations (distance of 20-25m) and calculate the absolute difference of each pair's ratings (for both perceived safety and attractiveness). A high difference implies that participants encountered within 20-25m characteristics that suddenly changed how they perceived the street. Then, we further examine the pairs of consecutive locations that exhibit the largest differences and based on the participants' input, we identify the characteristics responsible for these differences. Lastly, we explore the linearity of the relationship between perceived safety and attractiveness and estimate their correlation.

[1] https://www.nltk.org/
[2] https://spacy.io/

4.3. DATA

CITY STREETS

We applied our methodology for 27 paths (500-750m each), each path consisting of multiple streets, covering areas in the centre and the outskirts of Frankfurt, Germany. To select the paths, we first randomly collected 2000 street segments in Frankfurt. Then, we selected 50 streets that are diverse in terms of socioeconomic aspects, such as the average size of the household, purchasing power, the number of retail stores, the rate of unemployment, and the dominant age group based on data from WIGeoGIS [3]. We used a location in the middle of each of the 50 streets selected as the origin of our paths. Next, we selected a set of destinations based on the locations of pharmacies (collected from *OpenStreetMap*) since they are described by a relatively uniform regional coverage throughout Frankfurt. Particularly, we calculated the 3 shortest paths (500-750m) from each of our 50 origin locations to each destination. Then, we obtained street-level imagery data from Cyclomedia[4], depicting the selected paths. We removed any overlapping paths and previewed them to ensure that the paths were clearly and consistently depicted through the street-level images. After these manual adaptations, we kept 27 paths represented by 753 distinct locations for our analysis.

PARTICIPANTS

We recruited 403 individuals through the Prolific platform, amongst which 94 do not share any personal information. The remaining 309 participants came from 54 (and currently reside in 12) different countries, 129 were male, and 178 were female (2 preferred not to say), and their ages ranged from 19-71 (with 79% of the participants' ages ranging from 19-40). Each participant was asked to rate three different paths. From these 403 participants, we received 7989 rating pairs of perceived safety and attractiveness and 19114 and 18232 words that were used to explain the ratings of safety and attractiveness, respectively.

DATA AND SOFTWARE AVAILABILITY

The data collected from the participants, after being aggregated, and the code used for the analysis are publicly available in GitHub [5]. The code used for developing the crowdsourcing tool can also be found in Github [6]. The street-level imagery obtained by Cyclomedia cannot be publicly shared due to the company's data-sharing regulations.

4.4. RESULTS

This section reports the results of our analysis. We present the characteristics that influence how safe and attractive people perceive city streets, explore the degree of this influence, and investigate the relationship between the ratings of perceived safety and

[3]https://www.wigeogis.com
[4]https://www.cyclomedia.com/en
[5]https://github.com/MiliasV
[6]https://github.com/shahinsharifi/subjectivity

attractiveness.

4.4.1. CHARACTERISTICS THAT INFLUENCE THE PERCEIVED SAFETY AND ATTRACTIVENESS OF CITY STREETS

Perception of safety. Starting with perceived safety, 6% of locations (44 locations) are considered on average as "very unsafe" or "unsafe" ($r_{avg} \leq 2.5$), 50% of locations received ratings between 2.5 and 3.5, and 44% of locations are considered as safe or very safe ($r_{avg} \geq 3.5$, Fig. 4.2). Fig. 4.3 depicts the words participants most frequently used to explain their ratings. As observed, common reasons for a location to be considered unsafe revolve around the high number of "*cars*" and "*graffiti*", the "*traffic*", and the existence of "*construction sites/building work*" (e.g., "*There is lots of construction, therefore, people do not visit this area for daily activities*"). Regarding the locations that were rated as safe, participants often mentioned that they "*have limited traffic*", look "*residential*", are "*open*", "*clean*", and "*busy*" and "*have people around*". Fig. 4.4 depicts as indicative examples the three locations that received the highest and lowest ratings regarding perceived safety. Furthermore, Table 4.1 presents the percentages of locations considered (very) safe/unsafe when controlling for the gender and age of the participants. We observe that male participants rated 11% of locations as unsafe and 50% of locations as safe, while female participants rated 9% of locations as unsafe and 47% of locations as safe. Thus, male participants appear to provide more extreme ratings than female participants. To control for age, we divide our participants into two age groups, including both male and female participants, with each group having a similar number of participants: 19-35 years old and 35+. The 19-35 group rated 8% of locations as unsafe and 45% of locations as safe, while the 35+ group rated 13% of locations as unsafe and 50% as safe. Therefore, in this case, the older participants seem to provide more extreme ratings.

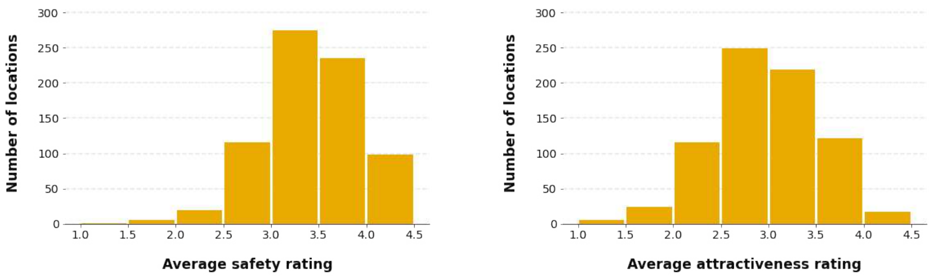


Figure 4.2.: Histograms of the locations' average safety (top) and attractiveness (bottom) ratings.

Perception of attractiveness. Regarding attractiveness, the locations' average ratings present a higher variability than the ones for safety (Fig. 4.2). 24% of locations are considered "very unattractive" or "unattractive" ($r_{avg} \leq 2.5$) while most locations received a rating between 2.5 and 3.5 (57% of locations). The most frequent words participants used to describe (very) unattractive ($r \leq 2.5$) or (very) attractive ($r \geq 3.5$) locations are depicted in Fig. 4.3. According to the participants, unattractive locations depict build-

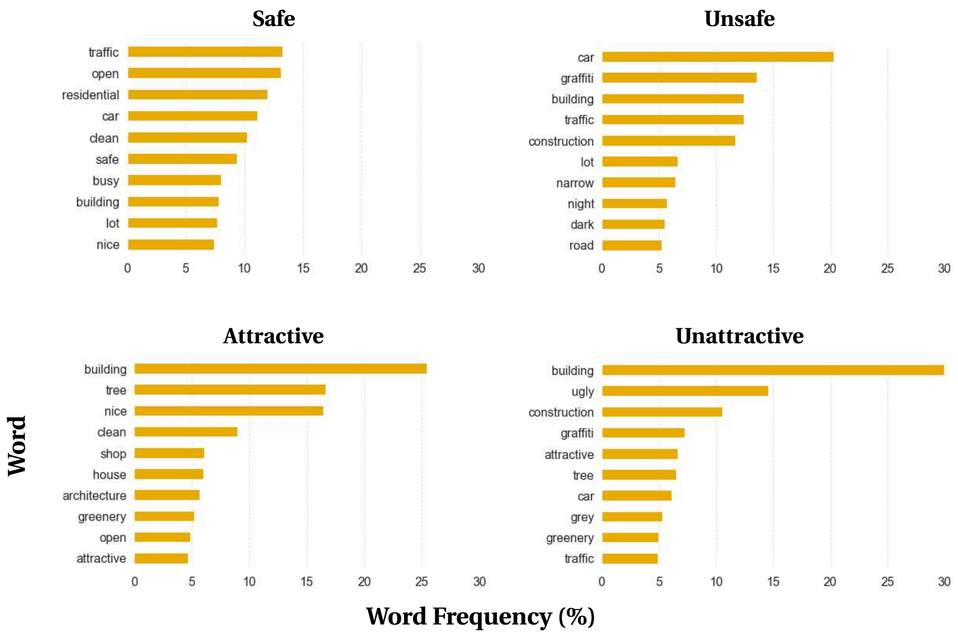


Figure 4.3.: Most frequent words participants used to explain their ratings for the locations they rated as safe, unsafe, attractive, or unattractive.

Percentages of locations rated as (un)safe or (un)attractive				
	Safe	**Unsafe**	**Attr.**	**Unattr.**
Males	50%	11%	22%	31%
Females	47%	9%	22%	27%
19-35 y.o.	45%	8%	20%	26%
35+ y.o.	50%	13%	22%	37%

Table 4.1.: Percentages of locations that were considered as (very) safe/attractive ($r_{avg} \geq 3.5$) or (very) unsafe/unattractive ($r_{avg} \leq 2.5$) when controlling for gender and age. The percentages of locations that received ratings higher than 2.5 and lower than 3.5 are not presented in the table.

ings that are "*ugly*", "*grey*", and "*dull*". Moreover, unattractive locations have "*graffiti*", "*lack of greenery*", and "*do not have many shops*". Similarly to the results about safety perception, participants mentioned the existence of construction sites as among the main reasons for considering a location unattractive. Oppositely, attractive locations were described as having "*trees*" and "*shops*" and being "*open*" and "*clean*". Buildings in

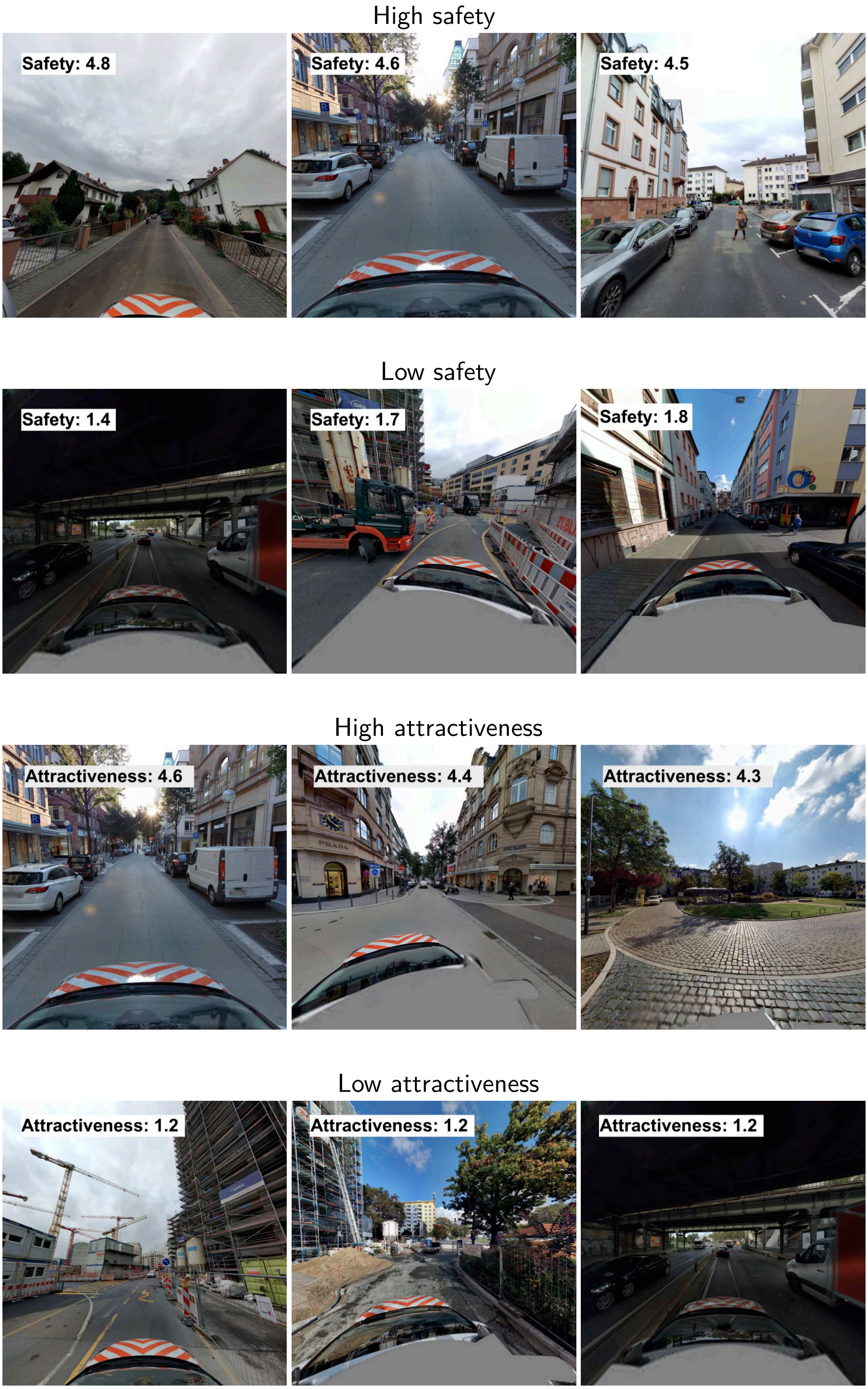


Figure 4.4.: Examples of the three locations that received the highest and lowest average ratings in terms of perceived safety (top) and attractiveness (bottom).

attractive locations are often considered "*nice*", "*aesthetic*", or "*beautiful*" and the architecture of such locations is characterized as "*old*", "*modern*", or "*nice*". Fig. 4.4, depicts as indicative examples the three locations that received the highest and lowest ratings in terms of average attractiveness (bottom). Moreover, Table 4.1, includes the percentages of locations that are considered (very) attractive/unattractive when considering different gender and age groups. Overall, we observe that the percentage of locations rated as attractive is similar among the different gender and groups (20-22%). However, male and older participants appear to rate more locations as unattractive than female and younger participants.

Graph analysis of participants' input As explained in the *Methodology* section, we construct four graphs based on the words participants used to describe the locations they perceive as safe, unsafe, attractive, and unattractive. These graphs allow us to identify the characteristics participants most often mention when explaining their ratings and the words they use to describe these characteristics. Our results are well aligned with the results we present in Fig. 4.3. The 5 most mentioned characteristics are depicted in Fig. 4.5.

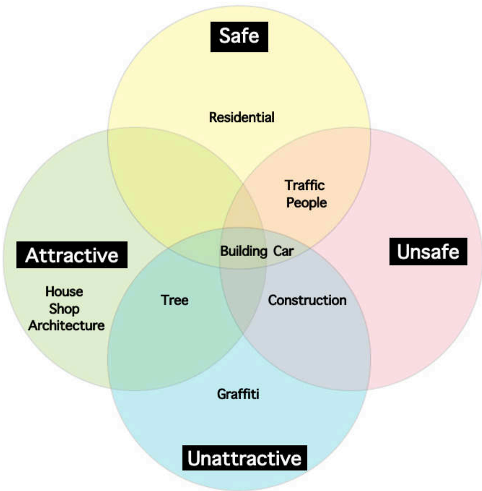


Figure 4.5.: Five most mentioned characteristics based on the words participants used to describe the locations they rated as safe, unsafe, attractive, and unattractive.

As could be observed, "*building*" is among the five most mentioned characteristics in all four graphs, meaning that participants often describe the buildings along the street to explain why they rated a location as attractive, unattractive, safe, or unsafe. Regarding the locations that are considered safe, participants often characterize them as "*residential*". Other characteristics that participants mention to explain their ratings regarding safe/unsafe locations are the "*people*", "*traffic*", and "*car*". However, these characteristics are not that frequently mentioned when participants explain their attractiveness ratings. Instead, participants frequently comment on the existence or absence of "*trees*" to explain why they consider a location attractive or unattractive. Therefore, trees appear to play a fundamental role in how attractive a location is perceived. When participants rate a location as attractive they also tend to explain their ratings by describing the "*shops*" and "*architecture*", while for unattractive locations they often mention "*graffiti*" as an important characteristic that influences their perception. Furthermore, the word "*construction*" is often used to describe why a location is rated as unsafe or unattractive.

We further examine the words most commonly used to describe the most mentioned characteristics by looking at the 10-nearest neighbours of these characteristics in our graphs. Table 4.2 presents an indicative example of the 10 most frequent words participants used to describe buildings in locations that are rated as safe, unsafe, attractive, or unattractive. As could be seen, participants often use different words to describe the buildings along a street depending on whether they rate perceived safety or attractiveness. For instance, to explain how buildings influence their perception of safety participants often mention the function of the buildings by using words such as "*residential*" or "*office*". For the safe locations, we could also see the word "*unattractive*" suggesting that some locations although perceived as safe they are also considered unattractive. For attractiveness, participants focus more on the aesthetics of the building using words such as "*colored*", "*high*", "*pretty*", "*tall*", "*big*", "*ugly*". Notably, in the case of unattractive locations, the word "*attractive*" is present. This, however, occurs because participants often mention that the buildings in this location "*are not attractive*". Similar results are found when looking at the words participants use to describe the other most mentioned characteristics.

4

Ten most frequent characterisations of "buildings" at locations rated as (un)safe or (un)attractive	
Safe	nice, office, modern, old, street, big, new, residential, car, unattractive
Unsafe	unattractive, site, nice, big, tall, closed, graffiti, construction, poor, bad
Attract.	old, modern, tree, attractive, beautiful, pretty, colored, clean, ugly, historic
Unattract.	ugly, high, unattractive, old, grey, big, plain, dull, attractive, tall

Table 4.2.: The 10-nearest-neighbours of the word "building" according to the computed safe, unsafe, attractive, and unattractive graphs.

Degree of influence To explore the degree to which streetscape characteristics influence perceived safety and attractiveness we look at how the collected ratings change as participants encounter different characteristics along the streets (example in Fig. 4.6). Regarding perceived safety, the absolute difference between the ratings of any two consecutive locations ($distance \leq 25m$) is less than or equal to 0.5 for 80% of the locations and less than 1 for 98% of the locations. The further apart two locations are located the more the ratings of perceived safety tend to differ (Table 4.3). For example, for the consecutive locations, we observe an average difference of safety ratings equal to 0.25. This difference grows to 0.51 when considering locations within 260-325 meters. Similarly, the maximum difference between the ratings of different locations tends to increase the further apart those locations are from each other. To statistically evaluate this observation, we measured the global spatial autocorrelation of the safety ratings using Moran's I correlation coefficient. As expected, we identified a strong and significant spatial autocorrelation ($I = 0.63$, $z = 18$, $p = 0.001$) when looking at locations within a distance of 25m (i.e., using a 2-nearest neighbours connectivity matrix). This correlation weakens as the distance between the nearest locations we use increases. Thus, our results suggest that participants' perception of safety is spatially clustered. It does not increase or decrease steeply from one location to the next, but rather gradually, as participants move past the different locations.

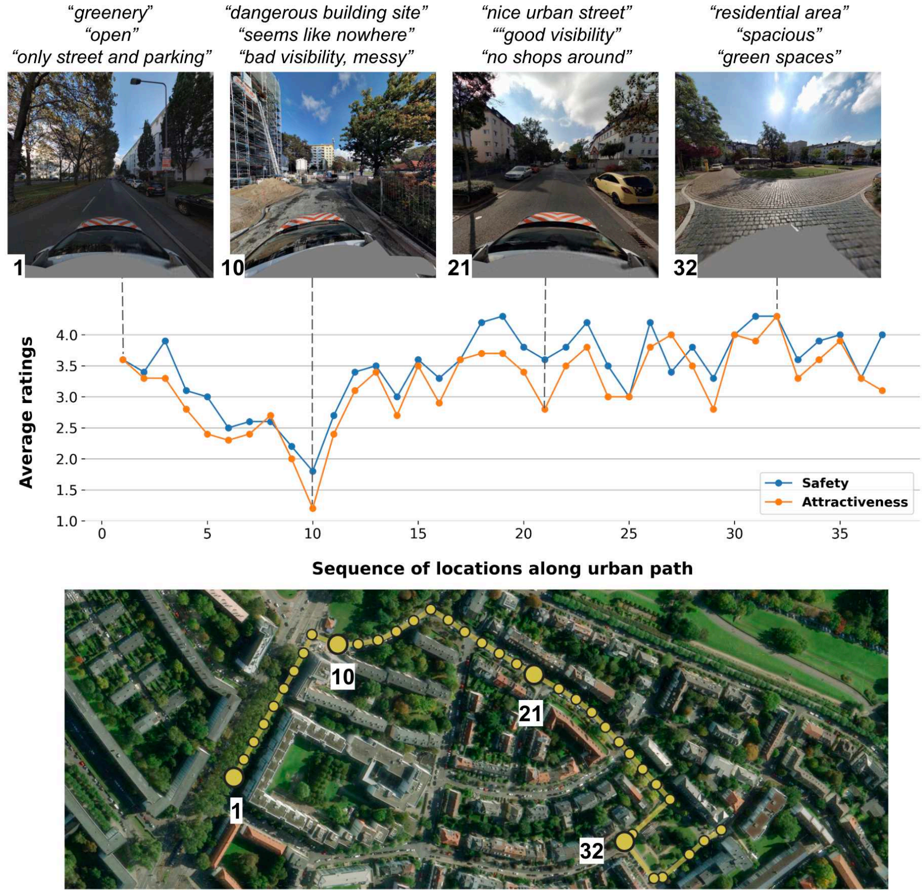


Figure 4.6.: Indicative example of the perceived safety and attractiveness ratings of 37 locations along a path located in the Bornheim/Ostend district of Frankfurt, Germany.

The largest differences between the safety ratings of two consecutive locations range from 1.6 to 1.9 and are often explained by a single infrequently observed dominant characteristic. For instance, in one situation, the relatively high difference in the ratings was explained by the construction work that occurred when the pictures were taken. The participants described the first location (example A, location I in Fig. 4.7) as "*openness*", "*nice houses*", and "*good looking*" and the next (example A, location II in Fig. 4.7) as "*roadworks*", "*looks very dodgy, doesn't feel good*", and "*barriers and building materials in road, iron railings and barriers*". In another example, the first location is under a bridge (example B, location I in Fig. 4.7), received an average safety rating of 1.4, and participants described it as "*dark*", "*hidden*", "*sketchy*", and "*dangerous*". The next location (example B, location II in Fig. 4.7), located 20 meters away and shortly after the bridge, received a rating of 3.5 and was described as "*close to the public area*", "*well organised*", and "*well lit*". In most cases for which consecutive locations received ratings of a relatively high difference the comments of the participants revolve around a single dominant characteristic that made them suddenly feel unsafe (e.g., construction work, being under the bridge, graffiti, iron bars on windows).

Regarding the difference between the attractiveness ratings of consecutive locations, the results are similar to the ones about safety perception. In particular, this difference is less than 0.5 for 76% of the locations and less than 1 for 95% of the locations. The farther apart two locations are located, the more likely the attractiveness ratings are to differ (Table 4.3). Once again, to statistically evaluate our observation, we calculated Moran's I spatial autocorrelation coefficient for the attractiveness ratings and received similar results to the ones for the safety ratings: there is a strong and significant spatial autocorrelation ($I = 0.63$, $z = 18$, $p = 0.001$) that weakens as the distance between the locations we consider as neighbours increases. Therefore, as for the safety perception, the attractiveness of streets does not tend to change suddenly but rather gradually along streets. Relatively large differences in the attractiveness ratings were found only in particular situations, similar to the ones described above for safety perception.

Difference between the safety (and attractiveness) ratings of locations that are D-meters apart and located within the same path (Likert scale 1-5)

	Distance							
	20-25m		100-125m		180-225m		260-325m	
	Max. diff.	Avg. diff.	Max. diff.	Avg. diff.	Max. diff.	Avg. diff.	Max. diff.	Avg. diff.
Safety	1.9	0.25	1.8	0.47	2.5	0.47	1.9	0.51
Attr.	2.0	0.28	2.3	0.52	2.5	0.52	2.8	0.57

Table 4.3.: Maximum and average ratings' difference between locations that are located within the same path and are D-meters apart (considering all 27 paths under study).

Relationship between safety and attractiveness perception. Since the normality test we performed on both the average ratings of safety and attractiveness indicated a normal distribution we used the Pearson correlation coefficient to calculate the correlation between the average ratings of safety and attractiveness. We identified a strong positive

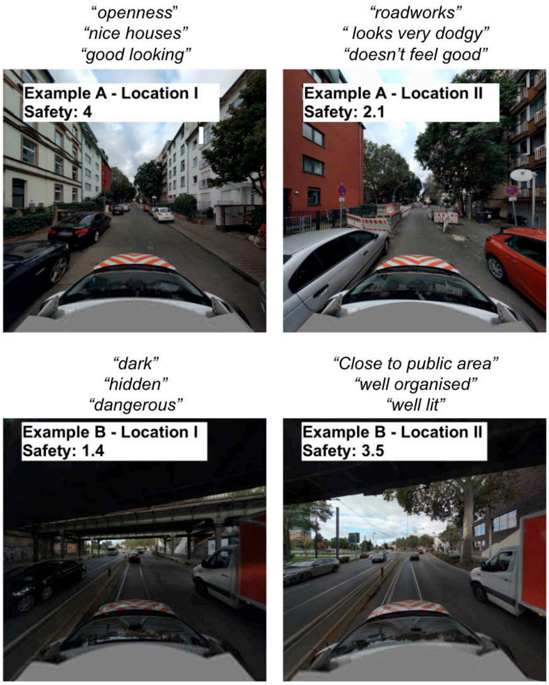


Figure 4.7.: Indicative examples of consecutive locations with average safety rating differences larger or equal than 1.9.

and statistically significant correlation between the two ($r = 0.82$, $p < 0.005$) and computed the following linear fit (with $std_{error} = 0.023$, $R^2 = 0.66$):

$$attractiveness = 0.88 * safety - 0.07 \tag{4.1}$$

The linear regression model (Fig. 4.8) suggests that, overall, participants tend to rate urban locations higher in terms of safety than attractiveness. Also, while there are no locations that are considered at the same time unsafe ($rating \leq 2.5$) and attractive ($rating \geq 3.5$), 2% of the locations are perceived as safe and unattractive. According to the participants' input, the locations that are perceived as safe and unattractive seem to be located on quiet, residential streets without shops or other types of facilities. They are often described in terms of safety as "*narrow street*","*slow traffic*", having "*people around*", "*safe*", or "*residential*" and received ratings ranging from 3.5 to 4. In terms of attractiveness, the participants continuously emphasize the lack of shops (e.g., "*no place for shops*"). In certain cases, participants also mentioned "*Not a lot to look at aside from buildings, cars and wheelie bins*" and "*Not very appealing as a place to visit or place to be*".

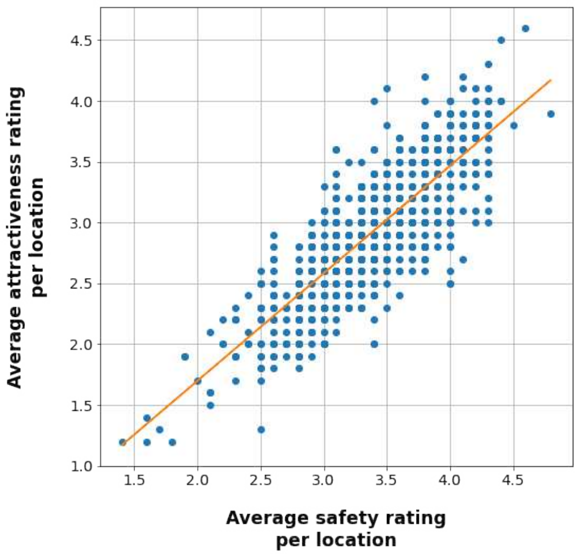


Figure 4.8.: Linear regression between the average ratings of perceived safety and attractiveness of urban locations.

4.5. Discussion

Our results highlight key similarities and differences in streetscape features that influence perceived safety and attractiveness. Furthermore, our method shows how crowdsourcing can be used to capture the elements of the built environment that influence how people perceive streets. In this section, we discuss our findings and make recommendations for the design of safer and more attractive streets that increase the probability of engaging in active travel.

Overall, our findings are consistent with previous research. According to our findings, the number of people and parked cars, the volume of traffic, and the presence of graffiti on city streets are among the factors that most frequently influence how safe a location is perceived to be, as suggested by other studies [169, 170]. We also discovered that the presence of trees or green spaces influences the attractiveness rating of streets. A number of related studies support this finding, emphasizing the link between the presence of green spaces and attractiveness levels in urban areas [171–173]. In line with Tobler's first law of geography [174], crowdsourced safety and attractiveness ratings exhibit a strong and significant spatial autocorrelation, implying that nearby locations have more in common than distant locations. This also suggests that crowdsourcing can be used as an acceptable alternative to field observations, which may be more accurate but are also more expensive and time-consuming. Looking at the relationship between the ratings of perceived safety and attractiveness, we find a statistically significant and strong correlation between the ratings of perceived safety and attractiveness, similar to the one found in previous studies [153, 161]. Specifically, our calculated linear fit ($coef = 0.88$, $R^2 = 0.66$) aligns well with [153]'s linear fit between perceived safety and pleasantness ($coef = 0.83$,

$R^2 = 0.55$).

Our findings also provide new insights not previously found in the literature. We discovered that single, negatively perceived features, such as the presence of construction sites or underpasses, outweigh any other set of features in causing the most abrupt changes in safety ratings. Given that these features are uncommon, they can easily be overlooked by computationally-driven characterizations that rely on common feature patterns. The consistently found negative impact of temporary construction sites on people's perceptions should be taken into account when managing short-term construction projects. Our analysis shows that participants' explanations for safety ratings favour elements of potential human activity over street design features. When evaluating the perceived qualities of streets, participants emphasize traffic, cars, construction sites, and the presence of people more than general aesthetics and design features such as the architecture or the colours of the buildings. Notable exceptions to this include a street's "openness" (most commonly used to describe areas with a high percentage of open public space) and lighting (e.g., dark parts of streets are always considered unsafe). Overall, participants approach the question "How safe is this place in your opinion?" by assessing either the risk of accidents (e.g., the risk of crossing the street due to traffic) or the risk of crime (e.g., it feels safer if there are people around). When asking participants about their perception of safety, it is critical that they distinguish between these two scenarios and respond accordingly. We also discovered differences in the safety ratings from various demographic groups. Female and younger participants, in particular, appear to provide less extreme ratings, rating fewer locations as (very) unsafe or (very) safe than male and older participants, respectively. However, more research is needed to determine whether the differences in perceptions observed between different groups are due to how the city streets are perceived or how different groups use the Likert scale.

Regarding attractiveness, the ratings are more dispersed along the Likert scale than the safety ratings, with a higher frequency of both low (i.e., 1-2.5) and high (3.5-5) average ratings. In other words, the perception of attractiveness tends to be more sensitive to the characteristics along the streets than the perception of safety. Once again, sudden changes are usually caused by single negatively perceived characteristics that outweigh the influence of any other characteristic (e.g., a part of the street located under a bridge or the existence of windows that are covered by iron bars). When looking at the different demographic groups in terms of gender and age, we observe that while all groups identified nearly the same percentage of locations as attractive, male and older participants rated more locations as unattractive than female and younger participants, respectively. Thus, once again our findings highlight the variations in how different demographic groups perceive the urban environment. When rating the attractiveness of city streets, participants tend to focus on either the aesthetics (e.g., describing the architecture and how the trees make the street aesthetically appealing) or the opportunities (e.g., shops and parks) that are offered along the street. In some instances, the words participants used to explain the attractiveness ratings could be interpreted both as positive and negative. Notable examples of such words are the "old", which could be positively used as "old-fashioned" or negatively as "not well maintained", and the "crowded", which could imply vibrancy or overcrowdedness. Thus, even though the text participants provided was intended to explain the ratings, the ratings occasionally allowed for a richer understanding of the text. Overall, the combination of ratings and text proved to be necessary for interpreting our results.

The statistically significant and strong correlation between the ratings of perceived safety and attractiveness highlights the high overlap among the characteristics that influence the perception of safety and attractiveness of streets. However, our findings provide additional evidence that this relation is not entirely symmetric. While we observed that all places that are considered attractive are also considered safe, the opposite is not always true (i.e., some places are considered safe but unattractive). Based on our results, this mainly occurs in quiet, strictly residential streets with few amenities or shops.

Our analysis shows that greenery and shops are important factors in making a street attractive, but we found no significant evidence, contrary to widely held assumptions, that these features also make a street feel safer. This finding should be taken into account by built-environment professionals when planning and designing for improved streetscape qualities. To further support or refute similar findings, there is a need to invest in acquiring fine-grained data that capture the perceived qualities of streets. Our results also indicated variations in how different demographic groups perceive the streets and how individuals interpret the questions they are asked. Thus, when gathering people's opinions, special care should be taken to include a demographically representative sample of participants and to ask clear, concise, and understandable questions.

4.6. Limitations

We acknowledge several limitations of this work that could be addressed in future research. First, people's perceptions of city streets rely on a range of factors that go beyond the visually observable streetscape features such as the sounds or smells along a street, people's past experiences, or their familiarity with similarly looking streets [147, 175, 176]. Thus, our work could be expanded to capture and combine additional factors. Second, the influence of streetscape features on people's perceptions could differ depending on the time of day, lighting conditions, weather, and season. Following our approach while including images that depict the streets under different conditions could allow for studying such differences. Third, studies have shown that crowdsourcing spatial information tasks often attract participants who are particularly interested in nature and landscapes [160]. To better capture the opinions of the general public there is a need for developing or combining recruiting strategies towards including a more representative set of participants. Lastly, in our work, we studied streets coming from a single city. In the future, we aim to replicate our study in different cities to further investigate the generalizability of our insights and the influence the city selection has on our results. Despite these limitations, our study provides new insights into people's perceptions of city streets and presents a replicable time and labour-efficient crowdsourcing approach that can be easily enhanced with additional data and applied in other cities.

4.7. Conclusion

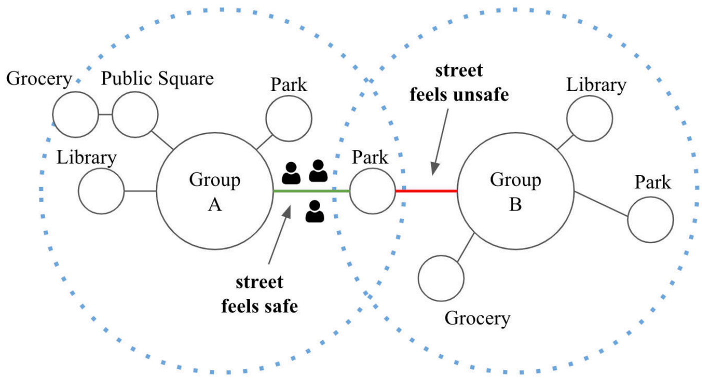
The design and structure of city streets can have a significant impact on the perceived level of safety and attractiveness. These, in turn, can encourage or discourage active travel and access to amenities, having an impact on people's well-being. Using a crowd-sourcing approach, this study adds to the body of literature on measuring urban design qualities by presenting empirically derived features that influence the perceived safety and attractiveness of city streets. Our findings suggest that the features that contribute to a street's perceived safety do not always overlap with those that contribute to its attractiveness, and vice versa. The number of people and parked cars, the volume of traffic, and the presence of graffiti all have an impact on the feeling of safety. In turn, the presence of greenery, as well as the number and type of amenities along a street, are the primary contributors to the attractiveness of a street. We also provide evidence that certain characteristics, such as underpasses and construction sites, have a negative impact on both the perceived safety and attractiveness of city streets, outweighing the influence of any other set of characteristics. Further studies of cities with varying morphological characteristics, sizes, and densities that also represent non-European contexts should be carried out in order to develop more robust and universally applicable guidelines for the design of safer and more attractive streets. Nonetheless, our work demonstrates how crowdsourcing can be useful for built-environment professionals seeking to understand the factors that influence the perceived qualities of the urban environment using a tool like the one developed in this study. It presents an interesting future research direction in the measurement of urban design qualities, which can be incorporated into evidence-informed design standards for safer and more attractive cities that promote health and well-being.

5

“Eyes on the street": Estimating perceived safety levels along city streets

The buildings on a street ... must be oriented to the street.
They cannot turn their backs or blank sides on it and leave it blind.

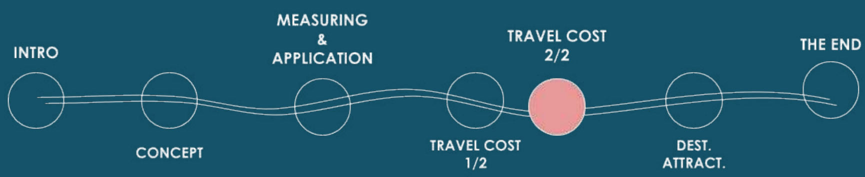
Jane Jacobs, The Death and Life of Great American Cities



Summary

Safety is considered among the primary factors that affect all age groups to walk. In this chapter, we propose a method that can be used as an estimator of how safe streets are perceived. This chapter draws from contemporary urban design guidelines that advocate urban forms that encourage natural surveillance or eyes on the street to promote community safety. We propose a method for measuring natural surveillance at scale by employing a combination of street-level imagery and computer vision techniques. We detect windows on building facades and calculate sightlines from the street level and surrounding buildings across forty neighborhoods in Amsterdam, the Netherlands. We show how perceived safety varies with window level and building distance from the street, and we find a non-linear relationship between natural surveillance and (perceived) safety.

5



*This chapter is based on a book chapter published in the book volume accompanying the 18th International Conference on Computational Urban Planning and Urban Management (CUPUM 2023) [55]

5.1. INTRODUCTION

A growing body of literature has shown that the design and structure of the built environment can influence both actual safety risks and how safety is perceived by different population groups, subsequently impacting citizens' physical and mental health and well-being [42–45]. Especially in neighborhoods where the fear of crime is disproportionate to the actual crime rates, there is evidence of significant associations with lower levels of physical activity (e.g., limited play among children and walking in older populations, or women being discouraged from using parts of the neighborhood), leading to increased levels of childhood obesity and social isolation amongst the elderly [152, 156, 177].

Design and planning approaches to community safety in urban spaces, including Newman's defensible space theory [178] and the Crime Prevention Through Environmental Design (CPTED) strategic framework [46], often advocate for neighborhoods with increased density, mixture of land uses, well-maintained walkways, and permeable street networks with high connectivity, even though there has been some recent criticism about the universality of these features in reducing actual crime risk and the fear of crime [151, 179–181]. Similar principles are also adopted by the recent United Nations' guidelines on safer cities and human settlements [49].

A common denominator across theories and design approaches aimed at improving actual and perceived safety is the provision of *natural* (or *passive*) *surveillance* in urban public spaces [46]. Originating in what Jane Jacobs referred to as "eyes on the street" [47], enhancing a neighborhood's level of natural surveillance has become a widely adopted design guideline towards safer urban environments [48, 49]. Natural surveillance is a byproduct of how citizens normally and routinely use public spaces [46]. Even though there are several factors that can influence the level of natural surveillance, it is generally assumed that characteristics such as good street lighting, abundance of unobstructed windows overlooking walkways, and more permeable streets contribute to an increased level of natural surveillance [181, 182]. However, evidence of how much of these built-environment characteristics contribute to increased natural surveillance and lead to improved perceptions of safety is still lacking. Several approaches to measuring natural surveillance have been proposed to date, ranging from collecting observations on the ground [183–185] to computational models for estimating sightlines [186, 187]. Yet, measurements across large spatial extents remain a challenge even for computational approaches, primarily due to the subjective nature of surveillance and the lack of relevant fine-grained data.

This chapter addresses these knowledge gaps, first, by introducing a method for measuring natural surveillance at scale using street-level imagery and computer vision techniques and, second, by providing evidence of a non-linear relationship between natural surveillance and (perceived) safety. We collect and analyze street-level imagery along all street segments across 40 neighborhoods in the city of Amsterdam, the Netherlands. Unlike related approaches that use generic proxies of visibility such as the distance between buildings [186, 188], street-level imagery gives us the opportunity to capture built-environment features that can affect natural surveillance, such as the location of windows on a building facade and any visibility blockages by fences or vegetation.

We extract these features with geolocalization and computer vision (i.e., facade labeling) techniques. We calculate sightlines from the windows to each street and vice versa, as well as the windows of surrounding buildings, using the extracted features. Drawing on the work of [185] and [187], we calculate two types of surveillance for each street segment: (1) *street surveillance*, which captures the surveillance of windows from the street level and vice versa, and (2) *occupant surveillance*, which captures the surveillance of windows from surrounding buildings. We then correlate the resulting surveillance values per street segment with publicly available data on (perceived) safety, crime, and nuisance in Amsterdam. Our research goes beyond defining the magnitude of associations between natural surveillance and (perceived) safety by identifying street-segment surveillance threshold values above which the feeling of safety remains unchanged. Such evidence can have significant implications for the design of safer neighborhoods and communities.

The remainder of this chapter is structured as follows. We first present our research methods and describe the data sources, the study area, and how we calculate the sightlines and measure street and occupant surveillance. We then report the results of our analysis of Amsterdam's neighborhoods, and correlate them with the Amsterdam Safety Index. Next, we discuss the outcomes of our analysis, identify threshold values and implications for the design of safer communities. Finally, we summarize the conclusions and suggest future lines of research.

5.2. ESTIMATING NATURAL SURVEILLANCE SCORES AT A STREET-LEVEL

We estimate natural surveillance at the street-segment level considering both *street* and *occupant* surveillance. Both of these surveillance types depend on the degree to which people are able to observe the street from a specified distance; what is usually referred to as *sightline*. We group sightlines according to three parameters. The first parameter is based on the assumption that surveillance from ground floor windows is associated with lower levels of street crime than surveillance from upper floor windows, which is supported by previous research [184]. We group sightlines based on their altitude a_{max} to study the impact surveillance from different window levels has on street safety. Assuming that each building story is approximately $3m$ high, the value of a_{max} for first-floor windows is $3m$, for first and second-floor windows it is $6m$, and for first, second, and third-floor windows it is $9m$. Second, existing literature indicates that the most reliable distance to observe and interpret an event is $15m$ [187, 189, 190]. Furthermore, events witnessed from a 43-meter distance produce weak but reliable eyewitness accounts. Therefore, we divide sightlines into two types: those with $d_{max} \leq 15m$ and those with $d_{max} \leq 43m$. Finally, we define an angle θ_{fov} as the field of view visible through a window. Outside of this field of view, sightlines are excluded.

DETECTION AND GEOLOCALIZATION OF WINDOWS

The first step in the calculation of sightlines is the detection of windows on building facades along streets. We collect street-level imagery along the streets of interest and detect windows using the facade labeling algorithm developed by [191]. The algorithm detects a set of four key-points (i.e., top-left, bottom-left, bottom-right, and top-right) using 2D heatmaps. Then, it links them together using a neural network trained on labeled images with varying facade structures, viewing angles, lighting, and occlusion conditions. Following this, we calculate the geolocation of each detected window by using and adapting the geolocalization algorithm that was originally developed in [192] and later modified in [193]. For each of the detected windows, this process calculates the latitude, longitude, and altitude of the four key-points in the street-level images (Fig. 5.1). We then compute the center-point and store it as the window's geolocation.

Figure 5.1.: Indicative outputs of the facade labeling algorithm developed by [191] on street-level images collected in Amsterdam.

STREET AND OCCUPANT SURVEILLANCE

To calculate *street surveillance*, we count all sightlines that have as a starting point the windows with an altitude lower than a_{max} and as an endpoint the location of the street-car camera, with a length lower than d_{max}. The number of these sightlines reflect the number of windows that have unobstructed views to points sampled across the street network (i.e., every $10m$). Regarding *occupant surveillance*, we calculate for each window the number of neighboring windows that have an unobstructed view (i.e., sightline) to it. Specifically, for each detected window $o_{viewpoint}$ with an altitude lower than a_{max}, we select all neighboring windows that have an altitude lower than a_{max} and are at a maximum distance d_{max} from each $o_{viewpoint}$. Next, we calculate all sightlines from the neighboring windows to the $o_{viewpoint}$ and remove the ones that are obstructed by the presence of intermediate buildings. In particular, for each sightline s, we calculate the angle θ_s between s and the building segment that contains $o_{viewpoint}$. If $\theta_s > \frac{1}{2}\theta_{fov}$, we consider s outside the field of view of the neighboring window and remove it from the set of sightlines to be considered. Due to the restriction of the sightline angle, a sightline originating from each window ($o_{viewpoint}$) to each neighboring window ($o_{neighbor}$) does not imply that the reverse also exists. By repeating these steps for each detected window, we calculate how many neighboring windows have unobstructed views to each window at hand.

To calculate the overall *natural surveillance* scores, we link all points with a street and occupant surveillance score to a given street segment q. We define a street segment as a section of the street between two junctions, or between a junction and the end of the street, if the street has a dead end. More specifically, each window is linked to the image where it was detected, and this is, in turn, linked to the corresponding street segment. We calculate the following two scores, normalized by the street segment's length:

$$S_q = \frac{1}{q_L} \sum_{i \in Pq} s_i \tag{5.1}$$

$$O_q = \frac{1}{q_L} \sum_{i \in P_q} o_i \tag{5.2}$$

where S_q and O_q respectively denote the street and occupant surveillance scores, P_q denotes the set of points linked to a street segment q, q_L is the length of street segment q in meters, and s_i and o_i denote the number of sightlines observing point i.

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We further aggregate our scores at the neighborhood level by calculating the sum of the sightlines of all points within each neighborhood, and divide it by the length of each street segment using the following formulas:

$$S_n = \frac{\sum_{i \in P_n} s_i}{\sum_{i \in Q_n} q_{Li}} \tag{5.3}$$

$$O_n = \frac{\sum_{i \in P_n} o_i}{\sum_{i \in Q_n} q_{Li}} \tag{5.4}$$

where S_n and O_n respectively denote the sum of street and occupant surveillance scores within a neighborhood n, Q_n is the set of sampled street segments within n, and P_n is the set of sampled points linked to the street segments within n. As previously stated, we further group our scores according to whether the distance between the windows and the corresponding street segment is reliable for witnessing an event ($d_{max} = 15m$) or dependable ($d_{max} = 43m$).

CORRELATION ANALYSIS

To investigate the relationship between natural surveillance and safety (both actual and perceived), we correlate the street surveillance and occupant surveillance scores with the Amsterdam Safety Index [194]. We first test the normality of the estimated natural surveillance scores using the Kolmogorov-Smirnov test, which indicated a non-normal distribution. Therefore, for each of the considered neighborhoods, we use Spearman's rank correlation coefficient (*rho*) to calculate the correlation between the natural surveillance scores and the Index's aggregate values and sub-components (i.e., crime, nuisance, and perceived safety).

5.3. DATA

We use the city of Amsterdam in the Netherlands as a case study to illustrate and validate how our method could be used to assess a neighborhood's level of natural surveillance. Amsterdam is the capital and most populated city in the Netherlands, characterized by a variety of neighborhoods with equally varying levels of reported (perceived) safety. The city combines a medieval center bustling with tourists all year round with new developments and strictly residential areas in the outskirts. A well-substantiated dataset on (perceived) safety for the entire city of Amsterdam is publicly available, making it an exemplary case to compare our measurements with real-world data on actual and perceived safety. The Amsterdam Safety Index [194] covers 104 neighborhoods in the city and is composed of three sub-components. These are, namely, the levels of *crime*, *nuisance*, and *perceived safety* in each neighborhood. The lower the index value, the safer the neighborhood is considered to be. We use OpenStreetMap (OSM), an open-source mapping platform, to collect data about the street network and the building footprints. We make use of the *OSMnx* [72] Python library to extract street network data, and the OSM *Overpass* Application Programming Interface (API) to collect the building footprints. Moreover, we used the Google Street View Static API to detect the location of windows on the building facades along the street segments. Due to budget limitations, we focused on 40 out of the 104 Amsterdam neighborhoods covered by the Safety Index. Neighborhoods were selected such that they are spatially contiguous (i.e., they share a common administrative boundary) and are characterized by a variety of safety index scores. In the final subset of 40 neighborhoods (Fig. 5.2), we collected 6,667 street segments from OSM and 109,988 street-level images from Google Street View along the street segments, with the maximum allowed resolution of 640 × 640 pixels and with orthogonal field of view and zero pitch to capture the building facades. The window detection and geo-localization algorithms provided a total of 872,360 windows, extracted with the use of the ResNet18 model for facade labeling.

5

5.4. RESULTS

This section provides an overview of the application of our method for estimating natural surveillance in Amsterdam, the Netherlands. We also present the correlation results between our measurements of street and occupant surveillance and the 2019 Amsterdam Safety Index and its sub-components, namely crime, nuisance, and perceived safety in each of the considered neighborhoods. Furthermore, we compare the influence of considering windows from different floor levels and distances from the street on indicating a neighborhood's actual and perceived safety levels.

Figure 5.3 illustrates the calculated street and occupant surveillance scores, considering windows within a distance of 43 meters from the streets and up to the first floor of the buildings, together with the overall Safety Index values of the 40 considered neighborhoods. We convert each of these scores into three categorical variables, namely, low, medium, and high, according to the tertile they belong to. This allows for easier visual comparison, given that each of the presented metrics is originally expressed in different units.

Most neighborhoods showcase consistency across the three scores, routinely result-

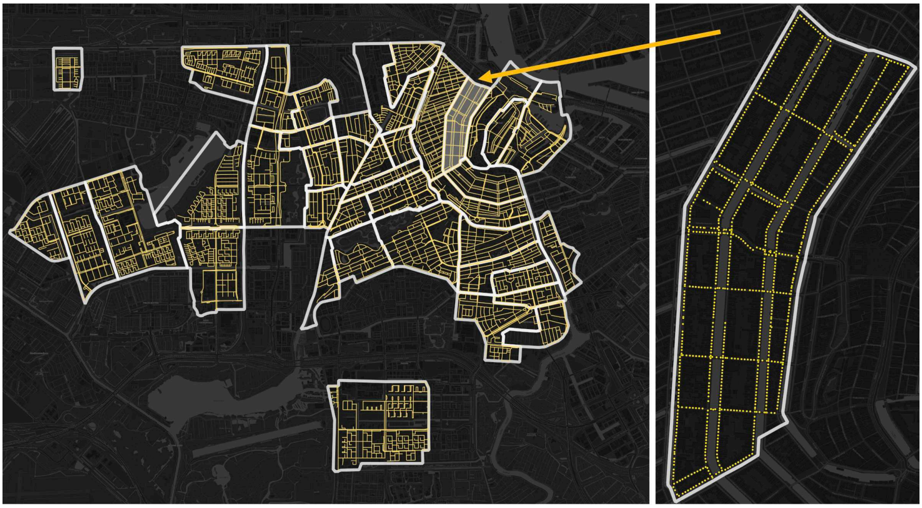


Figure 5.2.: Left: The 40 neighborhoods and their streets considered in our analysis. Right: An example of the geolocations of street-level images collected along street segments in Amsterdam's Grachtengordel-West neighborhood.

ing in high or low safety areas. Indicative examples of this include the Burgwallen-Oude Zijde (BOZ) and Burgwallen-Nieuwe Zijde (BNZ) neighborhoods, both in the historical center of Amsterdam, consistently scoring low across all metrics. Similarly, neighborhoods such as Museumkwartier (MU) and Staatsliedenbuurt (ST) consistently score among the safest. Examples of the opposite include Buitenveldert-West (BW), which scores low in terms of street surveillance, medium in occupant surveillance, and high in the Safety Index values. Figure 5.3 further zooms in on the street structure of select neighborhoods to elucidate the individual contributions of street segments to the overall street and occupant surveillance scores.

Table 5.1 shows the results of the correlation between our street and occupant surveillance scores and the Amsterdam Safety Index and its sub-components, using the Spearman's rank correlation coefficient (*rho*). Results yield a moderate negative and statistically significant correlation ($r = -0.49$, $p < .001$) between street surveillance and Safety Index values in the case of sightlines with $d_{max} = 43m$ and up to the first floor of buildings (i.e., 1F). The correlation becomes weaker when we consider sightlines from buildings within a $15m$ distance, or from higher floors. Looking at the Index's sub-components, the correlation between street surveillance and *crime* or *nuisance* also becomes weaker when we consider sightlines originating from floors higher than the first. Also, street surveillance scores generally present strong negative correlations with *perceived safety* values, with sightlines of 15-meter length yielding the strongest results. The correlations of occupant surveillance scores with the Safety Index and its sub-components are generally weaker in comparison with their street surveillance counterparts. The occupant surveillance scores have the highest correlation with the average Safety Index values ($r = 0.34$).

Figure 5.3.: (A) Street surveillance scores; (B) Occupant surveillance scores; (C) Amsterdam Safety Index values for the 40 considered Amsterdam neighborhoods, classified into tertiles.

Correlations of street and occupant surveillance with the Amsterdam Safety Index							
Index and sub-components	**Maximum sightline length**						
	15m (reliable)			43m (dependable)			None
	Included floors						
	1F	≤2F	≤3F	1F	≤2F	≤3F	All
Street surveillance							
Safety Index	-0.45 **	-0.38*	-0.39*	**-0.49****	-0.42**	-0.40*	-0.45**
Crime	-0.34*	-0.30	-0.31	**-0.40***	-0.37*	-0.34*	-0.33*
Nuisance	-0.23	-0.18	-0.15	**-0.29**	-0.21	-0.18	-0.27
Perceived Safety	**-0.48****	-0.43**	-0.44**	-0.45**	-0.36*	-0.38*	-0.43**
Occupant surveillance							
Safety Index	-0.34*	-0.38*	-0.39*	-0.40*	**-0.41***	-0.38*	
Crime	-0.23	-0.33*	-0.34*	-0.31*	**-0.35***	-0.31	
Nuisance	-0.25	-0.22	-0.20	**-0.32***	-0.24	-0.19	
Perceived Safety	**-0.36***	-0.35*	**-0.36***	-0.32**	-0.33*	-0.35*	

Table 5.1.: Spearman correlations of the street and occupant surveillance scores with the 2019 Amsterdam Safety Index.
* = $p <= .05$, ** = $p <= .01$

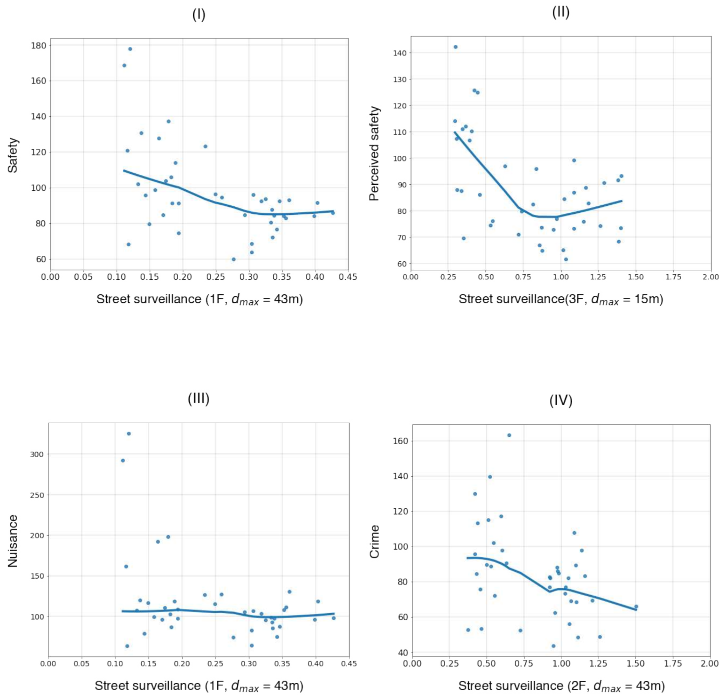


Figure 5.4.: Scatter plots and corresponding trendlines depicting the relationship between estimated street surveillance scores and the Amsterdam Safety Index (I) and its sub-components: perceived safety (II); nuisance (III); crime (IV).

The use of a locally weighted scatter plot smoothing (LOWESS) regression to examine the linearity of the relationship between the different scores, as shown in Fig. 5.4, provides additional insight into the correlations. Specifically, the comparison of the street surveillance scores with the overall Safety Index (Panel I) and the perceived safety sub-component (Panel II) yields an interesting non-linear pattern. We observe that as the street surveillance score increases, the trendline becomes relatively horizontal from a certain point onward. This suggests that even though an increased level of street surveillance is generally associated with higher safety — either actual or perceived — this association becomes weaker after a certain value (approximately 0.3 for safety and 0.8 for perceived safety). However, this does not seem to be the case when it comes to the association of street surveillance with the levels of nuisance (Panel III) and crime (Panel IV). The corresponding scatter plots and trendlines do not indicate any particular pattern.

5.5. DISCUSSION

The application of our method in several neighborhoods in Amsterdam demonstrates that the combination of street-level imagery with computer vision techniques offers a promising approach to measuring natural surveillance across large spatial extents. As such, it can provide a pathway to integrate the widely advocated, yet difficult to capture, notion of "eyes on the street" into the planning and design for safer neighborhoods. We also show that different aspects of surveillance (i.e., street or occupant-based) have varying contributions to a neighborhood's overall level of safety and elicit interesting non-linear relationships.

Our results suggest an overall significant negative correlation between our average natural surveillance scores and the Safety Index. Given that lower Index values indicate safer neighborhoods, an increased level of natural surveillance correspondingly indicates a safer neighborhood. This aligns with related expectations from the CPTED literature [46, 195]. We specifically detect stronger correlations between street surveillance scores and the Safety Index, whereas the correlations with occupant surveillance scores appear weaker. This suggests that the degree of street visibility from surrounding windows is a stronger predictor of a street's level of natural surveillance compared to window visibility from surrounding buildings.

Our analysis also uncovers aspects of natural surveillance that have largely been overlooked in the existing evidence base. Our findings, in particular, support our hypothesis that window levels and the distance of buildings from the street influence how natural surveillance correlates with overall safety. However, variations do exist between the two different facets of natural surveillance. Specifically, street visibility (i.e., street surveillance) from first-floor windows correlates most with the average values of the Safety Index and this association becomes stronger as the distance from the street increases. This appears to be less the case when it comes to the visibility of windows from surrounding buildings (i.e., occupant surveillance). We also observe a strong correlation between street surveillance and perceived safety. The consideration of different floor levels barely influences this correlation. However, the distance of the windows from the street does influence this association, with windows closer to the street (i.e., sightlines with a length of 15m) leading to stronger correlations.

The overall strong association between street surveillance and perceived safety would generally suggest that the higher the level of street surveillance, the more it would correlate with an increased perception of safety. However, our analysis of linearity indicates a natural surveillance threshold value above which the level of perceived safety remains relatively stable. Fig. 5.4 (Panel I) shows that street segments with street surveillance score up to 0.3 — this corresponds to an average of three windows overlooking a 10-meter-long street segment — accordingly lead to a gradually increasing level of neighborhood safety. However, street surveillance scores of 0.3 and above do not lead to any increases in the overall level of safety. Fig. 5.5 provides indicative examples of streets with street surveillance scores of 0, 0.15, 0.3, and 0.7 to showcase what streets of low or high street surveillance are like. This result provides an interesting insight into *how much* and *what kinds* of street features lead to increased (feelings of) safety and requires further research in different urban environments.

There are several limitations in this study that could be addressed in future research. First, our method depends on how well windows are depicted in street-level imagery. Some windows, however, are excluded from the street-level images either due to a lack of imagery along certain street segments or because the view from the street to the window is obstructed (e.g., by a tree). Second, the facade labeling algorithm used for window detection is occasionally inaccurate. Indicative inaccuracies include windows that are in shadow or with occluded openings, as well as storefront windows that may go undetected by the algorithm because it was trained on images of residential buildings [191]. Nonetheless, the facade labeling algorithm we used was tested on several datasets of building facade images and achieved a pixel accuracy of 90% on average [196–198]. Third, the geolocalization algorithm can introduce errors (namely, mean error of $1.07m$ and standard deviation of $1.09m$), the most significant of which are caused by inaccurate GPS metadata in street-level images. Fourth, natural surveillance is a broad concept that encompasses more than window-based surveillance. In fact, active street observation is largely dependent on residents' time, willingness, and capacity to watch and defend their streets and communities [181]. Therefore, our research could be expanded to take into account other factors that influence natural surveillance, such as citizens' daily activity patterns, time of day, or street lighting quality. Lastly, we only tested and evaluated our method in a few Amsterdam neighborhoods. For this reason, we intend to broaden the applicability of our method by implementing it in other cities.

5

5.6. CONCLUSION

Natural surveillance has drawn a lot of interest and is now a crucial component of design strategies aimed at improving actual and perceived safety in urban spaces. This chapter introduced a method for measuring natural surveillance at scale by leveraging a combination of street-level imagery and computer vision techniques. Our work has practical value for built-environment professionals who seek to understand and improve the levels of actual and perceived safety in urban neighborhoods. Specifically, our method draws on the new possibilities offered by street-level imagery in capturing built-environment features, such as the location of windows and any visibility blockages that have been shown to affect natural surveillance. It also employs geolocalization and facade labeling

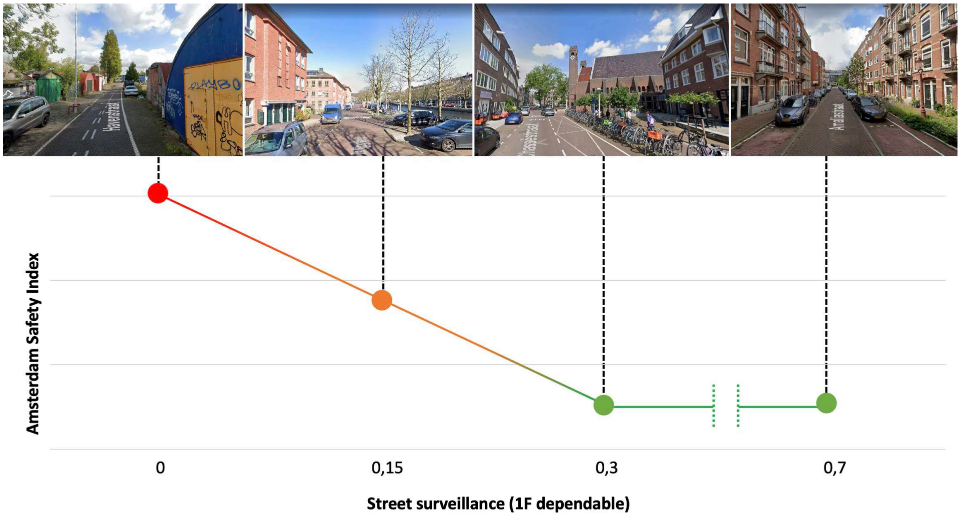


Figure 5.5.: A selection of Amsterdam streets, along with their street surveillance scores (1F reliable). Streets included in the figure, from left to right: Havenstraat, De Rijpgracht, Chasséstraat and Amaliastraat. As the street surveillance score rises to 0.3, neighborhoods feel safer. An increase to 0.7 does not appear to be associated with increased (perceived) safety.

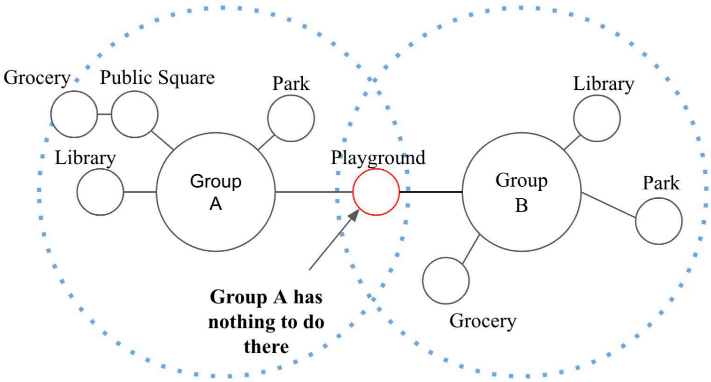
techniques to estimate the surveillance of windows from the street level and surrounding buildings across large spatial extents. We applied our method in neighborhoods of Amsterdam and correlated our measurements with various components comprising the city's Safety Index to validate its use as an estimator of neighborhood safety. Our analysis showcased that our method can be a promising and scalable alternative to the manual collection of observations around aspects of natural surveillance. Our results align with existing evidence from the CPTED literature and suggest that surveillance of windows from the street contributes more to the overall safety than surrounding buildings. Moreover, the window level and distance of buildings from the street appear to have varying influences on the feeling of safety. Another intriguing finding from our analysis is the identification of a natural surveillance threshold point, with scores above it not resulting in increased (perceived) safety. However, more research in different urban settings is required to provide more evidence of this. In particular, it presents an interesting avenue of future research in the fields of environmental criminology and next-generation CPTED [199] that can contribute to an improved understanding of what kinds of built-environment characteristics lead to increased (feelings of) safety.

6

EXPLORING THE INFLUENCE OF PHYSICAL FEATURES ON THE LIKELY USE OF PUBLIC OPEN SPACES

One is always wrong; but with two, truth begins.
One cannot prove his case, but two are already irrefutable.

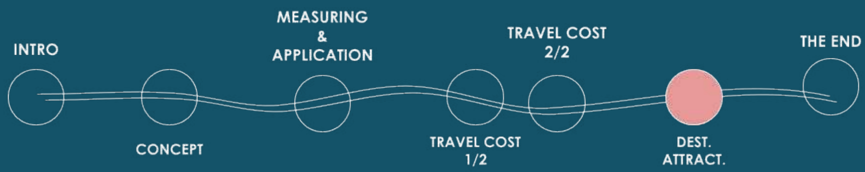
Friedrich Nietzsche, The Gay Science, 1882



Summary

In this chapter, we focus on understanding how the physical characteristics of urban locations impact the *destination attractiveness* component of co-accessibility. To do so, we focus on public open spaces. Public open spaces are an essential component of every city. When designed to appeal to a variety of individuals and demographic groups, they witness a high frequency of use, accommodating a multitude of activities, thereby serving as hubs of social interaction and activity. In this chapter, we study how the physical characteristics of public open spaces influence the likelihood of use across individuals and different age and gender groups by combining crowdsourcing, street-level images, statistical comparisons, and reflexive thematic analysis. Our findings allow us to gain an improved understanding of how a space's physical characteristics can impact the degree to which different people and groups are likely to perform activities there and, consequently, the co-accessibility of such spaces.

6



*This chapter is based on a journal article published in *Computational Urban Science*

6.1. INTRODUCTION

Public open spaces, such as public squares, greenspaces, and streets, constitute a fundamental part of every city where different people can perform a wide range of activities. In this work, “public open space" refers to spaces open to the general public, located outdoors, and typically owned by governmental authorities or organizations.

Various factors could impact how likely individuals are to engage in specific activities in public open spaces, with physical features playing a significant role [15, 47, 200]. Physical characteristics include the size of the space, the presence of seating, the abundance of amenities, and the presence of natural elements such as trees, grass, or water bodies. Such characteristics influence how frequently public open spaces are used and shape their capacity to serve as hubs for social interaction and for engaging in different activities [144, 146, 201–207]. For instance, narrower streets with various amenities, wider sidewalks, and the availability of street furniture along sidewalks have been identified to encourage social interactions [146]. Similarly, the size of greenspaces has been found to influence the range of activities conducted within them. Larger greenspaces are often deemed more suitable for physical activities, while smaller ones are considered preferable for socializing and relaxation [208, 209].

Additionally, the preferences of different population groups may lead to varied choices in using public open spaces for specific activities [210–212]. For example, research reveals that older individuals and women may perceive fewer spaces as suitable for exercise compared to men and younger adults [44]. Seniors and women have also reported feeling vulnerable and having greater security concerns when walking [171]. The importance of creating spaces that cater to the diverse preferences of various population groups is widely recognized [144, 146, 201–203], as emphasized by the United Nations Sustainable Development Target 11.7 [40], which underscores the necessity for inclusive spaces designed to accommodate everyone, with specific attention to the needs of women, children, and older individuals.

To comprehend how the physical attributes of public open spaces influence their use, researchers have employed various methods such as participant observation [144, 146, 157, 210], (online) questionnaires [213–215], or crowdsourcing approaches [142, 161]. Often, these studies are focused on specific activities like exercising or walking [216, 217], particular demographic groups such as the elderly [218] or children [219], or on specific qualities of a space like perceived safety or attractiveness for performing activities [142]. Nonetheless, our understanding of how the physical characteristics of public open spaces affect the suitability of various types of spaces for different activities, and the extent to which this suitability varies among different population groups, remains limited.

In this Chapter, we employ a crowdsourcing approach to explore how physical characteristics of public open spaces influence the likelihood of their utilization among individuals of various ages and genders. We recruit 409 participants from 21 European countries in a thorough examination of people’s propensity to use public open spaces. To ensure a broad range of physical characteristics, we select various public open spaces such as public squares, open marketplaces, greenspaces, pocket parks, play spaces, and streets, sourced from three European cities: Rotterdam, Barcelona, and Gothenburg. We formulate three hypotheses and subject them to statistical testing: (H1) The likely use of public open spaces varies significantly by place type (e.g., parks, squares, streets); (H2) The likely use of public open spaces varies significantly across age groups; and (H3) The likely use of public open spaces varies significantly across gender groups. Subsequently, guided by the outcomes of the statistical analyses, we pinpoint cases where noteworthy differences were observed. For these instances, we employ reflexive thematic analysis to qualitatively assess the characteristics of public open spaces mentioned by participants as reasons for the identified disparities.

In our approach, the collected ratings serve as a proxy for the probable use of space, indicating the likelihood that individuals would engage in activities there. By focusing on the likelihood of space usage rather than the observed behavior (i.e., real activities undertaken by people), we can account for factors unrelated to the physical characteristics of spaces that might discourage individuals from engaging in activities, such as not residing in close proximity [201]. Additionally, in contrast to conventional data collection approaches, such as participant observations or interviews, crowdsourcing serves as a time and resource-efficient method, allowing for the comprehensive study of various public open spaces and the recruitment of a diverse sample of participants in terms of age and gender.

The remainder of this Chapter is organized as follows. First, we explain our approach to capturing the likely use of public open spaces. Then, we describe the statistical tests conducted to scrutinize our hypotheses and how we qualitatively analyzed the collected data to identify the physical characteristics that influence the likely use of public open spaces. Next, we detail the data sources used in our empirical analysis and provide information about the participants of our study. Finally, we report the results of our study and discuss the empirical findings, implications, and limitations of our approach, as well as future lines of research.

6.2. METHOD

Our methodology consists of four main steps: (1) sampling a variety of public open spaces in three European cities, (2) crowdsourcing the types of likely use, (3) testing three hypotheses using statistical methods, and (4) qualitatively exploring the physical characteristics of public open spaces that affect their use.

6.2.1. SELECTING PUBLIC OPEN SPACES

We select public open spaces in three European cities: Barcelona (Spain), Rotterdam (Netherlands), and Gothenburg (Sweden). These cities represent urban environments in the Southern, Western, and Northern European regions. Consequently, our selection includes a wide range of spaces, enriching our study with a diverse set of spaces' physical characteristics and types.

The public open spaces included in this study were collected from OpenStreetMap (OSM) using the Overpass API and the OSMnx Python library [72]. OSM represents the physical features of the environment using tags. To ensure a broad range of public open spaces we selected a variety of tags from OSM. We identified OSM tags related to public open spaces which reflect three main types of spaces: (1) vegetated spaces such as parks or forests, (2) play spaces dedicated to children's activities such as playgrounds, and (3) other public open spaces such as squares and marketplaces. Since the tags related to the vegetated spaces encompass very different sizes of spaces, in accordance with recommendations by the [220], as well as the European Common Indicator for greenspace accessibility [221], we divided vegetated spaces into two types: greenspaces that are larger than 0.5 hectares, such as parks, forests, and nature reserves; and pocket parks that reflect the vegetated spaces that are up to 0.5 hectares. Additionally, given that streets reflect the largest portion of public open space in every city, we also collected streets that are accessible to pedestrians.

After defining these OSM tags, we collected all the spaces that fell under at least one of these five tags for all three case-study cities. Then, we investigated the spaces' representation in Google Street-View. Using Google's Street View Static API, we identified the spaces for which there is a street-level image within no more than 15 meters, a reliable distance to observe and interpret an event according to [222]. Ultimately, we randomly sampled 420 public open spaces (140 per city), balanced in terms of OSM type. We then manually examined their street-level images and excluded spaces with images of poor quality, shot during nighttime, or not accurately representing the public open space because other urban objects obstructed the view (e.g., hedges or fences), and replaced these with other randomly sampled locations of the same type until all street-level images passed the test. In case a place is located in direct vicinity to multiple types (e.g., a public square located within a park), we assign it to both types. Table 6.1 summarizes the types of public open spaces included in this study along with the number of collected spaces per type and city, and the tags used to collect them from OSM.

6.2.2. CAPTURING THE LIKELY USE OF PUBLIC OPEN SPACES THROUGH CROWDSOURCING

To collect information about how people of different ages and genders are likely to use public open spaces, we follow a crowdsourcing approach and use street-level images. Street-level imagery allows us to visually present the physical characteristics of spaces that potentially influence their use, such as seating, amenities, and trees.

Regarding the likely use of public open spaces, we focus on the following five types of activities: socializing, relaxing, exercising, commuting, and children-related activities. The selection of the activities considered in this work is aligned with and supported by [223] and [224], and aims to encompass a variety of activities that different individuals perform in public open spaces. In our experiments, we present to participants five different spaces and ask them to indicate to what degree, and why, they consider them suitable for any of the aforementioned activities.

Our crowdsourcing campaign is implemented using the cloud-based research platform Qualtrics. The crowdsourcing task consists of four steps and requires 15 to 20 minutes to be completed. First, we inform the participant about the task and ask for their consent to participate. Second, we ask the participant their age and self-reported gender. The third step consists of the main crowdsourcing task, as illustrated in Fig. 6.1. In this task, we initially show the participant a public open space represented as a 360° panoramic image and give them some time to pan around the image. Afterwards, drawing from the work of [223] and [224], we ask them to rate, on a 5-point Likert scale, if they find this place suitable for social, physical, relaxation, commuting, or children's activities, and explain in their own words what characteristics influenced their ratings. We repeat this question for five different public open spaces. In the fourth step, we ask participants how important it is for them to have a space near their home where they can carry out these activities.

We recruited participants using the Prolific platform. In total, we recruited 420 participants, evenly distributed across gender groups, as well as age groups categorized by decades (i.e., 18-30, 30-40, 40-50, 50-60, 60+). We selected participants based on the following criteria. First, we only allowed participation through a laptop or desktop. Second, to ensure a similar level of familiarity with the shown spaces we only recruited participants residing in Europe. In addition, we ensured that people have not visited the shown spaces in real life, through a question we included in our crowdsourcing task. Third, we selected participants only if they had a high approval rate, based on the previous tasks they had contributed to. Fourth, we only selected participants who are proficient in English. All participants were above 18 years old, provided informed consent to participate, and were compensated according to the minimum wage in [country hidden for anonymity due to the blind review process].

	Would you use this place for..?					What characteristics of the place made you decide this?
	Never	Rarely	Sometimes	Often	Always	Explain in a few words (at least 2/5)
How suitable do you find this place **for children's activities** (e.g., playing outdoors)	○	○	○	○	○	
Would you use this place **for social activities** (e.g., picnics, meeting friends or others)	○	○	○	○	○	
Would you use this place **to walk or bike to destinations** (e.g., to work or school)	○	○	○	○	○	
Would you use this place **for physical activities** (e.g., sports, walking or biking for fun)	○	○	○	○	○	
Would you use this place **for relaxation** (e.g., reading, simply doing nothing)	○	○	○	○	○	

Figure 6.1.: Main crowdsourcing task: participants first explore a public open space, represented as a 360° panoramic image, and then provide answers regarding the activities they would perform in that space

To ensure adequate quality of collected responses, we only kept responses from participants who passed a reCAPTCHA bot test, answered correctly to a simple attention check, and clicked at least four times inside the 360° images, as a proxy for panning around in the panoramic image. For each iteration, we ensured that the questions were displayed in a randomized order, and that the locations were selected at random from all public open spaces within one of the case-study cities.

6.2.3. HYPOTHESES TESTING

After the crowdsourcing task, we have a set of spaces accompanied by the participants' ratings reflecting how suitable these spaces are for social, relaxation, physical, commuting, or children's activities (Fig. 6.1). We use this information to examine how the characteristics of public open spaces influence how likely people are to perform activities there and the degree to which this varies among different age and gender groups. In particular, we formulate three hypotheses:

- **(H1)** *The likely use of public open spaces varies significantly by place type*
- **(H2)** *The likely use of public open spaces varies significantly across age groups*
- **(H3)** *The likely use of public open spaces varies significantly across gender groups*

With the first hypothesis, we explore the variation in the use of public open spaces based on their types, to examine queries such as: Does the likelihood of using a greenspace, public square, or pocket park for activities like socializing or exercise remain consistent, or do certain types of public open spaces naturally encourage specific activities more than others? With the second hypothesis, we examine whether there are variations in the likely use of public open spaces among different age groups, for instance: To what extent do younger adults consider the same spaces suitable for socializing or relaxing as older adults. With the third hypothesis, we investigate whether the likely use of public open spaces varies among different genders.

We test these hypotheses using the ratings provided by the participants (i.e., 5-point Likert scale ratings). For *H1*, we aggregate all ordinal ratings of each space using the median rating per activity. Therefore, each space is assigned five median ratings, one per activity-type. To test if the different types of spaces received statistically different ratings we use the Kruskal-Wallis test. The Kruskal-Wallis test is suitable for our analysis as it is a non-parametric statistical test used to detect variations among three or more independently sampled groups based on a single non-normally distributed variable. This test is often employed for ordinal data [225, 226]. We perform five Kruskal-Wallis tests and examine if the different types of spaces received significantly different ratings for each activity. To address the issue of multiple comparisons and reduce the likelihood of Type I errors, we applied the Bonferroni correction [227], setting our significance threshold to p-value=0.05/5. It's important to note that while the use of Bonferroni correction may elevate the risk of Type II errors, the decision to employ it reflects our emphasis on mitigating Type I errors, thus striving to minimize false discoveries.

For *H2*, participants' ratings were initially segmented based on age groups and then aggregated per space, again using the median value. To test *H2* we compared the spaces' ratings per activity between each pair of ages using the MannWhitney U test. The MannWhitney U test, is a non-parametric statistical method employed to detect variations between two groups on a single ordinal variable [228, 229]. For instance, we tested if the ratings of spaces for social activities differed significantly between the age groups [18-

29] and [30-39], and conducted nine additional tests to compare all age groups pairwise. This process was then repeated for other activity types. We opted for pairwise tests using the MannWhitney U test instead of simultaneously testing all age groups (e.g., using the Kruskal-Wallis test), due to the insufficient number of spaces for which we obtained ratings from all age groups, limiting statistical comparisons. Thus, for each activity, we performed ten pairwise comparisons (five age groups compared with each other), resulting in fifty tests across all five activities. To address the issue of multiple comparisons, we adjusted our significance threshold using the Bonferroni correction, setting the p-value to 0.05/50.

For *H3*, participants' ratings were first divided based on gender groups and then aggregated per space, employing the median value. Similar to *H1*, to test *H3* we compared the ratings of spaces per activity between genders using the MannWhitney U test. As our participant pool included two gender groups and five activities, we conducted one test per activity to assess differences between the two groups, totaling 5 tests. Once again, to address multiple comparisons, we employed the Bonferroni correction, setting the p-value to 0.05/5.

For *H2* and *H3*, participants' ratings were first segmented based on age or gender groups and then aggregated per space, using the median value. To test *H2* and *H3*, we compared the ratings of space per activity between every pair of age or gender groups using the MannWhitney U test. For instance, we assessed whether the ratings of spaces for social activities differed statistically between the age groups [18-29] and [30-39], and conducted nine additional tests to compare all age groups with each other. This process was then repeated for other activity types. We opted for pairwise tests using MannWhitney U test instead of simultaneously testing all age groups, because the number of spaces for which we received ratings from all age groups was insufficient to facilitate statistical comparisons.

6.2.4. Thematic analysis

To provide further insight into our quantitative results, we qualitatively explore the reasons individual participants provide to explain their ratings. Specifically, we focus on the cases for which we find significant differences in the likely use of public open spaces, whether those pertain to the types of space (H1) or to the demographic groups (H2, H3). We employ reflexive thematic analysis [230], using iterative inductive coding followed by identifying common themes, and document our analysis in Atlas TI.

6.3. Results

6.3.1. Descriptive statistics on participants and spaces

Among all recruited participants, 409 participants met our quality standards as described in 6.2.2. These 409 participants completed our task in March - May 2023 and reside in 21 different European countries. The duration for participants to complete their task varied between 15 and 20 minutes. Participants were evenly distributed across age groups categorized by decades with 80-82 participants per group (i.e., 18-30, 30-40, 40-50, 50-60, and 60+). Similarly, they were evenly spread among genders, including only female and male groups since most participants self-identified as such and we did not have enough data to perform statistical analyses on the other gender groups. Following the exclusion of data due to technical issues (such as delayed panorama loading) or in cases where participants showed no interaction with the panorama (i.e., no clicks to pan or zoom), 413 places were included in this study, representing 102 public squares and marketplaces, 107 streets, 114 greenspaces, 91 pocket parks, and 84 play spaces (Table 6.1). Each participant provided input for five different public open spaces, resulting in 9700 ratings and 6388 short explanations of these ratings.

All participants stated that they found the task clear, 93% stated they turned the 360 images to look around as requested, and 95% answered that they were not familiar with the spaces they were asked to rate, as planned. For most participants (> 70%), having space for nearly all activities is considered *important* or *very important*. Exceptions are observed for social and children-related activities. Having access to space for social activities is deemed *(very) important* by 60.8% of respondents, while 10.5% consider it *not important (at all)*. Moreover, having space for children-related activities is viewed as (very) important by 75.2% of participants with children, with 10.3% rating them as not important at all. Among respondents without children, such spaces are considered as (very) important by only 21.1%, while 56.5% regard them as not important at all.

Overall, participants would *often/always* use a relatively large proportion of public open spaces for commuting activities (41.4% of spaces), a smaller proportion for physical and children-related activities (≈ 20%), regardless of whether considering participants with or without children, and an even smaller for social and relaxation activities (≈ 12%).

6

6.3.2. HYPOTHESES TESTING

In this section, we present the results of our three hypotheses. In case the hypotheses are accepted, we perform exploratory analyses to gain deeper insights into the identified statistical differences.

H1: THE LIKELY USE OF PUBLIC OPEN SPACES VARIES SIGNIFICANTLY BY PLACE TYPE

Overview: With this hypothesis, we examine if the activities people would perform in a given public open space vary per type of space (e.g., public square, greenspace, street). To test our hypothesis, we perform five Kruskal-Wallis tests, one for each activity-type (i.e., social, relaxation, physical, commuting, children-related). For each activity, we test if participants' ratings are significantly different for different types of public open spaces.

Result: H1 was accepted for social ($p = 3.32 \times 10^{-11}$), relaxation($p = 5.04 \times 10^{-11}$), physical ($p = 2.71 \times 10^{-10}$), and children-related activities ($p = 1.26 \times 10^{-26}$). However, it was rejected for commuting activities ($p = 5.90 \times 10^{-1}$). In other words, the degree to which people are likely to use a space for social, relaxation, physical, or children-related activities varies for different types of public open spaces. For commuting activities, we did not find evidence for such variation.

Exploratory Analysis: Based on our results, we further explore (1) which types of spaces

Public Open Spaces						
Category	**Examples**	**OSM Tags**	**RTM**	**BAR**	**GOT**	**TOTAL**
Greenspaces	Parks, nature reserves, forests (larger than 0.5 hectares)	**leisure**:park|nature_reserve, **landuse**:meadow|grass |village_green|forest, **natural**:wood|scrub|heath| grassland|fell|shrubbery	37	42	35	114
Pocket parks	Parks, nature reserves (up to 0.5 hectares)	Same tags as for greenspaces	31	30	30	91
Play spaces	Playgrounds	**leisure**:playground|schoolyard (access!=private)	28	29	27	84
Public squares & marketplaces	Open public squares, open marketplaces	**place**:square, **amenity**:marketplace, **leisure**:common	30	44	28	102
Streets	Streets accessible to pedestrians	network_type=walk (OSMnx)	37	38	31	107

Activities	
Type	**Examples**
Socializing	Picnics, meeting friends or others
Relaxing	Reading, or simply do nothing
Exercising	Doing physical activities such as sports, walking/biking for fun
Commuting	Walk or bike to destinations
Children-related	Activities for children such as playing outdoors

Table 6.1.: Types of public open spaces, OSM tags used, number of collected spaces per type and city (Rotterdam (RTM), Barcelona (BAR), Gothenburg (GOT)), and examples of the activities examined

would participants more often use for social, relaxation, physical, or children-related activities (Fig. 6.2) and (2) what variety of activities people are likely to perform in the same space (Fig. 6.3).

Greenspaces, as illustrated in Fig. 6.2, emerge as highly favored locations for most activities. An exception to this is found for the children-related activities for which, unsurprisingly, play spaces are preferred the most. In particular, participants' ratings suggest that they would *often* use green spaces for commuting, *sometimes* for socializing, relaxing, and exercising, and *rarely/never* for children-related activities. Notably, pocket parks are less favored than greenspaces for all types of activities. Participants would *sometimes* use pocket parks for commuting and exercising and *rarely* for socializing, relaxing, and children-related activities.

Concerning public squares and marketplaces, we note that participants gave them relatively low ratings for most activities. In particular, participants would *never* or *rarely* use these spaces for relaxation or children-related activities, and would *rarely* or *sometimes* use them for social and physical activities. Public squares and marketplaces are predominantly preferred for commuting. We observe similar results for streets. Notably, streets received the lowest ratings among all types of spaces and for all activities except for commuting, for which participants would *sometimes* use them.

Finally, regarding play spaces, apart from being *often* considered to be used for

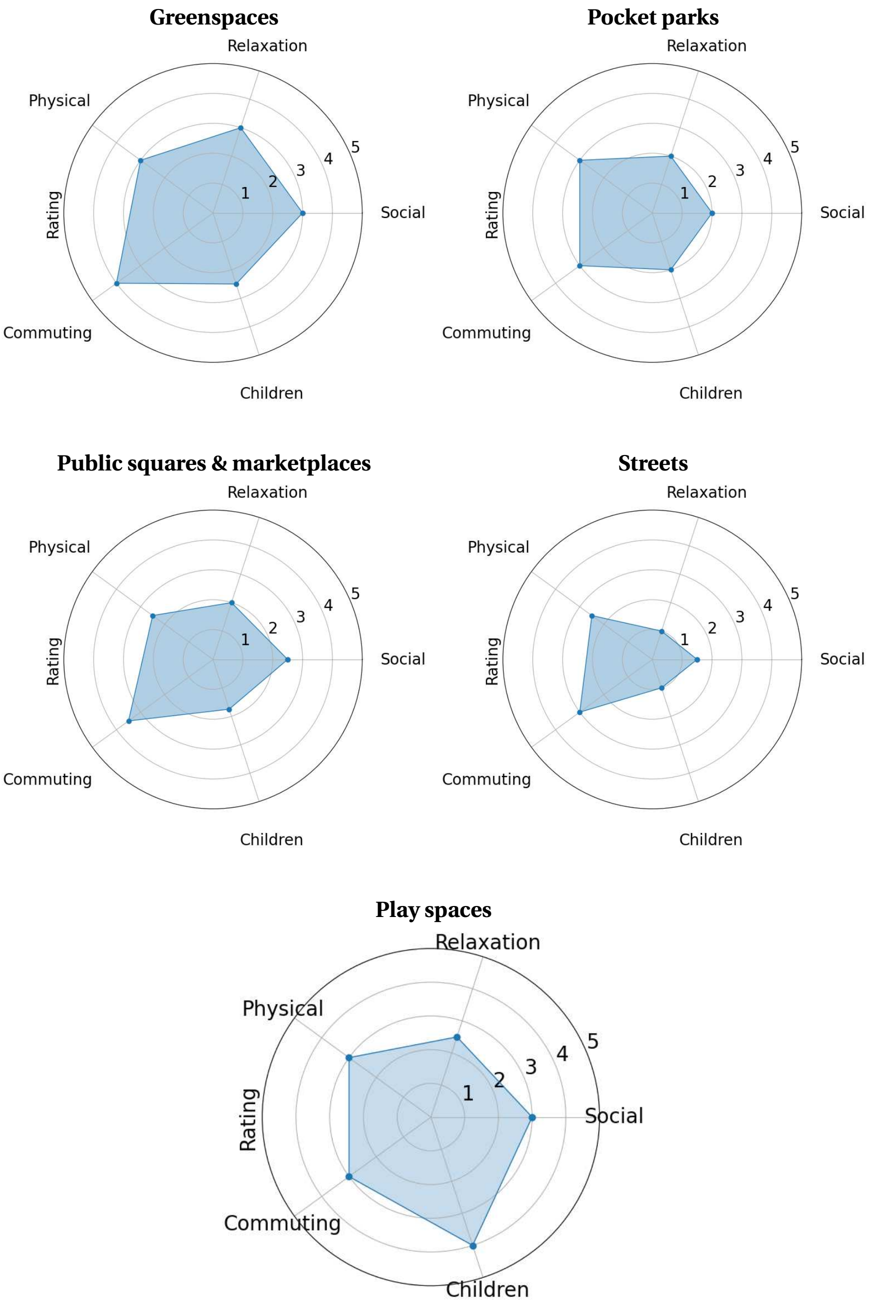


Figure 6.2.: Ratings of the likely use of public open spaces per activity.

children-related activities, they were also considered *sometimes* suitable for socializing, exercising, and commuting. The least appropriate activity to perform in a play space, as indicated by the participants, is relaxing.

Furthermore, to identify the different activities participants would perform in the same public open space, we measure the correlations among the spaces' ratings for each pair of activities using the Spearman's rank correlation coefficient. The corresponding correlation matrix is presented in Fig. 6.3. Overall, only positive correlations were found. A strong and statistically significant correlation was found between social and relaxation activities ($\rho = 0.76, p < 0.05$), indicating that spaces that are considered suitable for socializing are also deemed suitable for relaxing and vice versa. Children-related activities were also found to have a moderate and significant correlation with both relaxation ($\rho = 0.67, p < 0.05$) and social activities ($\rho = 0.57, p < 0.05$). Moreover, physical activities exhibit a significant weak or moderate correlation with all other activities. Notably, commuting is the sole activity type lacking a significant correlation with all the other activities, excluding exercising.

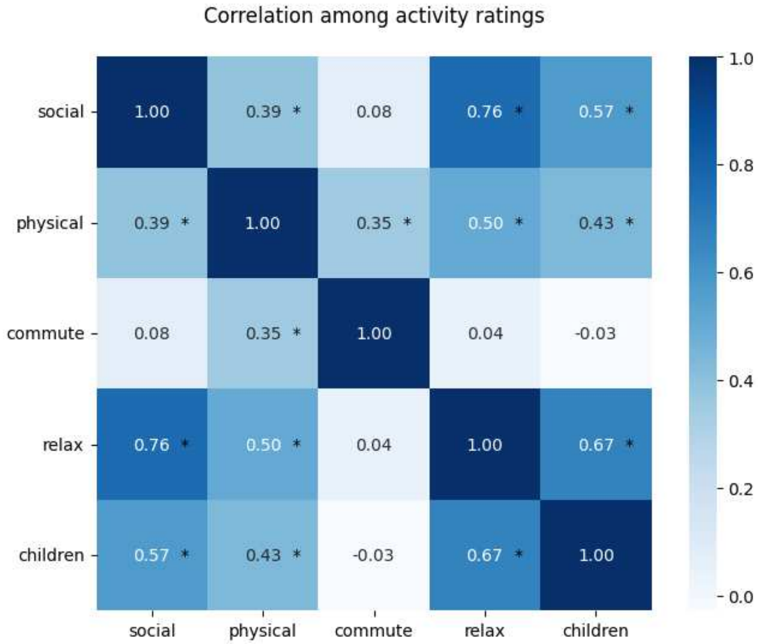


Figure 6.3.: Correlation of activity-based ratings

THE LIKELY USE OF PUBLIC OPEN SPACES VARIES SIGNIFICANTLY ACROSS AGE GROUPS

Overview: With this hypothesis, we examine if the activities participants are likely to perform in public open spaces vary per age group. To test our hypothesis, we perform Mann-Whitney U tests: one for each activity and each pair of age groups. As explained in Section 6.2.2, the age groups included in our tests are [18-29], [30-39], [40-49], [50-59], [60+].

Result: H2 was accepted for physical activities between the age groups [18-29]–[60+] and for commuting activities between the age groups [30-39]–[60+]. However, it was rejected for all other activities and age groups. That is, several age groups were found to differ in how likely they would use public open spaces for physical activities and commuting activities, but we do not have sufficient evidence to conclude that the degree to which different age groups would use a space to perform social, relaxation, or children-related activities differs significantly.

H3: THE LIKELY USE OF PUBLIC OPEN SPACES VARIES SIGNIFICANTLY ACROSS GENDERS

Overview: With this hypothesis, we examine if the activities participants intend to perform in public open spaces differ between gender groups. Out of all participants, 49% self-identified as males, 49% as females, and 2% as non-binary, third gender, or prefer to self-describe or not to say. To statistically test our hypothesis we limit to males and females since we do not have sufficient data to draw statistical conclusions for the other groups. In particular, we performed four Mann-Whitney U tests, one for each type of activity, between the ratings we received from male and female participants.

Result: H3 was rejected for all types of activities. That is, we do not have sufficient evidence to conclude that the likely use of public open spaces between males and females differs significantly.

6.3.3. THEMATIC ANALYSIS

The aim of the thematic analysis is to explore what characteristics people consider promoting or obstructing them from performing activities in an public open space. Informed by the results of the statistical hypotheses, we focus on the cases for which significant differences were found. Following up on *H1*, we analyze the explanations of the people's ratings to identify how the physical characteristics of a space contribute to differences in a space's likely use for social, relaxation, physical, or children-related activities. We summarize our findings at the end of this section in Table 6.2. In addition, following up on *H2*, we identified significant differences between the likely use of public open spaces for physical or commuting activities among several age groups. Thus, we also group participants' explanations per age group and examine if there are differences among the spatial characteristics they consider important to perform such activities.

WHAT CHARACTERISTICS MAKE A PUBLIC OPEN SPACE LIKELY TO BE USED (OR NOT) FOR DIFFERENT ACTIVITIES?

From H1, we found that the type of public open spaces significantly affects the likely use of a space for social, relaxation, physical, or children-related activities. In this section, we qualitatively analyze the input we received from participants to explore what are the characteristics of a space that promote or obstruct people from performing such activities there. Table 6.2 summarises the results of the qualitative analysis by presenting the most prevalent characteristics that positively or negatively influenced participants for performing an activity in a space.

Social Activities — vibrant versus calm

The most frequent reasons participants mentioned to explain why they would *often* or *always* use a place for socializing are relatively contradicting: on the one hand, places appropriate for socializing are *"vibrant"* and with a high number of amenities. As one participant mentioned *"I think it seems like a central place for meeting plus there is a shopping mall and restaurants close-by so fits well for socializing"*. On the other hand, participants also prefer places that look *"calm"* and *"open"*. Another important factor frequently mentioned is the existence of *"sitting places"* such as chairs or benches. When looking at the reasons one would *rarely* or *never* visit a place for socializing, participants most often mention the lack of amenities, sitting places, and space as well as the place being *"unattractive"*. The factors that most often co-occur with a place being described as unattractive revolve around the lack of sitting places, space, and nature, and the place looking *"busy"*, *"noisy"*, and *"industrial"*. Lastly, certain places received low ratings because they were considered to be dedicated to only certain age groups, as participants mentioned "*only for young people at night*" or "*only children/parents related*". Fig. 6.4 depicts examples of spaces that participants would *always* or *never* visit for socializing.

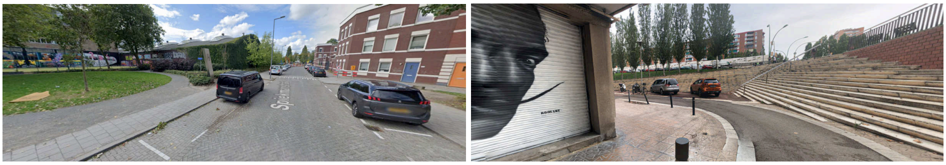
(a) Public open spaces that participants would *never* use for socializing

(b) Public open spaces that participants would *always* use for socializing.

Figure 6.4.: Public open spaces that participants would *never* (top) or *always* (bottom) use for socializing

Relaxation Activities — nature and privacy

Participants mentioned that the places they would "*Always*" or "*Often*" use for relaxing are places that are near "*nature*" (e.g., trees, water), are "*calm*" and "*quiet*", and have a high number of sitting places. In addition, participants relatively often commented positively about the sun or the shade; in their own words "*Has nice shade for hot days*" or "*Nice benches to sit and sun bath*". When participants explained why they would "*Never*" or *"Rarely"* visit a place for relaxation activities, they often mentioned the absence of nature and characteristics connected to a busy urban environment such as "*noisy*", "*industrial*", "*busy*", "*high traffic and cars*", "*construction sites*". Characteristics that were explicitly mentioned in relation to relaxation activities, and not often mentioned for other activities, were about the places looking "*polluted*" or not offering adequate "*privacy*". Notably, while places offering "*privacy*" are appreciated places that are considered "*isolated*" are not. Thus, participants make an explicit distinction between places that provide privacy by having areas not exposed to public view and places that appear to be isolated and abandoned. Fig. 6.5 depicts examples of spaces that participants would *always* or *never* visit for relaxing.



(a) Public open spaces that participants would *never* use for relaxing

(b) Public open spaces that participants would *always* use for relaxing

Figure 6.5.: Public open spaces that participants would *never* (top) or *always* (bottom) visit for relaxing

Physical Activities — space, nature, and safety

Regarding the physical activities, the most discussed characteristics were the amount of "*space*", and the existence of green spaces, trees, and blue spaces such as rivers. Additionally, several participants mentioned the place being "*busy*" as the main reason they would not perform physical activities at a place; as explained "*I would walk in this place, but I believe it would be too crowded to do some other sports*". Moreover, characteristics that were repeatedly mentioned positively revolved around specific sports, such as having tracks dedicated to walking, running, or cycling, or having space suitable for ball games. Lastly, in several cases, participants based their ratings on how safe a place appears to be. Fig. 6.6 depicts examples of spaces that participants would *always* or *never* visit for exercising.

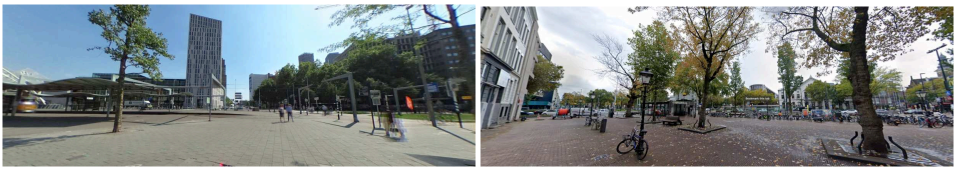
Children-related Activities — safety and "*something for the children to do*"

For a public open space to be suitable for children-related activities, participants clearly prioritized safety above any other characteristic. In particular, they mostly discussed safety in terms of potential accidents, for instance, due to the presence of cars and nearby streets "*Too many cars for children to be playing on their own safely*", or nearby blue spaces "*I think it would be dangerous for children to play unsupervised in this area due to water being present*". In addition to that, participants often explicitly complemented their comments on safety with how much supervision is needed or not, as a participant explained "*With adult supervision as there is not proper enclosure to make sure that kids cannot wander into the streets or get lost*". Thus, a space that is considered safe for children to visit along with their parents might not be a safe place for children to be unsupervised. The next most prevalent reason for a place not being considered suitable for children is not having anything that would entertain the children "*it doesn't look like there's anything that would entertain a child and doesn't seem stimulating enough.*". Overall, in comparison to the reasons related to the other activities, we observed fewer comments about how "attractive", "calm", or "polluted" a place looks. Instead, participants tend to mention more physical characteristics, like the presence of a street or particular amenities and play equipment. Fig. 6.7 depicts examples of spaces that participants would *always* or *never* visit for children-related activities.

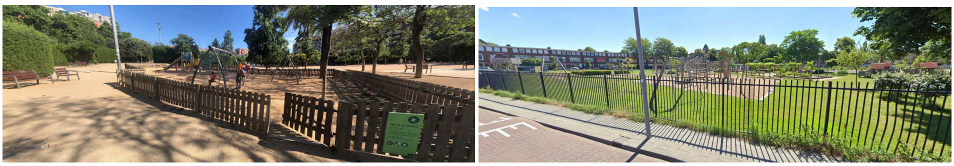
(a) Public open spaces that participants would *never* use for exercising

(b) Public open spaces that participants would *always* use for exercising

Figure 6.6.: Public open spaces that participants would *never* (top) or *always* (bottom) use for exercising



(a) Public open spaces that participants would *never* use for children-related activities



(b) Public open spaces that participants would *always* use for children-related activities

Figure 6.7.: Public open spaces that participants would *never* top or *always* (bottom) use for children-related activities

	Positive	Negative
Social	amenities, sitting spaces, calm, open, nice for picnic, vibrant, nature, nice meeting place, view	lack of amenities, lack of sitting spaces, unattractive, lack of space, road/traffic/cars, lack of nature, industrial, noisy, busy, dedicated to certain age groups, not calm
Relaxation	nature, calm, quiet, sitting spaces, nice for reading, sun/shade, open, view, little traffic/cars, attractive, private	noisy, busy, lack of sitting spaces, high traffic/cars, no nature, industrial, unattractive, no calm, lack of space, unsafe
Physical	space, nature, dedicated to specific sports (e.g., walking, biking, pools), safe, open, calm, little traffic, attractive, quiet, view	little space, busy, unsafe, unattractive, high traffic/cars, industrial, little nature, narrow, pollution, bad view
Children	play equipment, safe (supervised/unsupervised), amenities, nature, space, open, quiet, little traffic, sitting spaces	unsafe, high traffic/cars, nothing for children to do, nearby roads, little space, lack of amenities, industrial, blue spaces (considered unsafe), isolated, little nature

Table 6.2.: Most prevalent characteristics of public open spaces that positively or negatively influenced participants' ratings

6.3.4. WHAT CHARACTERISTICS MAKE A PUBLIC OPEN SPACE LIKELY TO BE USED FOR PHYSICAL AND COMMUTING ACTIVITIES ACROSS DIFFERENT AGE GROUPS?

From H2, we found that the likely use of public open spaces varies significantly among age groups only in two cases: (1) for physical activities when comparing age groups [18-29]-[60+], and (2) for commuting activities when comparing age groups [30-39]-[60+]. In this section, we qualitatively analyze the input we received from participants to explore what are the characteristics of a space that contribute to these differences.

PHYSICAL ACTIVITIES

Age group [18-29] — space, safety, nature, equipment
The youngest group of participants in our study, 18 to 29 years old, highlighted having enough space as one of the top priorities for a place to be considered suitable for physical activities. In particular, participants mentioned that they would not exercise in certain locations because there is "*not enough space*" or "*this area as a whole looks too constricted for physical activities*". Similarly, they also mentioned "large space" to explain why they considered a place suitable for exercising, as a participant said "*enough space for various types of sports activities.*" while often focusing on "open" space and nature-related characteristics such as trees, grass, or rivers. Moreover, this group of participants considered safety among the most important reasons they would exercise at a place. In

this case, safety was mostly related to potential accidents due to the place being close to high-traffic streets. Lastly, participants often focused on the lack or presence of specialized equipment for exercising, as one participant mentioned positively "*looks like an outdoor gym*".

Age group [60+] — space, nature, attractiveness, safety
For the participants older than 60 years old, having enough space was also highlighted among the most important characteristics for a place to be suitable for exercising. However, this age group emphasized more often the aesthetic and nature-related characteristics of these places, than the [18-29] age group. For instance, participants often explained their high ratings through comments such as "*it would be a nice area for walking or biking due to the presence of green spaces*" or "*picturesque for walking/biking*" and considered places that seem to be too crowded and busy or too industrial-looking as not appropriate for exercising. Lastly, safety was once again considered an important characteristic to consider a space as appropriate for physical activities. Therefore, although there are characteristics that both groups typically prioritize when evaluating how suitable places are for physical activities, we have also identified characteristics that vary between these groups.

Commuting Activities

Age group [30-39] — safety, space, connectivity, attractiveness
The most frequently mentioned characteristic of the spaces that were considered suitable for commuting by the participants aged from 30 to 39, is safety. In particular, participants often explained their high ratings by mentioning that a place or street looks safe to walk or cycle or that "*paths are well separated from roads*". Then, participants also considered having enough space to walk or cycle important often explicitly mentioning the width and quality of the sidewalks. Next, they provided comments related to how well-connected the corresponding places or streets seem to be to the rest of the city such as "*road looks like it's heading to the major destinations of the city*" or "*it has good transport links*". Similarly, places that were described as more isolated or dead ends received low ratings, as one person commented "*looks a bit deserted and out of the way of anywhere I would go*". Lastly, participants also mentioned that places suitable for commuting are attractive, quiet, and not too busy or crowded.

Age group [60+] — safety, connectivity, attractiveness, nature
The reasons participants older than 60 years old find a place suitable for commuting activities are similar to the ones described for the 30-39 age group. Once again, safety is the most emphasized explanation of high ratings, followed by connectivity and attractiveness. A difference between the two age groups is that the 60+ age group mentions more often nature-related characteristics to explain their high ratings such as greenery, water, and grass, and less often the size or space of the place.

6.4. DISCUSSION

6.4.1. KEY FINDINGS

CHARACTERISTICS AND TYPES OF PUBLIC OPEN SPACES THAT INFLUENCE LIKELY USE

Overall our findings align with prior research on public open space characteristics affecting use. Indicatively, we found that the presence of natural features such as trees, grass, or water bodies increases the likelihood of people using these spaces. The importance of such features extends to almost every activity, it was acknowledged by every population group studied, and is in line with previous studies [15, 231, 232]. Furthermore, we identified that the presence of seating spaces, such as chairs or benches, may promote socializing and relaxing. This is also in line with related work that found that the absence of seating spaces is a barrier to using public spaces for socializing and relaxing [146, 207, 233, 234]. Moreover, we found that spaces being small in size was frequently highlighted as a key deterrent to using public open spaces for physical and children-related activities, as also indicated by [234]. Similarly, characteristics diminishing perceptions of safety in spaces, such as the absence of nearby amenities and associated passive surveillance or being close to traffic, were considered to discourage probable use for all activities and by all population groups, in line with findings by [206] and [142].

In addition to previously documented findings in the literature, our study revealed statistically significant variations among diverse public open spaces in terms of their likely utilization. Greenspaces were identified as the most conducive for all activities, except those associated with children, where playgrounds were the preferred choice. In contrast, pocket parks were deemed less suitable than larger parks, receiving lower ratings across all activities. The lack of ample seating in these pocket parks or their smaller size may account for this observed difference, as these elements are commonly considered essential for human activities [146]. While natural features like vegetation or water bodies are generally well-received by individuals, their presence alone may not suffice to encourage human activity in public open spaces when there is a deficiency in seating or size.

Unlike greenspaces, streets exhibited the lowest likelihood of being utilized for any activity. Prior studies have identified that well-designed streets can support a wide range of activities such as social interaction, leisure, and play [146, 207, 235]. Our results, however, suggest that most streets lack the essential characteristics identified in previous works for facilitating these activities, such as having stores with street-fronts, trees, and seating spaces. Notably, the low ratings assigned to streets could also stem from the prevalent perception of streets primarily being for transport, and not for the activities considered in this work. Similarly, public open spaces, commonly regarded as important for social interaction [236], received low ratings in terms of most activities, including socializing and relaxing. These low ratings were frequently justified by the absence of nearby amenities such as cafes or restaurants, proximity to traffic, or perceived lack of attractiveness. Specific public open space types were consistently identified as either the most (e.g., greenspaces) or least (e.g., streets) likely to be used (Fig. 6.2). Additionally, our findings revealed a correlation between the probable use of spaces for multiple activities. Specifically, a space deemed likely for one type of activity was also predisposed to being used for others (Fig. 6.3). Hence, the suitability of an public open space for a particular

6

activity can serve as a key indicator of its appropriateness for other activities.

Likely use among individuals and age/gender groups

In general, there is a consensus among individuals regarding the features that render a public open space suitable for use. Nevertheless, instances of conflicting opinions were identified. For example, when considering socializing, divergent preferences emerged. Some participants favored lively spaces equipped with diverse amenities, while others leaned towards tranquility and quietness.

Consensus among individuals and groups

Contrary to both our hypotheses and existing literature, our analysis revealed no statistically significant disparities in the likelihood of public open space usage among various age and gender groups. Nevertheless, it is noteworthy that several other studies have identified variations in utilization patterns based on age and gender [171, 212, 237]. For instance, research has indicated that older adults and women tend to experience heightened vulnerability and express greater concerns about safety while walking [171]. These contradicting findings may arise from context-specific factors, such as crime rates in the surrounding area or daily visitation patterns, which are not necessarily linked to the observable physical features of a space captured in street-level imagery. For example, parks situated in areas with high crime rates have been found to discourage individuals from engaging in physical exercise there [238]. An alternative interpretation is that, while perceptions of safety may vary among different age and gender groups, the objective physical characteristics of a space, such as the quantity of trees, seating areas, or amenities, exert a more significant influence on the type of activities people intend to perform.

Differences among individuals and groups

In the cases where significant differences in likely use were found among different age groups — namely for exercising between the age groups [18-29] and [60+] and for commuting between the age groups [30-39] and [60+] — we identified two underlying patterns. First, our findings indicate that different groups deemed distinct characteristics of spaces as more desirable. For instance, older individuals placed greater emphasis on aesthetic and nature-related characteristics when contemplating the use of public open space, such as the space being perceived as “attractive", having a “picturesque" appearance, not having an “industrial" ambiance, and having abundant vegetation. This observation aligns with and is supported by previous research studies [152, 211]. Additionally, our results suggest that the physical characteristics of a space that contribute to its perceived safety may differ between individuals. In several circumstances, locations that one individual deemed safe were regarded as unsafe by another.

Second, spaces generally considered as designated for a specific age group, such as children or youngsters, often led to other groups claiming that they will not use them for any activity. This observation aligns with the conclusions of [210], who reported that young adults prefer spaces located away from playgrounds and residential areas to avoid disruptive noise from children and minimize disturbance to neighboring residents. Additionally, our findings indicate that public open spaces deemed likely for activities related to children are typically confined to designated play areas, such as playgrounds. Other spaces that we examined, including streets, pocket parks, or public squares, were not considered conducive for children-related activities.

6.4.2. IMPLICATIONS

IMPLICATIONS FOR FUTURE RESEARCH

Our results largely align with findings from previous studies, thereby further strengthening them. Additionally, our results indicate how crowdsourcing could complement traditional data collection approaches, such as field observations, for studying how the characteristics of public open spaces influence likely usage. Crowdsourcing solves the main challenges traditional approaches face. It is time and labor-efficient, enabling us to include a broad range of spaces from different cities, and a multitude of opinions from different individuals and population groups, into one single study. Thus, future research should consider crowdsourcing as a valuable supplementary method for evaluating the anticipated use of public open spaces. However, it is essential to proceed judiciously, considering the potential oversight of individuals and groups without access to digital resources. In addition, we also noted some differences between our results and those reported in earlier research. A potential reason for these differences is that we did not include context-dependent factors in our analysis, such as the crime levels of city or a neighborhood or which groups of people usually visit a space. Future research should explore how crowdsourcing could incorporate context-dependent factors that affect people's perceptions of public open spaces.

Our results also indicate the importance of considering diverse types and characteristics of public open spaces to enrich our understanding of how they can accommodate different activities and people. In terms of the types of public open spaces, future research could benefit by including and comparing a range of spaces such as public squares, parks of varying sizes, playgrounds, open marketplaces, streets, and other green spaces. Regarding the characteristics of public open spaces, focusing solely on specific features, such as natural features, may not suffice to determine what activities are likely to occur. Instead, scholars should consider including in their studies spaces with a diverse array of characteristics, such as varying levels of vegetation, proximity to busy streets, availability of amenities and seating, size, and spaces that are perceived differently in terms of how “calm", “vibrant", “attractive", or “safe" they are.

IMPLICATIONS FOR PRACTITIONERS

Our results suggest that likely use differs between types of public open spaces, and that, occasionally, the same space does not accommodate activities by different people equally. For instance, certain people prefer vibrant places with a variety of amenities for socializing, while others prefer calm places. Additionally, younger individuals emphasized the availability of exercise equipment for performing physical activities, whereas older individuals mentioned the aesthetic appeal of the spaces. Therefore, for an area to provide opportunities for a variety of people to engage in different activities, a diverse set of public open spaces might be needed to suit all people and preferences. This extends further from considering diversity between the types of spaces to also considering diversity within types. For instance, an area might need to have both “vibrant" and “relaxing" public squares or both “sports-oriented" and “social" greenspaces.

Moreover, our work demonstrates the value of employing crowdsourcing to study how public open spaces are likely to be used by different individuals. Crowdsourcing could be a valuable tool for built-environment professionals aiming to elicit the propensity of citizens to use various public open spaces in a city or neighborhood.

6.4.3. LIMITATIONS

Our study has several limitations that could be addressed in future work. First, public open space characteristics influencing how likely they are to be used extend beyond the visually observable such as smells, noises, or past experiences [54, 142, 171]. Accounting for these characteristics could further expand our work. Second, our study does not account for dynamic factors impacting how people perceive the physical characteristics of spaces, such as the time of day, weather, or season. Incorporating images reflecting diverse conditions could enable us to study these dynamic factors as well. Third, our approach requires participants to have access to digital resources (e.g., a computer). Complementing the proposed approach with traditional methods like participant observation or interviews for individuals without access to such resources can broaden the participant pool, leading to a more inclusive representation of the wider population. Finally, crowdsourcing tasks related to capturing spatial information have been found to introduce a participation selection bias, since such tasks attract a certain audience [160]. Recruiting participants through different strategies could result in a sample of participants that better reflects the broader population.

6.5. CONCLUSION

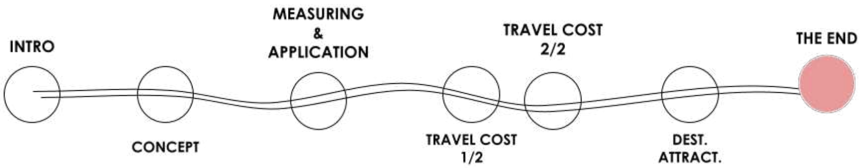
The way we design public open spaces has a significant impact on how different individuals and population groups use them. This study explores the influence of public open space features on the propensity of various individuals or groups to engage in activities, utilizing a varied selection of spaces and participants spanning a wide range of ages and genders. By employing a combination of crowdsourcing, street-level imagery, statistical tests, and thematic analysis, this work compares the preferences of diverse individuals, as well as various age and gender groups, regarding the activities they would engage in across a variety of public open spaces, and the characteristics that matter to them. Our findings reveal significant differences regarding the suitability of different types of public open spaces for different activities. Greenspaces emerged as the most favored for nearly all activities, while pocket parks were less preferred, and streets were considered the least suitable for engaging in various activities. Additionally, our findings suggest that the suitability of a space for one activity implies its suitability for other activities. Contrary to expectations, most instances did not reveal significant differences among different age and gender groups in their preferences for engaging in specific activities in public open spaces. When variations were observed, they stemmed either from distinct preferences for specific characteristics of public open spaces among various groups or from differing perceptions of shared, recognized characteristics. Our findings underscore the importance of ensuring diversity in public open spaces to accommodate the preferences of different individuals, activities, and population groups.

7

Discussion & Conclusion

The history of city growth, in essence, is the story of mans eager search for ease of human interaction

Melvin M. Webber [239]



7.1. OVERVIEW

During the past years, there has been a notable shift, both in research and in urban planning practices, transitioning from designing cities with a primary focus on mobility to cities with a primary focus on accessibility [9, 240, 241]. This can be observed by the growing interest in urban models that revolve around accessibility by proximity, promote walking and other modes of active transportation, and reduce the reliance on cars [65–68].

Similarly, new policies and global mandates have been formulated aiming towards the design of accessible and inclusive spaces for all. A prime example of such mandates comes from target 11.7 of the United Nations' Sustainable Development Goal 11 which focuses on ensuring that, by 2030, everyone has access to safe, inclusive, and accessible green and public spaces, with special attention to accommodating women, children, older persons, and persons with disabilities [40].

Despite the attention given to accessibility, existing place-based accessibility measures still fail to distinguish between destinations accessible to individuals from a single demographic group and those accessible to individuals from diverse demographic groups. Given that access to shared spaces is pivotal for physical encounters and interactions among individuals [242, 243], these constraints impede our ability to unveil the potential of the new urban models and accessibility-oriented interventions for facilitating place-based encounters among different (groups of) people.

This dissertation addresses these limitations by introducing the concept of co-accessibility and proposing a measure to assess how accessible a given destination is to different individuals and demographic groups.

7.2. ANSWERS TO RESEARCH QUESTIONS

In this section, we summarize our answers to each research question addressed in this work.

RQ1: WHAT ARE THE FORMULATION AND COMPONENTS OF CO-ACCESSIBILITY?

In Chapter 2, we introduced the concept of co-accessibility and proposed a measure designed to capture the accessibility of a given destination to different individuals and demographic groups. The components of co-accessibility are detailed through its mathematical formulation which can be broken into two main measures. The first is group-specific and is used to measure the co-accessibility of a destination d by n individuals who belong to the same demographic group g. This measure enables us to address the *isolation accessibility bias* (Chapter 1, Fig. 1.1) in which disparate destinations being accessible by distinct individuals is incorrectly equated with the same destination being accessible by different individuals and is expressed as:

$$c_g^d = h\left(A_{p_1}^d, A_{p_2}^d, \ldots, A_{p_n}^d\right), \forall p_j \in g \tag{7.1}$$

where c_g^d is the co-accessibility of destination d by individuals from group g. $A_{p_j}^d$ is the accessibility of destination d to a person p_j from group g (equation 2.2). $A_{p_j}^d$ is determined by factors that impact how attractive a destination is considered and are shared among the people from group g, the location of the person in relation to the destination, and factors that impact traveling and are shared among the people from group g. It can adopt various types of accessibility measures depending on the underlying assumptions made, as explained by [57]. h represents a function that is used to aggregate the accessibility of destination d to each $p_j \in g$ and provides the co-accessibility of destination d to all individuals.

The second measure, C_G^d, is focused on the co-accessibility of a destination d by individuals belonging to a set of n mutually exclusive demographic groups G (e.g., [children, adults, older persons]). It allows us to address the *homogeneity accessibility bias* (Chapter 1, Fig. 1.2), in which a destination being accessible by individuals from a homogeneous group is erroneously equated with a destination being accessible by individuals from different demographic groups and is formulated as:

$$C_G^d = H\left(c_{g1}^d, c_{g2}^d, .., c_{gn}^d\right), \forall g_i \in G \tag{7.2}$$

where H is a function used to aggregate the co-accessibility values of destination d for each of the groups in G and outputs the co-accessibility of the destination by people from all groups in G.

As can be observed from equations 7.1 and 7.2, the co-accessibility of a destination is directly determined by the travel cost to reach it and the destination's attractiveness. These two components play a pivotal role in the formulation of co-accessibility and are explored further through questions RQ3 and RQ4, in Chapters 3 and 4, respectively.

7

RQ2: HOW CAN CO-ACCESSIBILITY FACILITATE THE EVALUATION OF POTENTIAL ENCOUNTERS AMONG DIFFERENT INDIVIDUALS AND POPULATION GROUPS?

In Chapter 3, we proposed a method for measuring the pedestrian co-accessibility of urban destinations and empirically demonstrated how it can be applied to assess spatial age segregation, meaning the degree to which different age groups occupy the same space [98]. To measure co-accessibility we made three main assumptions regarding its two main components, namely the *destination attractiveness* and the *travel cost*. First, the destinations under study are equally attractive for different age groups. Second, the travel cost is calculated considering solely the walking time to reach a destination. Third, a destination is reachable by a pedestrian if the pedestrian can reach it within a 5, 10, or 15-minutes walk from their home. Based on these assumptions we calculated the co-accessibility of different destinations across the five most populated cities in the Netherlands, namely Amsterdam, Rotterdam, The Hague, Utrecht, and Eindhoven. Furthermore, we evaluated our method by comparing our results with existing measures of spatial age segregation. In particular, we compared the co-accessibility scores of each destination with the age structure of people who reside within the same neighborhood where the various destinations are located, assuming equal distribution of age structure over each neighborhood's geographic space.

The results of this comparative analysis suggested that, in several cases, the co-accessibility scores of urban destinations within a neighborhood often diverge from the scores that would derive from the sole consideration of the aggregated age structure in that neighborhood. These differences exemplify how the co-accessibility measure could lead to an improved understanding of the level of age segregation and enrich existing studies that focus on residential segregation on a city, neighborhood, urban block, or building unit level [108, 121]. Moreover, they indicate that besides the concentration and level of mixture of different age groups in residential spaces, the density and distribution of urban destinations can play an important role in how people experience age segregation in their daily encounters.

Another approach to assess segregation among individuals and population groups is through the utilization of person-based accessibility measures. In this context, person-based accessibility measures are used to capture individuals' activity spaces [110, 244] which could be defined as "*the subset of all locations within which an individual has direct contact as a result of his or her day-to-day activities*" [245]. Accordingly, segregation is estimated based on the overlap of different (groups of) individuals' activity spaces. Such an approach while useful and informative, is hindered by the availability of mobility and time allocation data on an individual level, the associated privacy and ethical concerns [35], and often considers the potential for encounters equal across geographic space. Co-accessibility has the potential to enhance these methods by offering a practical and replicable approach to evaluate the likelihood of encounters in specific locations, while also considering the varying capacity of different destinations to facilitate interactions among diverse individuals or groups.

7

RQ3: To what extent do physical characteristics of urban streets impact the travel cost in co-accessibility's formulation?

This question is addressed in Chapters 4 and 5. In examining how the physical characteristics of streets affect the *travel cost* within the context of co-accessibility, our analysis centered on pedestrians. Specifically, we investigated the influence of streetscape features on pedestrians' perceptions of safety and attractiveness. These perceptions are widely acknowledged as key factors influencing pedestrians' willingness to walk [41].

We pursued two distinct approaches. The first approach involved crowdsourcing perceptions from individuals. To capture the perceived safety and attractiveness of city streets we developed a crowdsourcing tool that enables people to virtually navigate streets represented as a sequence of street-level images, rate locations based on perceived safety and attractiveness, and explain their ratings. To study the extent to which different street qualities impact these perceptions, and if these differ among age and gender groups, we conducted an experiment with 403 participants, balanced among age and gender groups.

The second approach draws from contemporary urban design guidelines that often advocate urban forms that encourage natural surveillance or "eyes on the street" to promote community safety [46, 48, 49]. It proposed a method for measuring natural surveillance in an automated manner, to be used as an estimator of perceived safety. Our method employed street-level imagery and computer vision techniques to detect windows on building facades and calculate sightlines from the street level and surrounding buildings. To empirically evaluate our method we applied it across forty neighborhoods in Amsterdam, the Netherlands. By correlating our measurements with the city's Safety Index, we examined the degree to which the existence of windows with a view toward the street can be used as an estimator of neighborhood safety.

The results of these studies contributed new insights regarding the street qualities that influence perceived safety and attractiveness along city streets. We showed that the presence of human activity is strongly related to perceived safety, whereas attractiveness is influenced primarily by aesthetic qualities, as well as the number and type of amenities along a street. The significance of human presence was evident in perceptions of safety, even when it was indirectly suggested: a heightened score of natural surveillance, determined by analyzing sightlines from windows on building facades to the street, correspondingly indicated streets that are perceived as safer. In these cases, the window level and distance of buildings from the street appeared to have varying influences on the feeling of safety. Additionally, we uncovered an interesting observation: there is a threshold point of natural surveillance beyond which higher scores do not further enhance the feeling of safety.

Furthermore, we demonstrated that the presence of certain elements, such as construction sites and underpasses, has a disproportionately negative impact on perceived safety and attractiveness, outweighing the influence of any other features. When looking at the different demographic groups in terms of gender and age, we found that while all groups identified nearly the same percentage of locations as attractive, male and older participants tend to consider more locations as unattractive than female and younger participants, respectively. Female and younger participants also appeared to consider fewer locations as (very) unsafe or (very) safe than male and older participants, respectively. Furthermore, these analyses illustrated the utility of crowdsourcing, street-level imagery, and computer vision techniques for capturing the influence of streetscape features on the perceived qualities of the urban environment, both at the street and citywide scales.

Overall, our findings indicate the important influence of streetscape features on promoting or discouraging pedestrians from walking to a destination. These influences can vary according to the pedestrians' age or gender. This is also supported by the literature [171, 212, 237] and extends to other population groups such as ethnicity [246] or people from different cultural backgrounds [148]. In the context of co-accessibility, these differences can inform the weighting of the factors that impact the travel cost to reach a destination and are shared among the people of each demographic group (Chapter 2). In that way, the *travel cost* function can be parameterized for each demographic group to more realistically reflect the travel cost of individuals from a specific group to reach a destination.

7

RQ4: TO WHAT EXTENT DO PHYSICAL CHARACTERISTICS OF URBAN DESTINATIONS IMPACT THE DESTINATION ATTRACTIVENESS IN CO-ACCESSIBILITY'S FORMULATION?

In Chapter 6, we address this question by studying how the physical characteristics of outdoor spaces influence the likelihood of use across individuals and different age and gender groups combining crowdsourcing, street-level images, statistical comparisons, and reflexive thematic analysis.

Our results are aligned with prior research and, in addition to previously documented findings in the literature, uncover statistically significant variations in the suitability of different types of outdoor spaces for distinct activities, such as socializing or exercising. Greenspaces emerged as the preferred choice for almost all activities. In contrast, pocket parks were deemed less suitable than larger parks, receiving lower ratings across all activities suggesting that while natural features like vegetation or water bodies are generally well-received by individuals, their presence alone may not suffice to encourage human activity in outdoor spaces when there is a deficiency in seating or size.

Unlike greenspaces, streets exhibited the lowest likelihood of being utilized for any activity while well-designed streets have been found to support a wide range of activities [146, 207, 235]. Additionally, we identified various characteristics that influence the activities people are likely to engage in. These include the size of the space, the presence of seating, natural elements such as vegetation or water bodies, and the proximity to transport infrastructure.

Furthermore, and contrary to our hypotheses, in most cases, we did not identify statistically significant differences in how people from different age and gender groups intend to use outdoor spaces. In other studies, however, distinctions among age and gender groups have been observed [154, 171]. Such differences might be a result of context-specific factors (e.g., related to the city or neighborhood) that do not pertain to the physical characteristics of an outdoor space, as those are represented in an image. When variations were observed, those arose either due to distinct preferences among various groups for specific characteristics of outdoor spaces or because, despite shared recognition of certain characteristics as important, these were perceived differently among the groups. Moreover, we showed the practical value of combining crowdsourcing and reflexive thematic analysis to identify how the physical characteristics of outdoor spaces influence their use among different individuals and groups.

Within the context of co-accessibility, these findings can inform the prioritization and importance of the factors that impact how attractive a destination is considered by people belonging to a certain demographic group (Chapter 2). Consequently, the *destination attractiveness* function can be parameterized for each demographic group to better reflect the likelihood of different groups to use the same destination.

SYNOPSIS

Co-accessibility measures enable the assessment of the capacity of distinct destinations to bring together different individuals and individuals from different demographic groups by being accessible to them. An important question prior to applying a co-accessibility measure is: how to measure the *travel cost* and *destination attractiveness* for different (groups of) individuals? Our results indicate that even simplified measures of co-accessibility, which do not distinguish between individuals or groups in terms of *travel cost* or *destination attractiveness*, can complement existing measures designed to capture potential encounters among individuals, often expressed as indicators of spatial segregation [108, 121] (Chapter 2 and 3). Nevertheless, through Chapters 4-6 we also highlight the potential of enhancing the co-accessibility measures by capturing and incorporating the influence of urban environment's physical characteristics on the *travel cost* and *destination attractiveness* components. This incorporation involves considering the distinctive needs and preferences of the different groups of individuals. Capturing those at different scales, ranging from street-level to citywide, presents a formidable challenge, but employing crowdsourcing, street-level imagery, reflexive thematic analysis, and computer vision techniques can offer valuable assistance in this endeavor.

7.3. CONTRIBUTIONS

ADVANCEMENT OF KNOWLEDGE

This research introduces co-accessibility, thereby contributing a new concept and offering a fresh perspective to fields that study the urban environment and aim to improve urban life. Co-accessibility addresses two biases often found in existing accessibility measures, namely the *isolation* and *homogeneity* biases as illustrated in Figs. 1.1 and 1.2 (Chapter 1). It provides an interesting avenue of future research that can contribute to a deeper exploration of the social encounter potential among different individuals and demographic groups across various urban settings.

METHODOLOGICAL CONTRIBUTIONS

Throughout this dissertation, we contribute several methods that enable the measurement of co-accessibility and its components. In Chapter 3, we propose a method to measure the age-related co-accessibility of urban areas, meaning the extent to which different individuals and age groups have access to the same destinations. Our method is computational, leverages open data sources, and provides citywide measurements at a spatial resolution of $100x100m$. The code that implements this method is open-access, allowing for both replication and further development of the method.

In Chapter 4, we propose a method and contribute a tool for capturing perceived qualities along city streets and investigating the relation between these perceptions and the streetscape characteristics. The main novelty of this method and tool is that it allows researchers to explore, monitor, and prioritize how perceptions of safety and attractiveness develop as people (digitally) encounter different streetscape characteristics. Within the scope of this research, we used our method and tool to capture and study the perceived safety and attractiveness of city streets. However, with minor modifications, this tool can be adapted to capture other perceived qualities and further studies can be conducted to assess its appropriateness for these purposes. The developed tool is publicly available, allowing for both replication of the method and further development.

In Chapter 5, we present a time and labor-efficient computational approach to measure natural surveillance along city streets and show how these measurements can be used as a proxy of (perceived) safety. This method leverages street-level imagery and street network data and can be applied in a variety of different countries and cities. Considering the challenges in measuring perceived safety using existing data sources [247], this approach offers a promising direction for future studies in environmental criminology and the next-generation Crime Prevention Through Environmental Design (CPTED) [199]. It has the potential to enhance our knowledge about the specific characteristics of urban environments that contribute to heightened feelings of safety. The code representing this method is openly available, permitting its replication and further development.

EMPIRICAL FINDINGS

Through the study of co-accessibility, we have contributed a variety of empirical findings that could inform the design of urban environments. First, we studied the phenomenon of spatial age segregation across the five most populated cities in the Netherlands and demonstrated how the spatial distribution of urban destinations influences the degree to which the same destinations are accessible to different age groups. We highlighted areas within the cities under study that promote or discourage potential encounters among different age groups and showcased how the sole consideration of a neighborhood's overall age structure could often result in an overestimation of the degree to which different age groups are exposed to each other. These findings could be used to inform urban planners and policy makers to gain an improved understanding of the extent to which the spatial age segregation phenomenon occurs within different areas of the cities under study.

Furthermore, in Chapters 4 and 5, we show how the physical characteristics of the urban environment impact how safe or attractive a street feels. In each Chapter, we use the results to make evidence-informed recommendations for designing safer or more attractive streets that encourage walking and promote pedestrian accessibility. These recommendations can be taken into account by built-environment professionals when planning and designing for improved streetscapes.

Lastly, in Chapter 6, we studied how the physical characteristics of outdoor spaces influence the likelihood of use across individuals and different age and gender groups. Our findings highlight the potential and challenges to design outdoor spaces for all, ensuring they accommodate a broad set of individuals and a diverse set of activities. These findings can inform practitioners on how to design outdoor space with care, so that outdoor space, often scarce in growing and densifying cities, suits diverse activities for all.

TOOLS & DATASETS

This dissertation contributes the following open-access tools and datasets:

CTwalk Map[1] [52]: An interactive open-access web tool that unveils the potential of social encounters and access inequities in urban neighborhoods by leveraging open-access data. Drawing on information from various open sources, including population, location, and pedestrian network data, the tool estimates the number of individuals across different age groups who can reach city destinations within a 5 or 15-minute walk,

[1] https://bit.ly/ctwalkmap

highlighting opportunities for social cohesion and disparities in access. CTwalk Map serves as a demonstrator of a co-accessibility measure and enables users to compare the accessibility and co-accessibility of various destinations for the five most populated cities in The Netherlands: Amsterdam, Rotterdam, The Hague, Utrecht, and Eindhoven (Fig. 7.1). It was showcased at the Dutch Design Week in 2023 [248] and received the first prize demo award at the NWO ICT.OPEN conference in 2024 [53].

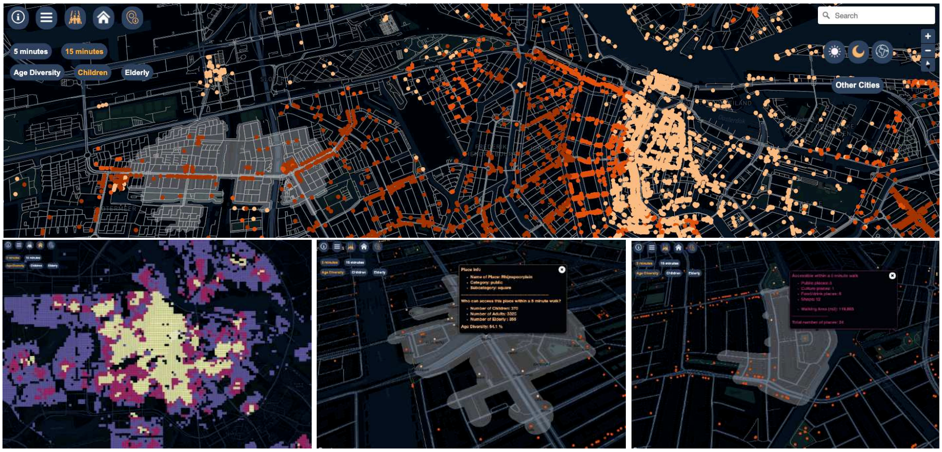


Figure 7.1.: Screenshots from CTwalk Map web tool.

CTstreets Map [2] [249]: An open-access web-based tool that maps walkability for the streets in Amsterdam, revealing neighborhoods that encourage walking and exposing disparities in walkability neighborhood and street level [249]. CTstreets was developed through a participatory approach in three main steps: (1) studied the literature and made a list of all the factors that are most commonly found to impact walkability; (2) asked urban experts who work in Amsterdam to prioritize the identified walkability factors while considering the characteristics and citizens of Amsterdam; (3) based on our discussions with the experts we created overall walkability scores, and scores per theme (e.g., related to landscape or proximity) and visualized them.

Dataset on streetscape perceptions [250]. A dataset that contains perceived safety and attractiveness ratings of city streets in Frankfurt, Germany. The data contain ratings of perceived safety and attractiveness (using a 5-point Likert scale) coming from 403 participants who were asked to virtually navigate city streets in Frankfurt, Germany, through a sequence of street-level images. Moreover, it contains their explanations of the ratings (in their own words). In total, we have collected data for 753 locations. In particular: (1) 7989 rating pairs of perceived safety and attractiveness, (2) 19114 keywords used to explain the safety ratings, and (3) 18232 keywords used to explain the attractiveness ratings.

[2] https://bit.ly/ctstreets

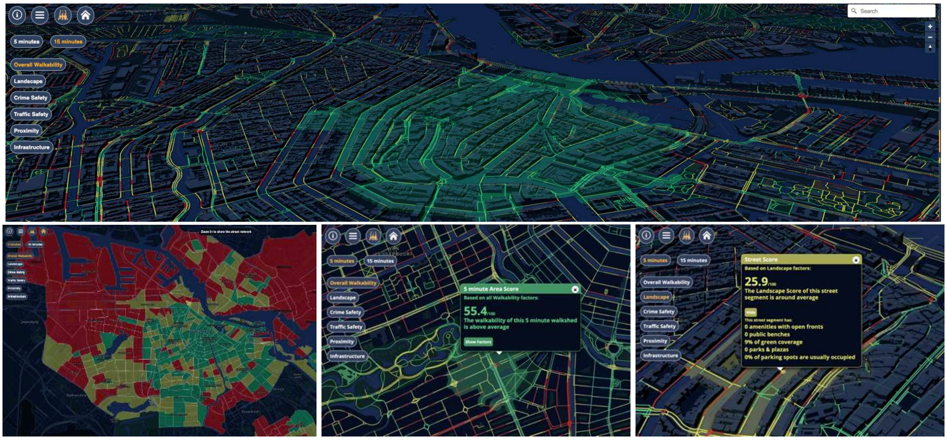


Figure 7.2.: Screenshots from CTstreets Map web tool.

Dataset on co-accessibility [251]. A dataset related to the co-accessibility scores of urban destinations across the five most populated Dutch cities: Amsterdam, Rotterdam, The Hague, Utrecht, and Eindhoven (Chapter 2 and 3).

Dataset on natural surveillance scores [252]. In Chapter 5, we proposed a methodology to detecte windows on building facades, calculate sightlines from the street level and surrounding buildings, and use them to estimate natural surveillance scores across forty neighborhoods in Amsterdam, The Netherlands. The dataset consisting of the estimated natural surveillance scores along Amsterdam's streets is openly shared .

7.4. LIMITATIONS & FUTURE WORK

This section outlines the limitations of this work and proposes future lines of research that could address these limitations.

THE AGGREGATION FUNCTIONS OF CO-ACCESSIBILITY

The proposed mathematical formulation of co-accessibility is purposefully quite broad, encompassing more of a conceptual formulation, aiming to guide and inspire the development of new context-specific co-accessibility measures, rather than a ready-to-follow recipe one can use to measure co-accessibility. Given the duration of this doctoral research, not equal focus could be given to all the components of co-accessibility.

More specifically, less focus was given to the functions h and H, also depicted in equations 7.1 and 7.2, that determine how the numbers of different individuals and groups who have access to each destination are aggregated. While in Chapter 3 we demonstrated how these functions could be operationalized to assess the spatial age segregation phenomenon, their adaptation to various problems and contexts wasn't explored in depth. In most cases, scientific fields such as ecology, that offer methods to estimate different aspects of diversity like richness, evenness, and their relation, can support this research. For instance, when the aggregation function aims to reflect diversity, reviewing the variety of studies that have already uncovered the potential and limitations of various diversity indices can be beneficial. By researching and outlining the different societal or research problems co-accessibility could be used to assess, one could also create a guiding protocol to inform about what aggregation functions to use when.

THE TRAVEL COST & DESTINATION ATTRACTIVENESS COMPONENTS

To understand how the physical characteristics of the urban environment impact the travel cost and destination attractiveness in co-accessibility's formulation we employed crowdsourcing campaigns and 360° street-level imagery data (Chapters 4 and 6). Our approaches introduce four main limitations that could be addressed in future work.

First, in our experiments, participants formed their opinions about urban locations based on street-level images, which only allowed us to capture visually observable characteristics. Consequently, our study did not consider other factors that influence people's perceptions of urban locations, such as noise, past experiences, or their familiarity with certain locations [54, 142, 171]. Our research could be broadened to include these additional factors. For instance, to evaluate noise, sound recordings could be integrated with the street-level images in crowdsourcing tasks. However, integrating factors such as familiarity is more challenging using our current method, and it might necessitate the combination of different approaches.

Second, our approaches primarily concentrate on capturing the static characteristics of the urban environment. However, dynamic factors like weather, season, day of the week, and varying times of a day could also impact how individuals perceive urban locations. Incorporating a wider set of images showing the same locations under different conditions could enhance our comprehension of the dynamic factors that affect people's perceptions of urban spaces.

Third, research indicates that tasks involving the crowdsourcing of spatial information tend to suffer from selection bias since they draw in participants who have a specific interest in nature and landscapes [160]. Employing diverse recruitment strategies and offering a variety of activities for participants to engage in could enhance the project's appeal to a wider audience, thereby potentially reducing the participant selection bias.

Lastly, all the cities under study are from European countries. Further studies of cities with varying morphological characteristics, sizes, and densities that also represent non-European contexts should be carried out in order to develop more robust and universally applicable guidelines for the design of safer, more attractive, and more likely to be used by diverse individuals and population groups spaces.

MEASURING CO-ACCESSIBILITY

In Chapter 3, we proposed a methodology to measure co-accessibility and applied a co-accessibility measure for the assessment of spatial age segregation. While our findings demonstrated how co-accessibility can be used to unveil the potential of encounters among different age groups across urban destinations, our approach to measuring co-accessibility introduces certain limitations.

First, our calculations of co-accessibility are based on the assumption that individuals are likely to engage in activities at locations near their homes. Therefore, these estimations reflect the potential of accessing various destinations within different walking distances (i.e., 5, 10, or 15-minutes walking trips) from home. Data on actual walking trips and visitation patterns (i.e., indicating when and for how long people visit given places), if available, can be easily integrated into our methodology yielding more precise calculations of the likelihood of potential encounters.

Second, pedestrian mobility behavior may further vary across cities, countries, cultures, or by the type of destination (e.g., people generally tend to visit the closest retail or grocery store to their home, as opposed to more specialized activities for which they might travel longer distances). Accounting for these context-based behaviors can further enhance the co-accessibility estimations.

Third, our calculations reflect static qualities of the urban environment and consequently do not account for dynamic factors such as the time, season, or weather. These dynamic factors undoubtedly impact the co-accessibility of a destination. For instance, whether it's daytime or nighttime has been found to influence the (co)accessibility of public spaces [148]. Integrating data sources that encompass these dynamic factors could enhance the effectiveness of the implemented co-accessibility metrics.

Fourth, as discussed in 2, and drawing on insights from Chapters 4-6, the characteristics and quality of the streets and urban destinations may influence the degree to which a destination is accessible to different individuals and groups of people. While we provided methods to study the components of co-accessibility that are related to these characteristics, namely the *travel cost* and *destination attractiveness*, and generated insights on how the characteristics of the urban environment impact them, we did not integrate our findings into a resulting co-accessibility measure. For this integration, the findings of our study need to be quantified, clustered by demographic group, and transformed into input parameters of the functions that estimate the travel cost to reach a destination and the attractiveness of the destination. Additional research aimed at quantifying our findings and incorporating them into the functions of travel cost and destination attractiveness could lead to their integration into co-accessibility metrics and to an enhanced approach for measuring and understanding co-accessibility.

7.5. Implications

7.5.1. Implications for Urban Planning

A growing body of literature underscores the societal and health benefits of facilitating interactions among people and different demographic groups [99–102] such as the strengthening of the social ties among different groups, the cultivation of a sense of community or the reduction of loneliness. An important factor contributing to individuals physically encountering and interacting with one another is their capability to access common spaces [242, 243].

The concept of co-accessibility can be used in assessing this capability, aiding in the comparison and prioritization of different regions and neighborhoods according to their capacity to nurture social encounters. For example, co-accessibility measures could be employed to gauge the extent to which a city provides destinations conducive to encounters among individuals from diverse ethnic, income, or educational backgrounds.

Furthermore, co-accessibility offers a new tool through which urban planners and policy-makers can make evidence-informed interventions to address spatial segregation by designing urban destinations that are accessible to people from different demographic groups. Typically, mitigating segregation involves influencing where people reside, which may not always align with the inhabitants' preferences. This approach, while aimed at fostering more integrated communities, can sometimes clash with personal or group preferences for residency. When considering co-accessibility, the focus is not only on where people reside but also on the extent to which different demographic groups are enabled and promoted to access common urban destinations.

Moreover, a thorough examination of co-accessibility enables a nuanced understanding not only of the potential of various areas and destinations to facilitate interactions among diverse individuals but also of the characteristics inherent to areas that cultivate this potential. Thus, co-accessibility can offer a new perspective for understanding how urban planning and design can contribute to fostering more integrated and interconnected communities.

Lastly, co-accessibility can be leveraged to inform the design of destinations such that they accommodate the needs and desires of the individuals who have access to them. For instance, the results of our analyses in Chapters 2 and 3 reveal the degree to which destinations are co-accessible to adults, children, or older individuals. In the cases for which the results of co-accessibility indicate that a destination is accessible to a substantial number of children and older persons, particular attention can be directed towards designing the destination to accommodate both children and older persons. However, this undertaking must be approached with care, as it carries a risk of developing urban destinations designed for the predominant population groups that have access to them, inadvertently marginalizing minority groups.

7.5.2. IMPLICATIONS FOR REVISITING RECENTLY POPULAR URBAN MODELS

In recent years, there has been a growing academic and professional interest in urban models that revolve around accessibility by proximity, promote walking and other modes of active transportation, and reduce reliance on cars. A prominent example of such models is founded upon the *15-minute city*, sometimes also referred to more generically as the *X-minute city* concept [67]. Based on the 15-minute city concept, essential amenities, goods, healthcare, and leisure activities can be easily reached within a 15-minute walk or bike ride (sometimes also considering the public transit). The concept gained significant attention in 2020 when Anne Hidalgo, the mayor of Paris, integrated the 15-minute city principle into her re-election campaign strategy and began its implementation [66]. Following Paris's lead, various other cities have since incorporated this approach into their urban development strategies [65, 68].

An implementation of the 15-minute city concept can have a substantial change in individuals' daily mobility patterns encouraging them to spend more time within the 15-minute walkable or bikeable area around their home. This shift can influence the social encounter potential of different places within a city and may restrict interaction between demographic groups, especially those from marginalized communities. For instance, individuals predominantly performing activities and utilizing amenities within their 15-minute areas, are more likely to encounter people living within the same proximity. Currently, there is a lack of measures that capture how these 15-minute areas, the distribution of urban places, the population structure, and the potential of social encounters are interrelated. Co-accessibility could fill this gap, and serve as a valuable place-based accessibility measure offering insights into the potential implications of such urban models on spatial segregation and the potential encounters among different people and population groups.

7.5.3. IMPLICATIONS FOR THE DEVELOPMENT OF METHODS FOR CAPTURING URBAN ENVIRONMENT'S CHARACTERISTICS

Throughout this dissertation, we developed computational methods that assess, measure, or capture characteristics of the urban environment. The development of these methods involved navigating a critical balance between accuracy and simplicity, a decision heavily influenced by the specific problem being addressed. By discussing with both researchers and practitioners, we observed a tendency of researchers to focus on accuracy and practitioners on simplicity. As a result, researchers often develop sophisticated and complicated methods that practitioners can either not understand, and therefore do not trust, or cannot replicate and use [7, 9, 253].

To bridge the long-recognized gap between academic research and practical application, future research should consider adapting the proposed methods and tools to the needs of practitioners. Opting for methods that are simpler while possibly less accurate — provided that this lesser accuracy does not detrimentally affect the ability of professionals to make informed decisions — may serve as a viable approach to better align the objectives and approaches of academia and practice. Yet, this endeavor requires careful consideration, since the objective of research also involves striving for “perfection" and offering novel insights that can guide the practitioners.

7

7.5.4. IMPLICATIONS FOR THE DEVELOPMENT OF TOOLS USED TO ASSESS URBAN ACCESSIBILITY AND CO-ACCESSIBILITY

Interactive web tools emerged as a valuable medium for disseminating our research findings to a broader audience, involving both citizens and practitioners. By providing open access to our tools, displaying them at exhibitions, featuring them in invited presentations, and noticing how people use them, we gathered three preliminary observations that could be beneficial for future developers or researchers working on relevant tools.

First, despite the common inclination for "all-in-one" tools, a toolkit consisting of a set of specialized tools, each aimed at a unique purpose, facilitates a smoother process for the users to understand the information provided by these tools and then utilize or enhance them further. Second, an in-depth understanding of the limitations of relevant tools is beneficial for the users. The degree to which users grasp these limitations and avoid uncritically accepting a tool's outcomes is essential for its proper application. Third, having a comprehensive understanding of the completeness and quality of the disaggregated data used by a specific tool is important for the right use of the tool. Potential implications of missing or bad-quality data should not lead to misinterpretations.

7.5.5. IMPLICATIONS FOR FUTURE RESEARCH - BEYOND THE SCOPE OF THIS WORK

This work introduces co-accessibility as a broad concept but subsequently narrows its focus to measure, apply, and study it further. In practice, within the context of this work, co-accessibility is measured while focusing on one mode of travel, namely walking, a certain type of demographic group, namely age, and how the physical characteristics of the urban environment and the distribution of population impact these measurements. However, the study of co-accessibility could be realized under different lenses and co-accessibility measures can be extended to account for other modes of travel, and other demographic groups, or consider other aspects that might affect it. Over the next paragraphs, we present three potential future lines of research in the realm of co-accessibility.

OTHER MODES OF TRAVEL

Co-accessibility can be studied and measured while considering different modes of travel. In this context, measures of co-accessibility can serve a valuable function. They can be utilized, for instance, to evaluate and contrast how effectively the public transportation systems in different cities promote social encounters among diverse individuals and groups. This analysis can extend to understanding how the potential of such encounters varies when comparing different travel modes such as public transport, private modes of transportation, or bikes. By doing so, it can provide insights into the social dynamics fostered by various transportation modes in urban settings.

OTHER DEMOGRAPHIC GROUPS

The concept of co-accessibility is strongly tied to people's demographic characteristics. Throughout this dissertation, we focused on the age-related co-accessibility of urban destinations, assessing the potential of cities to foster intergenerational encounters. However, the definition and mathematical formulation of co-accessibility can support the study of other demographic characteristics as well. For instance, by adopting the proposed co-accessibility measures, the vast and expanding body of research that examines segregation phenomena, typically centered around ethnicity [81] or income [82], can benefit. Co-accessibility can offer a fresh lens through which to investigate segregation, extending beyond the commonly studied domains of residential [84], workplace [85], and educational environments [86].

VISITATION PATTERNS

In this work, co-accessibility is used to assess the potential of various individuals and groups to encounter each other across diverse urban locations. Our research is centered on assessing if there are opportunities offered within a city for such encounters to occur, rather than on whether these encounters actually take place. Studying the relation between the co-accessibility of urban destinations and actual visitation patterns can lead to an enhanced understanding of how offering spaces that are simultaneously accessible to different people and groups facilitates social encounters among them. This relationship might also reveal differences influenced by aspects outside the urban environment, such as the culture or social norms prevailing in an area. Understanding these nuances could unveil other underlying mechanisms that facilitate social encounters, shedding more light on the interplay between physical space, cultural context, and social behavior.

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REFERENCES

[1] M. L. Talal and M. V. Santelmann. 'Visitor access, use, and desired improvements in urban parks'. In: *Urban Forestry & Urban Greening* 63 (2021), p. 127216.

[2] D. A. Cohen, T. L. McKenzie, A. Sehgal, S. Williamson, D. Golinelli and N. Lurie. 'Contribution of public parks to physical activity'. In: *American journal of public health* 97.3 (2007), pp. 509–514.

[3] K. Lucas, B. Van Wee and K. Maat. 'A method to evaluate equitable accessibility: combining ethical theories and accessibility-based approaches'. In: *Transportation* 43.3 (2016), pp. 473–490.

[4] S. L. Handy and D. A. Niemeier. 'Measuring accessibility: an exploration of issues and alternatives'. In: *Environment and planning A* 29.7 (1997), pp. 1175–1194.

[5] W. G. Hansen. 'How accessibility shapes land use'. In: *Journal of the American Institute of planners* 25.2 (1959), pp. 73–76.

[6] G. H. Pirie. 'Measuring accessibility: a review and proposal'. In: *Environment and planning A* 11.3 (1979), pp. 299–312.

[7] K. T. Geurs and B. Van Wee. 'Accessibility evaluation of land-use and transport strategies: review and research directions'. In: *Journal of Transport geography* 12.2 (2004), pp. 127–140.

[8] M. Batty. 'Accessibility: in search of a unified theory'. In: *Environment and Planning B: Planning and Design* 36.2 (2009), pp. 191–194.

[9] S. Handy. 'Is accessibility an idea whose time has finally come?' In: *Transportation Research Part D: Transport and Environment* 83 (2020), p. 102319.

[10] P. R. Gould. 'Spatial Diffusion, Resource Paper No. 4.' In: (1969).

[11] Oxford English Dictionary. *accessible, adj.* Oxford University Press. Sept. 2023. URL: https://doi.org/10.1093/OED/1203427411.

[12] *The American Heritageő Dictionary of the English Language, Fifth Edition.* 5th. Copyright l'2022 by HarperCollins Publishers. All rights reserved. HarperCollins Publishers, 2022.

[13] M. Q. Dalvi and K. Martin. 'The measurement of accessibility: some preliminary results'. In: *Transportation* 5.1 (1976), pp. 17–42.

[14] M. Ben-Akiva and S. R. Lerman. 'Disaggregate travel and mobility-choice models and measures of accessibility'. In: *Behavioural travel modelling*. Routledge, 1979, pp. 654–679.

[15] V. Mehta. 'Evaluating public space'. In: *Journal of Urban design* 19.1 (2014), pp. 53–88.

[16] H. Wu and D. Levinson. 'Unifying access'. In: *Transportation Research Part D: Transport and Environment* 83 (2020), p. 102355.

[17] B. Moya-Gómez and J. C. García-Palomares. 'Working with the daily variation in infrastructure performance on territorial accessibility. The cases of Madrid and Barcelona'. In: *European Transport Research Review* 7 (2015), pp. 1–13.

[18] T. Hägerstrand. 'What about people in regional science?' In: *Papers of the Regional Science Association*. Vol. 24. 1970.

[19] H. J. Miller. 'Modelling accessibility using space-time prism concepts within geographical information systems'. In: *International Journal of Geographical Information System* 5.3 (1991), pp. 287–301.

[20] T. Neutens, T. Schwanen, F. Witlox and P. De Maeyer. 'My space or your space? Towards a measure of joint accessibility'. In: *Computers, Environment and Urban Systems* 32.5 (2008), pp. 331–342.

[21] J. Tang, Y. Song, H. J. Miller and X. Zhou. 'Estimating the most likely space–time paths, dwell times and path uncertainties from vehicle trajectory data: A time geographic method'. In: *Transportation Research Part C: Emerging Technologies* 66 (2016), pp. 176–194.

[22] C. Carrion and D. Levinson. 'Over-and under-estimation of travel time on commute trips: GPS vs. self-reporting'. In: *Urban Science* 3.3 (2019), p. 70.

[23] K. Martens. *Transport justice: Designing fair transportation systems*. Routledge, 2016.

[24] R. Kitamura, P. L. Mokhtarian and L. Laidet. 'A micro-analysis of land use and travel in five neighborhoods in the San Francisco Bay Area'. In: *Transportation* 24 (1997), pp. 125–158.

[25] E. Papa and P. Coppola. 'Gravity-based accessibility measures for integrated transport-land use planning (GraBAM)'. In: *Accessibility instruments for planning practice* 117 (2012), p. 124.

[26] E. Cascetta, A. Carten and M. Montanino. 'A new measure of accessibility based on perceived opportunities'. In: *Procedia-Social and Behavioral Sciences* 87 (2013), pp. 117–132.

[27] H. d. S. Lopes, V. Ribeiro and P. Remoaldo. 'Spatial accessibility and social inclusion: The impact of Portugal's last health reform'. In: *GeoHealth* 3.11 (2019), pp. 356–368.

[28] J. B. Lee and S. H. Salih. 'Passive transit accessibility: Modelling and application for transit gap analysis and station area assessment'. In: *Journal of Transport Geography* 114 (2024), p. 103757.

[29] H. J. Miller. 'Place-based versus people-based accessibility'. In: *Access to destinations*. Emerald Group Publishing Limited, 2005.

[30] M.-P. Kwan. 'From place-based to people-based exposure measures'. In: *Social science & medicine* 69.9 (2009), pp. 1311–1313.

[31] M. Flamm and V. Kaufmann. 'The concept of Network of Usual Places as a tool for analysing human activity spaces'. In: *11th World conference on transport research Berkeley*. 2007, pp. 1–28.

[32] C. Perchoux, B. Chaix, S. Cummins and Y. Kestens. 'Conceptualization and measurement of environmental exposure in epidemiology: accounting for activity space related to daily mobility'. In: *Health & place* 21 (2013), pp. 86–93.

[33] Y. Song, H. J. Miller, J. Stempihar and X. Zhou. 'Green accessibility: Estimating the environmental costs of network-time prisms for sustainable transportation planning'. In: *Journal of Transport Geography* 64 (2017), pp. 109–119.

[34] S. Farber, T. Neutens, H. J. Miller and X. Li. 'The social interaction potential of metropolitan regions: A time-geographic measurement approach using joint accessibility'. In: *Annals of the Association of American Geographers* 103.3 (2013), pp. 483–504.

[35] V. Brum-Bastos and A. Páez. 'Hägerstrand meets big data: time-geography in the age of mobility analytics'. In: *Journal of Geographical Systems* 25.3 (2023), pp. 327–336.

[36] S. Farber, M. O'Kelly, H. J. Miller and T. Neutens. 'Measuring segregation using patterns of daily travel behavior: A social interaction based model of exposure'. In: *Journal of transport geography* 49 (2015), pp. 26–38.

[37] OpenStreetMap contributors. *Planet dump retrieved from https://planet.osm.org*. https://www.openstreetmap.org.

[38] Centraal Bureau voor de Statistiek. *Kaart van 100 meter bij 100 meter met statistieken (Map of 100 meters by 100 meters with statistics 2020)*. https://www.cbs.nl/nl-nl/dossier/nederland-regionaal/geografische-data/kaart-van-100-meter-bij-100-meter-met-statistieken. Dataset. 2020.

[39] R. Vicente-Saez and C. Martinez-Fuentes. 'Open Science now: A systematic literature review for an integrated definition'. In: *Journal of business research* 88 (2018), pp. 428–436.

[40] UN General Assembly. *Transforming our world: the 2030 Agenda for Sustainable Development*. Resolution adopted by the General Assembly on 21 October 2015, A/RES/70/1. 2015. URL: https://www.refworld.org/docid/57b6e3e44.html (visited on 26/07/2023).

[41] M. A. Alfonzo. 'To walk or not to walk? The hierarchy of walking needs'. In: *Environment and behavior* 37.6 (2005), pp. 808–836.

[42] M. Stafford, T. Chandola and M. Marmot. 'Association between fear of crime and mental health and physical functioning'. In: *American journal of public health* 97.11 (2007), pp. 2076–2081.

[43] J. Jackson and M. Stafford. 'Public health and fear of crime: A prospective cohort study'. In: *The British Journal of Criminology* 49.6 (2009), pp. 832–847.

[44] S. Foster and B. Giles-Corti. 'The built environment, neighborhood crime and constrained physical activity: an exploration of inconsistent findings'. In: *Preventive medicine* 47.3 (2008), pp. 241–251.

[45] P. Mason, A. Kearns and M. Livingston. 'Safe Going: the influence of crime rates and perceived crime and safety on walking in deprived neighbourhoods'. In: *Social science & medicine* 91 (2013), pp. 15–24.

[46] T. D. Crowe. *Crime prevention through environmental design: applications of architectural design and space management concepts*. 2nd ed. Boston, Mass: Butterworth-Heinemann, 2000, p. 333. ISBN: 9780750671989.

[47] J. Jacobs. *The Death and Life of Great American Cities*. 1961.

[48] M. Carmona. *Public places urban spaces: The dimensions of urban design*. Routledge, 2021.

[49] UN-Habitat. *United Nations system-wide guidelines on safer cities and human settlements*. Report. 2020.

[50] V. Milias, A. Psyllidis and A. Bozzon. 'Bridging or separating? Co-accessibility as a measure of potential place-based encounters'. In: *Journal of Transport Geography* (). Under review.

[51] V. Milias and A. Psyllidis. 'Measuring spatial age segregation through the lens of co-accessibility to urban activities'. In: *Computers, Environment and Urban Systems* 95 (2022), p. 101829.

[52] *CTwalk Map: An interactive web tool that maps pedestrian accessibility and co-accessibility*. 2023. URL: https://bit.ly/ctwalkmap.

[53] V. Milias. *CTwalk: Mapping pedestrian (co)accessibility*. Demo presentation at NWO ICT.OPEN conference, Utrecht, the Netherlands, Apr. 2024. URL: https://bit.ly/ctwalkmap.

[54] V. Milias, S. Sharifi Noorian, A. Bozzon and A. Psyllidis. 'Is it safe to be attractive? Disentangling the influence of streetscape features on the perceived safety and attractiveness of city streets'. In: *AGILE: GIScience Series* 4 (2023), p. 8.

[55] T. Van Asten*, V. Milias*, A. Bozzon and A. Psyllidis. 'Eyes on the Street: Estimating Natural Surveillance Along Amsterdams City Streets Using Street-Level Imagery'. In: *International Conference on Computers in Urban Planning and Urban Management*. Springer. 2023, pp. 215–229.

[56] V. Milias, R. Teeuwen, A. Bozzon and A. Psyllidis. 'Crowdsourcing the influence of physical features on the likely use of public open spaces'. In: *Computational Urban Science* 4 (2024).

[57] D. Levinson and H. Wu. 'Towards a general theory of access'. In: *Journal of Transport and Land Use* 13.1 (2020), pp. 129–158.

[58] M. Schimpl, C. Moore, C. Lederer, A. Neuhaus, J. Sambrook, J. Danesh, W. Ouwehand and M. Daumer. 'Association between walking speed and age in healthy, free-living individuals using mobile accelerometrya cross-sectional study'. In: *PloS one* 6.8 (2011), e23299.

[59] C. E. Shannon. 'A mathematical theory of communication'. In: *The Bell system technical journal* 27.3 (1948), pp. 379–423.

[60] E. H. Simpson. 'Measurement of diversity'. In: *nature* 163.4148 (1949), pp. 688–688.

[61] C. W. Gini. 'Variability and mutability, contribution to the study of statistical distributions and relations'. In: *Studi Economico-Giuridici della R. Universita de Cagliari* (1912).

[62] R. Oldenburg. *The great good place: Cafés, coffee shops, community centers, beauty parlors, general stores, bars, hangouts, and how they get you through the day*. Paragon House Publishers, 1989.

[63] A. El-Geneidy and D. Levinson. 'Mapping accessibility over time'. In: *Journal of Maps* 3.1 (2007), pp. 76–87.

[64] D. O'Sullivan, A. Morrison and J. Shearer. 'Using desktop GIS for the investigation of accessibility by public transport: an isochrone approach'. In: *International Journal of Geographical Information Science* 14.1 (2000), pp. 85–104.

[65] M. Weng, N. Ding, J. Li, X. Jin, H. Xiao, Z. He and S. Su. 'The 15-minute walkable neighborhoods: Measurement, social inequalities and implications for building healthy communities in urban China'. In: *Journal of Transport & Health* 13 (2019), pp. 259–273.

[66] K. Willsher. 'Paris mayor unveils 15-minute cityplan in re-election campaign'. In: *the Guardian* 7 (2020), p. 2020.

[67] C. Moreno, Z. Allam, D. Chabaud, C. Gall and F. Pratlong. 'Introducing the 15-Minute City: Sustainability, resilience and place identity in future post-pandemic cities'. In: *Smart Cities* 4.1 (2021), pp. 93–111.

[68] G. Pozoukidou and Z. Chatziyiannaki. '15-Minute City: Decomposing the new urban planning eutopia'. In: *Sustainability* 13.2 (2021), p. 928.

[69] B. Caselli, M. Carra, S. Rossetti and M. Zazzi. 'Exploring the 15-minute neighbourhoods. An evaluation based on the walkability performance to public facilities'. In: *Transportation research procedia* 60 (2022), pp. 346–353.

[70] A. J. Daly, J. M. Baetens and B. De Baets. 'Ecological diversity: measuring the unmeasurable'. In: *Mathematics* 6.7 (2018), p. 119.

[71] R. S. Mendes, L. R. Evangelista, S. M. Thomaz, A. A. Agostinho and L. C. Gomes. 'A unified index to measure ecological diversity and species rarity'. In: *Ecography* 31.4 (2008), pp. 450–456.

[72] G. Boeing. 'OSMnx: New Methods for Acquiring, Constructing, Analyzing, and Visualizing Complex Street Networks'. In: *Computers, Environment and Urban Systems* 65 (2017), pp. 126–139. URL: https://geoffboeing.com/publications/osmnx-complex-street-networks/.

[73] C. Barrington-Leigh and A. Millard-Ball. 'The worlds user-generated road map is more than 80% complete'. In: *PloS one* 12.8 (2017), e0180698.

[74] D. Zielstra and H. H. Hochmair. 'Using free and proprietary data to compare shortest-path lengths for effective pedestrian routing in street networks'. In: *Transportation Research Record* 2299.1 (2012), pp. 41–47.

[75] Kadaster. *Basisregistratie grootschalige topografie*. https://www.kadaster.nl/zakelijk/registraties/basisregistraties/bgt. 2020.

[76] B. Hillier, A. Penn, J. Hanson, T. Grajewski and J. Xu. 'Natural movement: or, configuration and attraction in urban pedestrian movement'. In: *Environment and Planning B: planning and design* 20.1 (1993), pp. 29–66.

[77] L. Zhang and D. Pfoser. 'Using OpenStreetMap point-of-interest data to model urban changeA feasibility study'. In: *PloS one* 14.2 (2019), e0212606.

[78] T. Koukoletsos, M. Haklay and C. Ellul. 'Assessing data completeness of VGI through an automated matching procedure for linear data'. In: *Transactions in GIS* 16.4 (2012), pp. 477–498.

[79] T. M. Logan, M. J. Anderson, T. Williams and L. Conrow. 'Measuring inequalities in urban systems: An approach for evaluating the distribution of amenities and burdens'. In: *Computers, Environment and Urban Systems* 86 (2021), p. 101590.

[80] A. Pred. 'The choreography of existence: comments on Hägerstrand's time-geography and its usefulness'. In: *Economic geography* 53.2 (1977), pp. 207–221.

[81] S. F. Reardon and D. OSullivan. 'Measures of spatial segregation'. In: *Sociological methodology* 34.1 (2004), pp. 121–162.

[82] L. Vaughan and S. Arbaci. 'The challenges of understanding urban segregation'. In: *Built Environment* 37.2 (2011), pp. 128–138.

[83] I. Gordon and V. Monastiriotis. 'Urban size, spatial segregation and inequality in educational outcomes'. In: *Urban Studies* 43.1 (2006), pp. 213–236.

[84] C. Z. Charles. 'The dynamics of racial residential segregation'. In: *Annual review of sociology* 29.1 (2003), pp. 167–207.

[85] J. K. Hellerstein and D. Neumark. 'Workplace segregation in the United States: Race, ethnicity, and skill'. In: *The review of economics and statistics* 90.3 (2008), pp. 459–477.

[86] D. M. Frankel and O. Volij. 'Measuring school segregation'. In: *Journal of Economic Theory* 146.1 (2011), pp. 1–38.

[87] G. Lyons and K. Chatterjee. 'A human perspective on the daily commute: costs, benefits and trade-offs'. In: *Transport reviews* 28.2 (2008), pp. 181–198.

[88] D. Bissell. 'Micropolitics of mobility: Public transport commuting and everyday encounters with forces of enablement and constraint'. In: *Annals of the American Association of Geographers* 106.2 (2016), pp. 394–403.

[89] J. Jacobs. 'Jane jacobs'. In: *The Death and Life of Great American Cities* 21.1 (1961), pp. 13–25.

[90] E. Talen. 'The spatial logic of parks'. In: *Journal of Urban Design* 15.4 (2010), pp. 473–491.

[91] C. Rishbeth. 'Ethnic minority groups and the design of public open space: an inclusive landscape?' In: *Landscape research* 26.4 (2001), pp. 351–366.

[92] C. Gargiulo, F. Zucaro and F. Gaglione. 'A set of variables for the elderly accessibility in urban areas'. In: *TeMA-Journal of Land Use, Mobility and Environment* (2018), pp. 53–66.

[93] L. A. Merlin, D. Teoman, M. Viola, H. Vaughn and R. Buehler. 'Redrawing the planners circle: Analyzing trip-level walk distances across two national surveys'. In: *Journal of the American Planning Association* 87.4 (2021), pp. 470–483.

[94] R. Ewing and S. Handy. 'Measuring the unmeasurable: Urban design qualities related to walkability'. In: *Journal of Urban design* 14.1 (2009), pp. 65–84.

[95] T. M. DeJong. 'A comparison of three diversity indices based on their components of richness and evenness'. In: *Oikos* (1975), pp. 222–227.

[96] M. Schläpfer, L. Dong, K. OKeeffe, P. Santi, M. Szell, H. Salat, S. Anklesaria, M. Vazifeh, C. Ratti and G. B. West. 'The universal visitation law of human mobility'. In: *Nature* 593.7860 (2021), pp. 522–527.

[97] X. Xiao, L. Aultman-Hall, R. Manning and B. Voigt. 'The impact of spatial accessibility and perceived barriers on visitation to the US national park system'. In: *Journal of Transport Geography* 68 (2018), pp. 205–214.

[98] G. O. Hagestad and P. Uhlenberg. 'The social separation of old and young: A root of ageism'. In: *Journal of social issues* 61.2 (2005), pp. 343–360.

[99] G. O. Hagestad and P. Uhlenberg. 'Should we be concerned about age segregation? Some theoretical and empirical explorations'. In: *Research on aging* 28.6 (2006), pp. 638–653.

[100] J. S. Coleman. *The asymmetric society*. Syracuse University Press, 1982.

[101] R. Douglas and A. Barrett. 'Creative Cities Creating Connections: Fostering Cross-Age Interaction Through Leisure'. In: *Innovation in Aging* 4.Suppl 1 (2020), p. 438.

[102] W. H. Organization. *Global age-friendly cities: A guide*. World Health Organization, 2007.

[103] P. A. Rogerson and D. A. Plane. 'The dynamics of neighborhood age composition'. In: *Environment and Planning A* 30.8 (1998), pp. 1461–1472.

[104] D. O. Cowgill. 'Residential segregation by age in American metropolitan areas'. In: *Journal of Gerontology* 33.3 (1978), pp. 446–453.

[105] H. Beguin. 'The effect of urban spatial structure on residential mobility'. In: *The Annals of regional science* 16.3 (1982), pp. 16–35.

[106] S. Athey, B. Ferguson, M. Gentzkow and T. Schmidt. 'Estimating experienced racial segregation in US cities using large-scale GPS data'. In: *Proceedings of the National Academy of Sciences* 118.46 (2021).

[107] K. A. Cagney. 'Neighborhood age structure and its implications for health'. In: *Journal of Urban Health* 83.5 (2006), pp. 827–834.

[108] A. Sabater, E. Graham and N. Finney. 'The spatialities of ageing: Evidencing increasing spatial polarisation between older and younger adults in England and Wales'. In: *Demographic Research* 36 (2017), pp. 731–744.

[109] G. Deng and L. Mao. ‘Spatially Explicit Age Segregation Index and Self-Rated Health of Older Adults in US Cities’. In: *ISPRS International Journal of Geo-Information* 7.9 (2018), p. 351.

[110] D. W. Wong and S.-L. Shaw. ‘Measuring segregation: An activity space approach’. In: *Journal of geographical systems* 13.2 (2011), pp. 127–145.

[111] Y. Song, L. Merlin and D. Rodriguez. ‘Comparing measures of urban land use mix’. In: *Computers, Environment and Urban Systems* 42 (2013), pp. 1–13.

[112] J. Xu. ‘From walking buffers to active places: An activity-based approach to measure human-scale urban form’. In: *Landscape and urban planning* 191 (2019), p. 103452.

[113] J.-P. Zock, R. Verheij, M. Helbich, B. Volker, P. Spreeuwenberg, M. Strak, N. A. Janssen, M. Dijst and P. Groenewegen. ‘The impact of social capital, land use, air pollution and noise on individual morbidity in Dutch neighbourhoods’. In: *Environment international* 121 (2018), pp. 453–460.

[114] D. W. Wong. ‘Spatial indices of segregation’. In: *Urban studies* 30.3 (1993), pp. 559–572.

[115] I. Schnell and B. Yoav. ‘The sociospatial isolation of agents in everyday life spaces as an aspect of segregation’. In: *Annals of the Association of American Geographers* 91.4 (2001), pp. 622–636.

[116] D. W. Wong. ‘Modeling local segregation: a spatial interaction approach’. In: *Geographical and Environmental Modelling* 6.1 (2002), pp. 81–97.

[117] M.-P. Kwan. ‘Beyond space (as we knew it): Toward temporally integrated geographies of segregation, health, and accessibility: Space–time integration in geography and GIScience’. In: *Annals of the Association of American Geographers* 103.5 (2013), pp. 1078–1086.

[118] M. W. Horner. ‘Exploring metropolitan accessibility and urban structure’. In: *Urban Geography* 25.3 (2004), pp. 264–284.

[119] D. S. Vale, M. Saraiva and M. Pereira. ‘Active accessibility: A review of operational measures of walking and cycling accessibility’. In: *Journal of transport and land use* 9.1 (2016), pp. 209–235.

[120] A. Páez, D. M. Scott and C. Morency. ‘Measuring accessibility: positive and normative implementations of various accessibility indicators’. In: *Journal of Transport Geography* 25 (2012), pp. 141–153.

[121] R. Winkler and R. Klaas. ‘Residential segregation by age in the United States’. In: *Journal of Maps* 8.4 (2012), pp. 374–378.

[122] A. J. Lehning, N. Mattocks, R. J. Smith, K. Kim and J. H. Cheon. ‘Neighborhood Age Composition and Self-Rated Health: Findings from a Nationally Representative Study’. In: *Journal of Gerontological Social Work* 64.3 (2021), pp. 257–273.

[123] W. H. Organization *et al.* ‘Measuring the age-friendliness of cities: A guide to using core indicators’. In: (2015).

[124] Z. A. Hamstead, D. Fisher, R. T. Ilieva, S. A. Wood, T. McPhearson and P. Kremer. ‘Geolocated social media as a rapid indicator of park visitation and equitable park access’. In: *Computers, Environment and Urban Systems* 72 (2018), pp. 38–50.

[125] E. Talen and L. Anselin. ‘Assessing spatial equity: an evaluation of measures of accessibility to public playgrounds’. In: *Environment and planning A* 30.4 (1998), pp. 595–613.

7

[126] K. Kelobonye, H. Zhou, G. McCarney and J. C. Xia. 'Measuring the accessibility and spatial equity of urban services under competition using the cumulative opportunities measure'. In: *Journal of Transport Geography* 85 (2020), p. 102706.

[127] E. Moro, D. Calacci, X. Dong and A. Pentland. 'Mobility patterns are associated with experienced income segregation in large US cities'. In: *Nature communications* 12.1 (2021), pp. 1–10.

[128] N. I. Larson, M. T. Story and M. C. Nelson. 'Neighborhood environments: disparities in access to healthy foods in the US'. In: *American journal of preventive medicine* 36.1 (2009), pp. 74–81.

[129] A. L. Escaron, A. M. Meinen, S. A. Nitzke and A. P. Martinez-Donate. 'Peer reviewed: supermarket and grocery store–based interventions to promote healthful food choices and eating practices: a systematic review'. In: *Preventing chronic disease* 10 (2013).

[130] S. Hoogendoorn-Lanser, N. T. Schaap and M.-J. OldeKalter. 'The Netherlands Mobility Panel: An innovative design approach for web-based longitudinal travel data collection'. In: *Transportation Research Procedia* 11 (2015), pp. 311–329.

[131] B. S. Pushkarev and J. M. Zupan. *Urban Space for Pedestrians.* MIT Press, 1975.

[132] C. M. Guy and N. Wrigley. 'Walking trips to shops in British cities: an empirical review and policy re-examination'. In: *The Town Planning Review* (1987), pp. 63–79.

[133] J. Zacharias. 'Pedestrian behavior and perception in urban walking environments'. In: *Journal of planning literature* 16.1 (2001), pp. 3–18.

[134] P. Waddell and G. F. Ulfarsson. 'Accessibility and agglomeration: Discrete-choice models of employment location by industry sector'. In: *82nd annual meeting of the Transportation Research Board, Washington, DC.* Vol. 63. Citeseer. 2003.

[135] M. Kent. *Vegetation description and data analysis: a practical approach.* John Wiley & Sons, 2011.

[136] E. C. Pielou. 'The measurement of diversity in different types of biological collections'. In: *Journal of theoretical biology* 13 (1966), pp. 131–144.

[137] Centraal Bureau voor de Statistiek. *More and more young children grow up in large cities.* `https://www.cbs.nl/en-gb/news/2013/07/more-and-more-young-children-grow-up-in-large-cities`. Statistics. 2013.

[138] A. Sevtsuk and R. Kalvo. 'Predicting pedestrian flow along city streets: A comparison of route choice estimation approaches in downtown San Francisco'. In: *International Journal of Sustainable Transportation* (2020), pp. 1–15.

[139] A. S. Miranda, Z. Fan, F. Duarte and C. Ratti. 'Desirable streets: Using deviations in pedestrian trajectories to measure the value of the built environment'. In: *Computers, Environment and Urban Systems* 86 (2021), p. 101563.

[140] J. Anderson, K. Ruggeri, K. Steemers and F. Huppert. 'Lively social space, well-being activity, and urban design: findings from a low-cost community-led public space intervention'. In: *Environment and behavior* 49.6 (2017), pp. 685–716.

[141] M. Stevenson, J. Thompson, T. H. de Sá, R. Ewing, D. Mohan, R. McClure, I. Roberts, G. Tiwari, B. Giles-Corti, X. Sun *et al.* 'Land use, transport, and population health: estimating the health benefits of compact cities'. In: *The lancet* 388.10062 (2016), pp. 2925–2935.

[142] M. Traunmueller, P. Marshall and L. Capra. 'Crowdsourcing safety perceptions of people: Opportunities and limitations'. In: *International Conference on Social Informatics.* Springer. 2015, pp. 120–135.

[143] C. Harvey, L. Aultman-Hall, S. E. Hurley and A. Troy. 'Effects of skeletal streetscape design on perceived safety'. In: *Landscape and Urban Planning* 142 (2015), pp. 18–28.

[144] W. H. Whyte. *City: Rediscovering the center*. University of Pennsylvania Press, 2012.

[145] A. Adkins, J. Dill, G. Luhr and M. Neal. 'Unpacking walkability: Testing the influence of urban design features on perceptions of walking environment attractiveness'. In: *Journal of urban design* 17.4 (2012), pp. 499–510.

[146] V. Mehta. 'Look closely and you will see, listen carefully and you will hear: Urban design and social interaction on streets'. In: *Journal of Urban Design* 14.1 (2009), pp. 29–64.

[147] R. Basu and A. Sevtsuk. 'How do street attributes affect willingness-to-walk? City-wide pedestrian route choice analysis using big data from Boston and San Francisco'. In: *Transportation research part A: policy and practice* 163 (2022), pp. 1–19.

[148] Y. Park and M. Garcia. 'Pedestrian safety perception and urban street settings'. In: *International journal of sustainable transportation* 14.11 (2020), pp. 860–871.

[149] J. F. Sallis, E. Cerin, J. Kerr, M. A. Adams, T. Sugiyama, L. B. Christiansen, J. Schipperijn, R. Davey, D. Salvo, L. D. Frank *et al.* 'Built environment, physical activity, and obesity: findings from the international physical activity and environment network (IPEN) adult study'. In: *Annual review of public health* 41 (2020), pp. 119–139.

[150] D. Ding and K. Gebel. 'Built environment, physical activity, and obesity: what have we learned from reviewing the literature?' In: *Health & place* 18.1 (2012), pp. 100–105.

[151] Y. Rydin, A. Bleahu, M. Davies, J. D. Dávila, S. Friel, G. De Grandis, N. Groce, P. C. Hallal, I. Hamilton, P. Howden-Chapman *et al.* 'Shaping cities for health: complexity and the planning of urban environments in the 21st century'. In: *The lancet* 379.9831 (2012), pp. 2079–2108.

[152] D. W. Barnett, A. Barnett, A. Nathan, J. Van Cauwenberg and E. Cerin. 'Built environmental correlates of older adults total physical activity and walking: a systematic review and meta-analysis'. In: *International journal of behavioral nutrition and physical activity* 14.1 (2017), pp. 1–24.

[153] D. Candeia, F. Figueiredo, N. Andrade and D. Quercia. 'Multiple images of the city: Unveiling group-specific urban perceptions through a crowdsourcing game'. In: *Proceedings of the 28th ACM Conference on Hypertext and Social Media*. 2017, pp. 135–144.

[154] X. J. Cao. 'How does neighborhood design affect life satisfaction? Evidence from Twin Cities'. In: *Travel behaviour and society* 5 (2016), pp. 68–76.

[155] C. Y. Jim and X. Shan. 'Socioeconomic effect on perception of urban green spaces in Guangzhou, China'. In: *Cities* 31 (2013), pp. 123–131.

[156] J. Won, C. Lee, S. N. Forjuoh and M. G. Ory. 'Neighborhood safety factors associated with older adults' health-related outcomes: a systematic literature review'. In: *Social Science & Medicine* 165 (2016), pp. 177–186.

[157] A. Uslu *et al.* 'Social interaction in urban transformation areas and the characteristics of urban outdoor spaces: a case study from Turkey'. In: *African Journal of Agricultural Research* 5.20 (2010), pp. 2801–2810.

[158] H. Zhou, J. Wang and K. Wilson. 'Impacts of perceived safety and beauty of park environments on time spent in parks: Examining the potential of street view imagery and phone-based GPS data'. In: *International Journal of Applied Earth Observation and Geoinformation* 115 (2022), p. 103078.

[159] F. Biljecki and K. Ito. 'Street view imagery in urban analytics and GIS: A review'. In: *Landscape and Urban Planning* 215 (2021), p. 104217.

[160] M. Bubalo, B. T. van Zanten and P. H. Verburg. 'Crowdsourcing geo-information on landscape perceptions and preferences: A review'. In: *Landscape and Urban Planning* 184 (2019), pp. 101–111.

[161] P. Salesses, K. Schechtner and C. A. Hidalgo. 'The collaborative image of the city: mapping the inequality of urban perception'. In: *PloS one* 8.7 (2013), e68400.

[162] N. Naik, J. Philipoom, R. Raskar and C. Hidalgo. 'Streetscore-predicting the perceived safety of one million streetscapes'. In: *Proceedings of the IEEE conference on computer vision and pattern recognition workshops*. 2014, pp. 779–785.

[163] K. Mouratidis. 'The impact of urban tree cover on perceived safety'. In: *Urban Forestry & Urban Greening* 44 (2019), p. 126434.

[164] H. C. Borst, H. M. Miedema, S. I. de Vries, J. M. Graham and J. E. van Dongen. 'Relationships between street characteristics and perceived attractiveness for walking reported by elderly people'. In: *Journal of environmental psychology* 28.4 (2008), pp. 353–361.

[165] S. Beliga, A. Metrovi and S. Martini-Ipi. 'An overview of graph-based keyword extraction methods and approaches'. In: *Journal of information and organizational sciences* 39.1 (2015), pp. 1–20.

[166] R. Abascal-Mena, R. Lema and F. Sèdes. 'Detecting sociosemantic communities by applying social network analysis in tweets'. In: *Social Network Analysis and Mining* 5.1 (2015), pp. 1–17.

[167] M. Honnibal and M. Johnson. 'An improved non-monotonic transition system for dependency parsing'. In: *Proceedings of the 2015 conference on empirical methods in natural language processing*. 2015, pp. 1373–1378.

[168] Y. Vasiliev. *Natural Language Processing with Python and SpaCy: A Practical Introduction*. No Starch Press, 2020.

[169] T. Ramírez, R. Hurtubia, H. Lobel and T. Rossetti. 'Measuring heterogeneous perception of urban space with massive data and machine learning: An application to safety'. In: *Landscape and Urban Planning* 208 (2021), p. 104002.

[170] R. Ewing, O. Clemente, K. M. Neckerman, M. Purciel-Hill, J. W. Quinn and A. Rundle. *Measuring urban design: Metrics for livable places*. Vol. 200. Springer, 2013.

[171] N. Basu, O. Oviedo-Trespalacios, M. King, M. Kamruzzaman and M. M. Haque. 'The influence of the built environment on pedestrians perceptions of attractiveness, safety and security'. In: *Transportation research part F: traffic psychology and behaviour* 87 (2022), pp. 203–218.

[172] D. Quercia, N. K. O'Hare and H. Cramer. 'Aesthetic capital: what makes London look beautiful, quiet, and happy?' In: *Proceedings of the 17th ACM conference on Computer supported cooperative work & social computing*. 2014, pp. 945–955.

[173] R. C. Smardon. 'Perception and aesthetics of the urban environment: Review of the role of vegetation'. In: *Landscape and Urban planning* 15.1-2 (1988), pp. 85–106.

[174] W. R. Tobler. 'A computer movie simulating urban growth in the Detroit region'. In: *Economic geography* 46.sup1 (1970), pp. 234–240.

[175] C. P. Tribby, H. J. Miller, B. B. Brown, C. M. Werner and K. R. Smith. 'Analyzing walking route choice through built environments using random forests and discrete choice techniques'. In: *Environment and Planning B: Urban Analytics and City Science* 44.6 (2017), pp. 1145–1167.

[176] V. Mehta. 'Walkable streets: pedestrian behavior, perceptions and attitudes'. In: *Journal of Urbanism* 1.3 (2008), pp. 217–245.

[177] L. Groshong, S. A. Wilhelm Stanis, A. T. Kaczynski and J. A. Hipp. 'Attitudes about perceived park safety among residents in low-income and high minority Kansas City, Missouri, neighborhoods'. In: *Environment and Behavior* 52.6 (2020), pp. 639–665.

[178] O. Newman. *Defensible Space*. Macmillan New York, 1972. ISBN: 0851391362.

[179] H. Barton. 'Strengthening the roots of planning'. In: *Planning theory & practice* 11.1 (2010), pp. 95–101.

[180] P. Cozens and D. Hillier. 'Revisiting Jane Jacobs's eyes on the street for the twenty-first century: Evidence from environmental criminology'. In: *The Urban Wisdom of Jane Jacobs*. Routledge, 2012, pp. 196–214. ISBN: 9780203095171. DOI: 10.4324/9780203095171.

[181] P. Cozens. 'Crime and community safety: Challenging the design consensus'. In: *The Routledge handbook of planning for health and well-being*. Routledge, 2015, pp. 196–211.

[182] S. Foster, B. Giles-Corti and M. Knuiman. 'Creating safe walkable streetscapes: Does house design and upkeep discourage incivilities in suburban neighbourhoods?' In: *Journal of Environmental Psychology* 31.1 (2011), pp. 79–88. ISSN: 0272-4944. DOI: 10.1016/j.jenvp.2010.03.005.

[183] D. M. Reynald and H. Elffers. 'The Future of Newman's Defensible Space Theory'. In: *European Journal of Criminology* 6.1 (2009), pp. 25–46. ISSN: 1477-3708. DOI: 10.1177/1477370808098103.

[184] I. Lee, S. Jung, J. Lee and E. Macdonald. 'Street crime prediction model based on the physical characteristics of a streetscape: Analysis of streets in low-rise housing areas in South Korea'. In: *Environment and Planning B: Urban Analytics and City Science* 46.5 (2017), pp. 862–879. ISSN: 2399-8083. DOI: 10.1177/2399808317735105.

[185] M. Peeters and T. Vander Beken. 'The relation of CPTED characteristics to the risk of residential burglary in and outside the city center of Ghent'. In: *Applied Geography* 86 (2017), pp. 283–291. ISSN: 0143-6228. DOI: 10.1016/j.apgeog.2017.06.012.

[186] D. Shach-Pinsly. 'Measuring security in the built environment: Evaluating urban vulnerability in a human-scale urban form'. In: *Landscape and Urban Planning* 191 (2019), p. 103412. ISSN: 0169-2046. DOI: 10.1016/j.landurbplan.2018.08.022.

[187] S. Amiri and D. R. Crain. 'Quantifying Jacobs notion of eyes upon the streetin 3-dimensions'. In: *Journal of Urban Design* 25.4 (2020), pp. 467–485.

[188] M. De Nadai, Y. Xu, E. Letouzé, M. C. González and B. Lepri. 'Socio-economic, built environment, and mobility conditions associated with crime: a study of multiple cities'. In: *Scientific Reports* 10.1 (2020). ISSN: 2045-2322. DOI: 10.1038/s41598-020-70808-2.

[189] M. D. Jong, W. A. Wagenaar, G. Wolters and I. M. Verstijnen. 'Familiar face recognition as a function of distance and illumination: a practical tool for use in the courtroom'. In: *Psychology, Crime and Law* 11.1 (2005), pp. 87–97. ISSN: 1068-316X. DOI: 10.1080/10683160410001715123.

[190] R. C. Lindsay, C. Semmler, N. Weber, N. Brewer and M. R. Lindsay. 'How variations in distance affect eyewitness reports and identification accuracy'. In: *Law Hum Behav* 32.6 (2008), pp. 526–35. ISSN: 0147-7307. DOI: 10.1007/s10979-008-9128-x.

[191] C.-K. Li, H.-X. Zhang, J.-X. Liu, Y.-Q. Zhang, S.-C. Zou and Y.-T. Fang. 'Window Detection in Facades Using Heatmap Fusion'. In: *Journal of Computer Science and Technology* 35.4 (2020), pp. 900–912. DOI: 10.1007/s11390-020-0253-4. URL: %7Bhttp://jcst.ict.ac.cn/CN/abstract/article_2660.shtml%7D.

[192] S. Qiu, A. Psyllidis, A. Bozzon and G.-J. Houben. 'Crowd-Mapping Urban Objects from Street-Level Imagery'. In: *The World Wide Web Conference*. 2019, pp. 1521–1531.

[193] S. Sharifi Noorian, S. Qiu, A. Psyllidis, A. Bozzon and G.-J. Houben. 'Detecting, Classifying, and Mapping Retail Storefronts Using Street-level Imagery'. In: *Proceedings of the 2020 International Conference on Multimedia Retrieval*. 2020, pp. 495–501.

[194] Gemeente Amsterdam. *Verantwoordingsdocument Veiligheidsindex 2014*. Report. 2015.

[195] P. Cozens and T. Love. 'A Review and Current Status of Crime Prevention through Environmental Design (CPTED)'. In: *Journal of Planning Literature* 30.4 (2015), pp. 393–412. ISSN: 0885-4122. DOI: 10.1177/0885412215595440.

[196] O. Teboul, I. Kokkinos, L. Simon, P. Koutsourakis and N. Paragios. 'Shape grammar parsing via reinforcement learning'. In: *CVPR 2011*. IEEE. 2011, pp. 2273–2280.

[197] F. Korc and W. Förstner. 'eTRIMS Image Database for interpreting images of man-made scenes'. In: *Dept. of Photogrammetry, University of Bonn, Tech. Rep. TR-IGG-P-2009-01* (2009).

[198] H. Riemenschneider, U. Krispel, W. Thaller, M. Donoser, S. Havemann, D. Fellner and H. Bischof. 'Irregular lattices for complex shape grammar facade parsing'. In: *2012 IEEE conference on computer vision and pattern recognition*. IEEE. 2012, pp. 1640–1647.

[199] G. Saville and G. Cleveland. 'Second-Generation CPTED: The rise and fall of opportunity theory'. In: *21st century security and CPTED*. Auerbach Publications, 2008, pp. 93–104.

[200] R. Ewing, S. Handy, R. C. Brownson, O. Clemente and E. Winston. 'Identifying and measuring urban design qualities related to walkability'. In: *Journal of Physical Activity and Health* 3.s1 (2006), S223–S240.

[201] T. Neutens, S. Farber, M. Delafontaine and K. Boussauw. 'Spatial variation in the potential for social interaction: A case study in Flanders (Belgium)'. In: *Computers, Environment and Urban Systems* 41 (2013), pp. 318–331.

[202] R. D. Putnam *et al. Bowling alone: The collapse and revival of American community*. Simon and schuster, 2000.

[203] J. Montgomery. 'Making a city: Urbanity, vitality and urban design'. In: *Journal of urban design* 3.1 (1998), pp. 93–116.

[204] D. A. Cohen, T. Marsh, S. Williamson, K. P. Derose, H. Martinez, C. Setodji and T. L. McKenzie. 'Parks and physical activity: why are some parks used more than others?' In: *Preventive medicine* 50 (2010), S9–S12.

[205] B. B. Lin, R. A. Fuller, R. Bush, K. J. Gaston and D. F. Shanahan. 'Opportunity or orientation? Who uses urban parks and why'. In: *PLoS one* 9.1 (2014), e87422.

[206] J. R. Wolch, J. Byrne and J. P. Newell. 'Urban green space, public health, and environmental justice: The challenge of making cities just green enough'. In: *Landscape and urban planning* 125 (2014), pp. 234–244.

[207] W. H. Whyte *et al. The social life of small urban spaces*. Conservation Foundation Washington, DC, 1980.

[208] A. C. K. Lee, H. C. Jordan and J. Horsley. ‘Value of urban green spaces in promoting healthy living and wellbeing: prospects for planning’. In: *Risk management and healthcare policy* (2015), pp. 131–137.

[209] K. K. Peschardt, J. Schipperijn and U. K. Stigsdotter. ‘Use of small public urban green spaces (SPUGS)’. In: *Urban forestry & urban greening* 11.3 (2012), pp. 235–244.

[210] E. P. Sundevall and M. Jansson. ‘Inclusive parks across ages: Multifunction and urban open space management for children, adolescents, and the elderly’. In: *International journal of environmental research and public health* 17.24 (2020), p. 9357.

[211] C. Wen, C. Albert and C. Von Haaren. ‘The elderly in green spaces: Exploring requirements and preferences concerning nature-based recreation’. In: *Sustainable cities and society* 38 (2018), pp. 582–593.

[212] T. Skelton. ‘Nothing to do, nowhere to go?: teenage girls and publicspace in the Rhondda Valleys, South Wales’. In: *Children’s geographies*. Routledge, 2004, pp. 69–85.

[213] A. Phillips, A. Z. Khan and F. Canters. ‘Use-related and socio-demographic variations in urban green space preferences’. In: *Sustainability* 13.6 (2021), p. 3461.

[214] P. Jankowski, M. Czepkiewicz, M. Modkowski and Z. Zwoliski. ‘Geo-questionnaire: A method and tool for public preference elicitation in land use planning’. In: *Transactions in GIS* 20.6 (2016), pp. 903–924.

[215] E. Talen, K. W. Choe, G. N. Akcelik, M. G. Berman and K. L. Meidenbauer. ‘Street design preference: an on-line survey’. In: *Journal of Urban Design* 28.1 (2023), pp. 1–24.

[216] M. J. Koohsari, J. A. Karakiewicz and A. T. Kaczynski. ‘Public open space and walking: the role of proximity, perceptual qualities of the surrounding built environment, and street configuration’. In: *Environment and Behavior* 45.6 (2013), pp. 706–736.

[217] Y. Lu. ‘Using Google Street View to investigate the association between street greenery and physical activity’. In: *Landscape and Urban Planning* 191 (2019), p. 103435.

[218] L. Levy-Storms, L. Chen and A. Loukaitou-Sideris. ‘Older adults needs and preferences for open space and physical activity in and near parks: A systematic review’. In: *Journal of Aging and Physical Activity* 26.4 (2018), pp. 682–696.

[219] E. Talen and M. Coffindaffer. ‘The utopianism of children: an empirical study of children’s neighborhood design preferences’. In: *Journal of Planning Education and Research* 18.4 (1999), pp. 321–331.

[220] World Health Organization Regional Office for Europe. *Urban green spaces: a brief for action*. Report. 2017.

[221] Ambiente Italia. *European Common Indicators: Towards a Local Sustainability Profile*. Report. Ambiente Italia Research Institute, 2003.

[222] S. Amiri and D. R. Crain. ‘Quantifying Jacobs notion of eyes upon the street in 3-dimensions’. In: *Journal of Urban Design* 25.4 (2019), pp. 467–485. ISSN: 1357-4809 1469-9664. DOI: 10.1080/13574809.2019.1691440.

[223] H. Kruize, I. van Kamp, M. van den Berg, E. van Kempen, W. Wendel-Vos, A. Ruijsbroek, W. Swart, J. Maas, C. Gidlow, G. Smith *et al.* ‘Exploring mechanisms underlying the relationship between the natural outdoor environment and health and well-being–Results from the PHENOTYPE project’. In: *Environment international* 134 (2020), p. 105173.

7

[224] M. Van den Berg, M. Van Poppel, I. Van Kamp, S. Andrusaityte, B. Balseviciene, M. Cirach, A. Daneliciute, N. Ellis, G. Hurst, D. Masterson *et al.* 'Visiting green space is associated with mental health and vitality: A cross-sectional study in four european cities'. In: *Health & place* 38 (2016), pp. 8–15.

[225] W. H. Kruskal and W. A. Wallis. 'Use of ranks in one-criterion variance analysis'. In: *Journal of the American statistical Association* 47.260 (1952), pp. 583–621.

[226] P. E. McKight and J. Najab. 'Kruskal-wallis test'. In: *The corsini encyclopedia of psychology* (2010), pp. 1–1.

[227] R. A. Armstrong. 'When to use the B onferroni correction'. In: *Ophthalmic and Physiological Optics* 34.5 (2014), pp. 502–508.

[228] H. B. Mann and D. R. Whitney. 'On a test of whether one of two random variables is stochastically larger than the other'. In: *The annals of mathematical statistics* (1947), pp. 50–60.

[229] F. Wilcoxon. 'Individual comparisons by ranking methods'. In: *Breakthroughs in statistics: Methodology and distribution.* Springer, 1992, pp. 196–202.

[230] V. Clarke and V. Braun. 'Successful qualitative research: A practical guide for beginners'. In: *Successful qualitative research* (2013), pp. 1–400.

[231] W. C. Sullivan, F. E. Kuo and S. F. Depooter. 'The fruit of urban nature: Vital neighborhood spaces'. In: *Environment and behavior* 36.5 (2004), pp. 678–700.

[232] R. L. Coley, W. C. Sullivan and F. E. Kuo. 'Where does community grow? The social context created by nature in urban public housing'. In: *Environment and behavior* 29.4 (1997), pp. 468–494.

[233] N. Linday. 'It all comes down to a comfortable place to sit and watch'. In: *Landscape Architecture* 68.6 (1978), pp. 492–497.

[234] B. Golinik and C. W. Thompson. 'Emerging relationships between design and use of urban park spaces'. In: *Landscape and urban planning* 94.1 (2010), pp. 38–53.

[235] L. Bertolini. 'From streets for traffic to streets for people: can street experiments transform urban mobility?' In: *Transport reviews* 40.6 (2020), pp. 734–753.

[236] C. W. Thompson. 'Urban open space in the 21st century'. In: *Landscape and urban planning* 60.2 (2002), pp. 59–72.

[237] P. Navarrete-Hernandez, A. Vetro and P. Concha. 'Building safer public spaces: Exploring gender difference in the perception of safety in public space through urban design interventions'. In: *Landscape and Urban Planning* 214 (2021), p. 104180.

[238] E. Rees-Punia, E. D. Hathaway and J. L. Gay. 'Crime, perceived safety, and physical activity: A meta-analysis'. In: *Preventive medicine* 111 (2018), pp. 307–313.

[239] M. M. Webber. *The urban place and the nonplace urban realm.* 1964.

[240] J. Ryan and R. H. Pereira. 'What are we missing when we measure accessibility? Comparing calculated and self-reported accounts among older people'. In: *Journal of transport geography* 93 (2021), p. 103086.

[241] C. Silva, L. Bertolini, M. te Brömmelstroet, D. Milakis and E. Papa. 'Accessibility instruments in planning practice: Bridging the implementation gap'. In: *Transport Policy* 53 (2017), pp. 135–145.

[242] J. Levine, J. Grengs and L. A. Merlin. *From mobility to accessibility: Transforming urban transportation and land-use planning.* Cornell University Press, 2019.

[243] G. Lanza, P. Pucci and L. Carboni. ‘Measuring accessibility by proximity for an inclusive city’. In: *Cities* 143 (2023), p. 104581.

[244] O. Järv, A. Masso, S. Silm and R. Ahas. ‘The link between ethnic segregation and socio-economic status: An activity space approach’. In: *Tijdschrift voor economische en sociale geografie* 112.3 (2021), pp. 319–335.

[245] R. G. Golledge. *Spatial behavior: A geographic perspective.* Guilford Press, 1997.

[246] G. P. Whitfield, S. A. Carlson, E. N. Ussery, K. B. Watson, D. R. Brown, D. Berrigan and J. E. Fulton. ‘Racial and ethnic differences in perceived safety barriers to walking, United States National Health Interview Survey–2015’. In: *Preventive medicine* 114 (2018), pp. 57–63.

[247] A. Karner, K. Levine, L. Alcorn, M. Situ, D. Rowangould, K. Kim and A. Kocatepe. *Accessibility measures in practice: A guide for transportation agencies.* NCHRP Project 08-121. 2022.

[248] V. Milias. *CTwalk: Mapping pedestrian (co)accessibility.* Dutch Design Week. Eindhoven, Netherlands, 2023. URL: https://bit.ly/ctwalkmap.

[249] *CTstreets Map: An interactive web tool that maps walkability in Amsterdam, The Netherlands.* Online. 2023. URL: https://bit.ly/ctstreets.

[250] *Chapter 4: Dataset including perceived safety and attractiveness ratings of city streets in Frankfurt, Germany.* Github/Zenodo, Mar. 2023. DOI: https://zenodo.org/records/7712811.

[251] *Chapters 2 and 3: Code and data of the empirical analysis.* Github/Zenodo, May 2022. DOI: https://doi.org/10.5281/zenodo.10656707. URL: https://github.com/MiliasV/coaccessibility/.

[252] *Chapter 5: Code and data for the empirical analysis.* Github/Zenodo, May 2023. DOI: https://zenodo.org/doi/10.5281/zenodo.10782534. URL: https://github.com/MiliasV/natural-surveillance.

[253] E. J. Miller. ‘Accessibility: measurement and application in transportation planning’. In: *Transport Reviews* 38.5 (2018), pp. 551–555.

[254] M. Cardoso, V. Milias and M. Harteveld. ‘Developing a city-specific walkability index through a participatory approach’. In: *AGILE: GIScience Series* (2024).

[255] R. Teeuwen, V. Milias, A. Bozzon and A. Psyllidis. ‘How well do NDVI and OpenStreetMap data capture peoples visual perceptions of urban greenspace?’ In: *Landscape and Urban Planning* 245 (2024), p. 105009.

[256] A. Gómez Ortega, V. Milias, J. S. Broadhead, C. v. der Valk and J. Bourgeois. ‘Dataslip: How Far Does Your Personal Data Go?’ In: *IFIP Conference on Human-Computer Interaction.* Springer. 2023, pp. 295–299.

[257] V. Milias and A. Psyllidis. ‘Assessing the influence of point-of-interest features on the classification of place categories’. In: *Computers, Environment and Urban Systems* 86 (2021), p. 101597.

[258] V. Milias and A. Psyllidis. *New tool shows accessibility of public areas for different population groups.* Industrial Design Engineering News, Sept. 2023. URL: https://www.tudelft.nl/en/ide/delft-design-stories/new-tool-shows-accessibility-of-public-areas-for-different-population-groups.

[259] V. Milias, R. Teeuwen and A. Psyllidis. *Towards the design of healthy and sustainable cities: What Factors Impact Access to Public Spaces and for Whom?* Book of Abstracts at WHO European Healthy Cities Network Annual Conference 2023, Utrecht, the Netherlands, Nov. 2023.

[260] R. Teeuwen, V. Milias and A. Psyllidis. *Kinderen in de openbare ruimte. Urban Analytics Lab biedt inzicht in knelpunten leefomgeving (Children in public space. The Urban Analytics Lab provides insight into bottlenecks in the living environment)*. Onze Jeugd (Our Youth), Nov. 2023.

[261] C. Giehl, R. Teeuwen, S. Jansen and V. Milias. *Equal-Life team: Improving child exposome and quality of life*. Open Access Government, Oct. 2022. DOI: https://doi.org/10.56367/OAG-036-10295.

[262] V. Milias, R. Teeuwen and A. Psyllidis. *Measuring access to public spaces: what factors matter for whom?* Workshop at the Equal-Life Stakeholder Forum, Helsinki, Finland, Sept. 2023.

[263] V. Milias and A. Psyllidis. *What Factors Impact Access to Public Spaces and for Whom?* Online workshop with the support of the American Planning Association and the Consulting Planners of Massachusetts, May 2023.

[264] V. Milias, S. Norian, A. Psyllidis and A. Bozzon. *Crowdsourcing perceived qualities of city streets using street-level images*. Poster presentation at NWO ICT.OPEN conference 2023, Utrecht, the Netherlands, Apr. 2023. DOI: http://dx.doi.org/10.13140/RG.2.2.36333.36324.

[265] V. Milias, A. Psyllidis and A. Bozzon. *Exposure to street environment features and perceptions of safety and attractiveness*. Presentation at the EHEN 2023 Conference, Leuven, Belgium, May 2023.

[266] V. Milias and R. Teeuwen. *Digital tools for urban analytics*. Demonstration (online) for Rijksprogramma voor Duurzaam Digitale Informatiehuishouding (Dutch Programme for Sustainable Digital Information Management), May 2023.

[267] V. Milias, A. Psyllidis and A. Bozzon. *Co-accessibility: A new lens towards age-inclusive and accessible public spaces*. Presentation and Poster at the EHEN 2022 Conference, Barcelona, Spain, May 2022. DOI: http://dx.doi.org/10.13140/RG.2.2.24078.74563.

[268] *CTnetwork: Python Library to calculate street network centrality metrics such as street betweenness, street sinuosity, and intersection closeness*. Zenodo/Github, Mar. 2022. DOI: https://doi.org/10.5281/zenodo.10656707. URL: https://github.com/MiliasV/ctnetwork.

[269] *Chapter 4: Code for the crowdsourcing tool*. Github/Zenodo, Nov. 2022. DOI: https://zenodo.org/doi/10.5281/zenodo.10782593. URL: https://github.com/MiliasV/crowdsourcing_street_perceptions.

[270] *Chapter 4: Code for the analysis*. Github/Zenodo, Oct. 2022. DOI: https://zenodo.org/doi/10.5281/zenodo.10656786. URL: https://github.com/MiliasV/streetception.

[271] *Chapter 6: Data included in the empirical analysis*. Zenodo, Apr. 2024. DOI: 10.5281/zenodo.10974190. URL: https://zenodo.org/doi/10.5281/zenodo.10974190.

7

ACKNOWLEDGMENTS

It's August. It's summer. It's hot. I am in Greece, on the small island of Symi. In one month I will be defending my dissertation at TU Delft. But before that, my dissertation needs to be printed. The only barrier left to start the printing process is for me to write the *Acknowledgments* section. So, I am skipping my trip to the beach today as a token of appreciation for the people who, one way or another, directly or indirectly, willingly or by chance, contributed to this work. But...who are they? Let's take a walk and meet some of them.

First, let's take a short walk to the main offices where I went to ask questions, discuss, and sometimes playfully debate regarding my research, the offices of my promotor and co-promotor, Alessandro and Achilleas. **Alessandro**, you are sharp! Thanks for being there to unveil the complexity of seemingly simple questions, and to push for clarity. Your ability to dive quickly to the heart of my work and pinpoint potential fallacies or future challenges I had not seen coming, always impressed me. I truly enjoyed all our one-on-one discussions: from the ones I left your office more troubled than I entered, which were highly educative, to the ones I had convinced you that my research plan made sense, which were filled with a joyful victorious sentiment.

Achillea(s), spatial autocorrelation is cool, "The Return of the King" is not a proper title for a book since it spoils the ending, and the details on how the historic triangle of Athens was designed are fascinating. How do I know? You taught me! Seven years ago, during our first meeting where we discussed the possibility of you supervising my MSc thesis, you introduced me to the wonderful world of Urban Analytics, revealed to me its beauty, and showed me how my CS/Data Science skills can be utilized and enhanced to tackle existing and future urban issues and challenges. I consider my MSc thesis project to be the origin story of my PhD adventure, and you were there from the beginning. Thank you for so passionately sharing your knowledge and love for this field and for teaching me not to be limited by a single research field but to embrace the integration of knowledge from various disciplines when necessary. Thanks for being there at each and every step, for supporting and encouraging me, for teaching me and learning with me, and for being the most responsive co-promotor anyone could have.

Now, walking back to my office, to thank my first PhD office-mates, the wonderful people I started sharing my office space with, and continued sharing much more. **Alejandra**, thank you for not considering me the office-nerd, and for all the laughter and knowledge-sharing throughout the PhD. However, I can't say I'm grateful for the countless nightmares you've brought into my life, featuring thermal printers chasing me. **Di**, thanks for always smiling, laughing, and being there to offer your help. And remember, creative minds are often so full of ideas that they sometimes forget the small details of daily life, like closing the office's window before they leave. **Hosana**, your passion for learning and teaching always inspired me. Thank you for the countless discussions on

what design is, for smoothly easing me into the world of design, and for all the rest of our random and very fun conversations. **Roos**, we worked together in the Urban Analytics team and the Equal Life project, traveled together to our first conferences, learned from each other, and shared many wonderful and less wonderful moments. Thank you for the many things I learned from you and for helping me appreciate the positive side of planning ahead (still learning that).

Walking to the nearby offices, I want to thank my KInD colleagues throughout these past four years: **Andrea**, **Carlo**, **Chaofan**, **Céline**, **Denis**, **Evangelos**, **Francesca**, **Garoa**, **Gerd**, **Himanshu**, **Jacky**, **James**, **Jeff**, **Jered**, **Julia**, **Kars**, **Mireia**, **Ruben**, **Samuel**, **Sara**, **Shatha**, **Tianhao**, **Tilman**, **Uğur**, **Wilfred**, **Wo**, **Yen-Chia**. Whenever I needed help, either to discuss my work or to pilot experiments you were all there to help. **Himanshu** thanks for the amazing mini-seminars in statistics. **Carlo** thanks for being the CS wizard of our group and for making *Machine Learning for Design*, together with **Yen-Chia**, **Denis**, and **Chaofan** so fun. **James** thanks for showing me your Freddie Mercury side and **Tianhao** thanks for joining every single experiment I asked you to join and for bringing such nice treats to the office. **Julia** thanks for always bringing a smile to the office and for all the thrilling conversations we shared, ranging from urban analytics topics to philosophy. **Gerd** thank you for all the nice discussions and for suggesting the term “co-accessibility" in one of our group meetings. **Wo** thank you for all the incredibly fun discussions and for passionately sharing your knowledge about... everything! I truly enjoyed even the most random bits of facts you shared. **Uğur** thank you for shedding some light into the darkness of Javascript. **Céline** and **Francesca** our PhD trajectories didn’t overlap much, but it was fun seeing you bringing some coolness to our group. **Jeff**, I highly appreciated your super welcoming attitude, and I thank you for always being there to steward my data. **Jered** I always enjoyed, learned from, and looked forward to listening to your sharp comments whenever I presented my research at our group meetings. **Mireia** and **Garoa** thanks for always being there to help and assist with these beautiful landlord-related complexities.

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Walking around the IDE faculty, to other corridors and floors... **Alexander**, thanks for lifting my spirit by constantly losing when we played padel together, **Mehmet** thanks for all the discussions around the importance of *Design* and CHI, and **Clarice** thanks for teaching me that on any surface there is always room for one more plant.

Walking in other departments of TUD, I want to thank **Maurice**, **Shahin**, **Kai**, **Timo**, **Matias**, and **Charalampos**, with whom I had the pleasure to collaborate through my PhD and from whom I learned a lot. **Shahin** and **Timo**, thank you for your great contribution to my dissertation. **Matias** and **Charalampos**, it was great being part of your MSc supervision team. I learned so much from you and admired both your academic skills and positive attitude.

Walking to Utrecht, to a place that’s felt like a second home over the past few years, I can’t help but thank my dear friend **Alex**. **Alex** your excitement for discussing my research always flattered me (sometimes even surprised me) and I am genuinely touched by your constant support, even if I try not to show it and play it cool.

Walking around Europe, I also want to thank the people I met from Equal-Life. The Equal-Life project supported my PhD and the people I met there made my PhD trip so much more enjoyable. It was a pleasure being part of such a project and working along-

side so many great researchers and practitioners. A special thanks to **Irene** who showed us that it is possible to bring together researchers and practitioners from such diverse fields and enable them to work together and to my Cretan friend **Michalis** who was my Equal-Life laughing partner. **Michali** I still laugh when I recall our chats during the EL's events.

Walking back in time, I want to thank my friends from my MSc, with whom I started my trip to NL and collaborated on many projects, **Lorenzo**, **Giannis**, and **Ajay**. Guys, I will always cherish our late-working nights at the spaceboxes and the laughs we shared. And I also want to thank **Tolga**, my first (and last?) barman colleague. Thanks for all the wonderful discussions we had around beers, architecture, and urban design my friend. And a quick shout-out to the Oostblok team, all these wonderful people who were part of the first place I felt at home in the Netherlands. Thank you **Kelly**, **Manw**, **Kosta**, **Fani**, **Chris**, **Kalliroi** (and many more) for making studying in Delft so much fun!

Walking further away, to Greece, to the center of Athens, I want to thank my dear friends **Ari**, **Dimitri**, **Nansy**, **Pano** for listening about co-accessibility, even when they really didn't want to. I missed you all these years living in the Netherlands, and I am glad we are going to spend more time together from now on (we will, right?). And to be fair, a special thanks to **Nansy** who was, or seemed to be (?), genuinely interested in my topic, taught me new perspectives, and supported me with her fierce criticism. Now moving to Pagrati. **Thodwri**, my wonderful talented friend, our discussions throughout the years have shaped me, our lovely debates have equipped me to defend my work better, and our interactions pushed me to think more critically about the application side of my research.

Walking a bit further, to the first university I ever joined, I want to thank my friends from NTUA starting with **Kostis**, **Dimitris**, and **Apostolis** who were always there to discuss my PhD math-related questions, three incredibly smart and talented people. My friends, observing your thinking process has always been fascinatingly educational for me. Similarly, I want to thank **Giwrgos** and **Souxes** (sorry I couldn't use your first name, you will always be "Souxes" for me). It was so fun sharing my BSc life with you guys. Learning from you and your way of studying was a privilege. Also, I want to thank **Alex**, one of the greatest programmers I've had the pleasure of knowing (to be fair, along with you **Lorenzo**), who has generously shared — and keeps sharing — his wisdom with me throughout my entire academic journey.

Now, let's walk to a place very familiar to me, my first home, in Athens, in Chalandri. **Mom** and **dad**, what can I say without being cliché? You are amazing! You have never stopped supporting me, you have a unique way of calming me down, and you always get excited with my excitement, independently of where this excitement is coming from. Mom, thanks for teaching me how to build connections with people, how to smile, and how to laugh open-heartedly. These skills proved to be essential in helping me engage with qualitative approaches during my PhD, which were entirely new to my previously quantitative-focused perspective. Dad thanks for showing me the beauty of math and how challenging answering the most fundamental questions can be, and for teaching me that understanding is different from knowing. And **Reno(s)** (yeah, I still consider you part of the Chalandri team), my big (and slightly shorter than me) brother, allow me to be a bit cheesy — after all, you were the first who discovered that Im quite sentimental.

Thank you for always being by my side, supporting me to the fullest, advocating for my success, and, most importantly, being excited to critically discuss any random ideas I might have. Also, thank you for teaching me why getting overly excited about your skill in playing blind chess isnt cool. To be honest, I cant help but still feel that way.

Lastly, it's time to walk home. And these past years, “home" is not spatially constrained, it moves. Home is where **Dimitra** is. **Dimitra** you shared my excitement, stress, and joy. You passionately grieved with me my rejected papers and celebrated the newly accepted ones. You helped me develop co-accessibility through our countless discussions, taught me that I should be mindful when using the term 'participatory approach' and not throw it around too casually, and educated me regarding the complexities of qualitative methods. Even better, these past four years you also taught me Me. Knowing you're not a huge fan of 'thank yous', I'll just stick to saying: you're the best!

List of Publications

(during my PhD)

Peer Reviewed

(* denotes equal contribution)

9. V. Milias, A. Psyllidis and A. Bozzon. ‘Bridging or separating? Co-accessibility as a measure of potential place-based encounters’. In: *Journal of Transport Geography* (). Under review

8. V. Milias, R. Teeuwen, A. Bozzon and A. Psyllidis. ‘Crowdsourcing the influence of physical features on the likely use of public open spaces’. In: *Computational Urban Science* 4 (2024)

7. M. Cardoso, V. Milias and M. Harteveld. ‘Developing a city-specific walkability index through a participatory approach’. In: *AGILE: GIScience Series* (2024).

6. R. Teeuwen, V. Milias, A. Bozzon and A. Psyllidis. ‘How well do NDVI and OpenStreetMap data capture peoples visual perceptions of urban greenspace?’ In: *Landscape and Urban Planning* 245 (2024), p. 105009

5. V. Milias, S. Sharifi Noorian, A. Bozzon and A. Psyllidis. ‘Is it safe to be attractive? Disentangling the influence of streetscape features on the perceived safety and attractiveness of city streets’. In: *AGILE: GIScience Series* 4 (2023), p. 8

4. T. Van Asten*, V. Milias*, A. Bozzon and A. Psyllidis. ‘Eyes on the Street: Estimating Natural Surveillance Along Amsterdams City Streets Using Street-Level Imagery’. In: *International Conference on Computers in Urban Planning and Urban Management*. Springer. 2023, pp. 215–229

3. A. Gómez Ortega, V. Milias, J. S. Broadhead, C. v. der Valk and J. Bourgeois. ‘Dataslip: How Far Does Your Personal Data Go?’ In: *IFIP Conference on Human-Computer Interaction*. Springer. 2023, pp. 295–299

2. V. Milias and A. Psyllidis. ‘Measuring spatial age segregation through the lens of co-accessibility to urban activities’. In: *Computers, Environment and Urban Systems* 95 (2022), p. 101829

1. V. Milias and A. Psyllidis. ‘Assessing the influence of point-of-interest features on the classification of place categories’. In: *Computers, Environment and Urban Systems* 86 (2021), p. 101597

Other Publications

4. V. Milias and A. Psyllidis. *New tool shows accessibility of public areas for different population groups*. Industrial Design Engineering News, Sept. 2023. URL: https://www.tudelft.nl/en/ide/delft-design-stories/new-tool-shows-accessibility-of-public-areas-for-different-population-groups

3. V. Milias, R. Teeuwen and A. Psyllidis. *Towards the design of healthy and sustainable cities: What Factors Impact Access to Public Spaces and for Whom?* Book of Abstracts at WHO European Healthy Cities Network Annual Conference 2023, Utrecht, the Netherlands, Nov. 2023

2. R. Teeuwen, V. Milias and A. Psyllidis. *Kinderen in de openbare ruimte. Urban Analytics Lab biedt inzicht in knelpunten leefomgeving (Children in public space. The Urban Analytics Lab provides insight into bottlenecks in the living environment).* Onze Jeugd (Our Youth), Nov. 2023

1. C. Giehl, R. Teeuwen, S. Jansen and V. Milias. *Equal-Life team: Improving child exposome and quality of life.* Open Access Government, Oct. 2022. DOI: https://doi.org/10.56367/OAG-036-10295

EXHIBITIONS, CONFERENCES, AND WORKSHOPS

8. V. Milias. *CTwalk: Mapping pedestrian (co)accessibility.* 🏆 Demo presentation at NWO ICT.OPEN conference, Utrecht, the Netherlands, Apr. 2024. URL: https://bit.ly/ctwalkmap

7. V. Milias. *CTwalk: Mapping pedestrian (co)accessibility.* Dutch Design Week. Eindhoven, Netherlands, 2023. URL: https://bit.ly/ctwalkmap

6. V. Milias, R. Teeuwen and A. Psyllidis. *Measuring access to public spaces: what factors matter for whom?* Workshop at the Equal-Life Stakeholder Forum, Helsinki, Finland, Sept. 2023

5. V. Milias and A. Psyllidis. *What Factors Impact Access to Public Spaces and for Whom?* Online workshop with the support of the American Planning Association and the Consulting Planners of Massachusetts, May 2023

4. V. Milias, S. Norian, A. Psyllidis and A. Bozzon. *Crowdsourcing perceived qualities of city streets using street-level images.* Poster presentation at NWO ICT.OPEN conference 2023, Utrecht, the Netherlands, Apr. 2023. DOI: http://dx.doi.org/10.13140/RG.2.2.36333.36324

3. V. Milias, A. Psyllidis and A. Bozzon. *Exposure to street environment features and perceptions of safety and attractiveness.* Presentation at the EHEN 2023 Conference, Leuven, Belgium, May 2023

2. V. Milias and R. Teeuwen. *Digital tools for urban analytics.* Demonstration (online) for Rijksprogramma voor Duurzaam Digitale Informatiehuishouding (Dutch Programme for Sustainable Digital Information Management), May 2023

1. V. Milias, A. Psyllidis and A. Bozzon. *Co-accessibility: A new lens towards age-inclusive and accessible public spaces.* Presentation and Poster at the EHEN 2022 Conference, Barcelona, Spain, May 2022. DOI: http://dx.doi.org/10.13140/RG.2.2.24078.74563

TOOLS, DATA, & CODE

9. *CTwalk Map: An interactive web tool that maps pedestrian accessibility and co-accessibility.* 2023. URL: https://bit.ly/ctwalkmap

8. *CTstreets Map: An interactive web tool that maps walkability in Amsterdam, The Netherlands.* Online. 2023. URL: https://bit.ly/ctstreets

7. *CTnetwork: Python Library to calculate street network centrality metrics such as street betweenness, street sinuosity, and intersection closeness.* Zenodo/Github, Mar. 2022. DOI: https://doi.org/10.5281/zenodo.10656707. URL: https://github.com/MiliasV/ctnetwork

6. *Chapters 2 and 3: Code and data of the empirical analysis.* Github/Zenodo, May 2022. DOI: https://doi.org/10.5281/zenodo.10656707. URL: https://github.com/MiliasV/coaccessibility/

5. *Chapter 4: Dataset including perceived safety and attractiveness ratings of city streets in Frankfurt, Germany.* Github/Zenodo, Mar. 2023. DOI: https://zenodo.org/records/7712811

4. *Chapter 4: Code for the crowdsourcing tool.* Github/Zenodo, Nov. 2022. DOI: https://zenodo.org/doi/10.5281/zenodo.10782593. URL: https://github.com/MiliasV/crowdsourcing_street_perceptions

3. *Chapter 4: Code for the analysis.* Github/Zenodo, Oct. 2022. DOI: https://zenodo.org/doi/10.5281/zenodo.10656786. URL: https://github.com/MiliasV/streetception

2. *Chapter 5: Code and data for the empirical analysis.* Github/Zenodo, May 2023. DOI: https://zenodo.org/doi/10.5281/zenodo.10782534. URL: https://github.com/MiliasV/natural-surveillance

1. *Chapter 6: Data included in the empirical analysis.* Zenodo, Apr. 2024. DOI: 10.5281/zenodo.10974190. URL: https://zenodo.org/doi/10.5281/zenodo.10974190

A

CURRICULUM VITÆ

EDUCATION AND EXPERIENCE

2020–2024	PhD Candidate Delft University of Technology Delft, The Netherlands
2019–2020	Spatial Data Specialist HERE Technologies Eindhoven, The Netherlands
2017–2018	R&D Intern - Personal Spaces & Data Science Philips Lighting Eindhoven, The Netherlands
2016–2018	M.Sc. in Computer\Data Science Delft University of Technology Delft, The Netherlands
2010-2016	B.Sc. & M.Sc. in Electrical and Computer Engineering National Technical University of Athens Athens, Greece

Personal webpage:
`https://miliasv.github.io/bio_VM/`

B
POSTERS

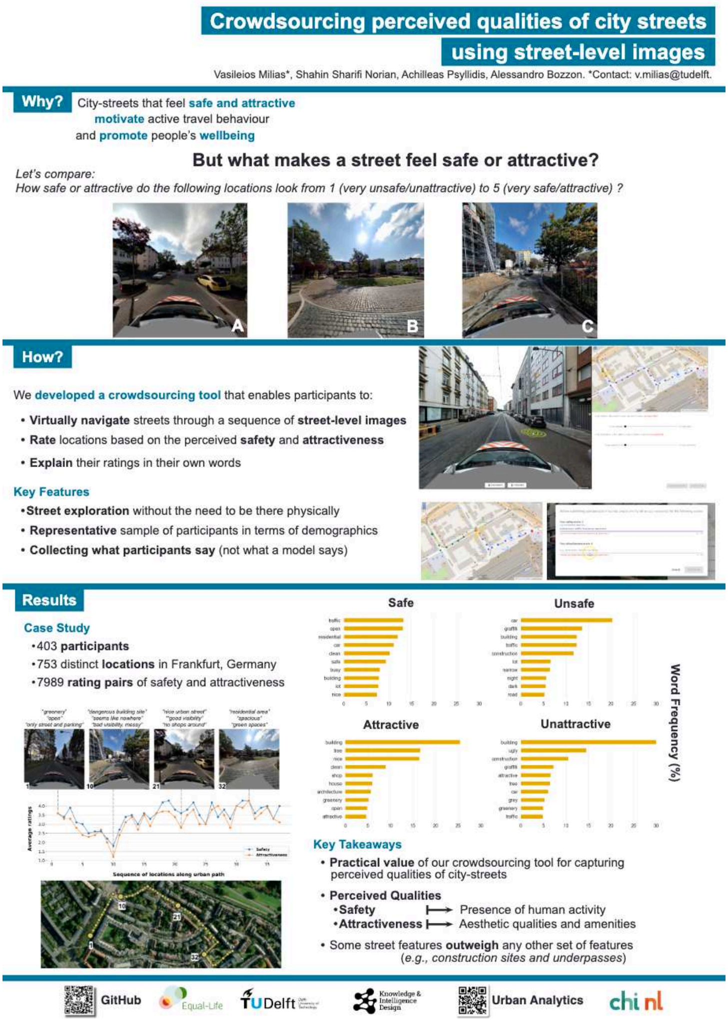

Figure B.1.: Poster presentation at ICT Open 2023, Utrecht, the Netherlands, April 2023.

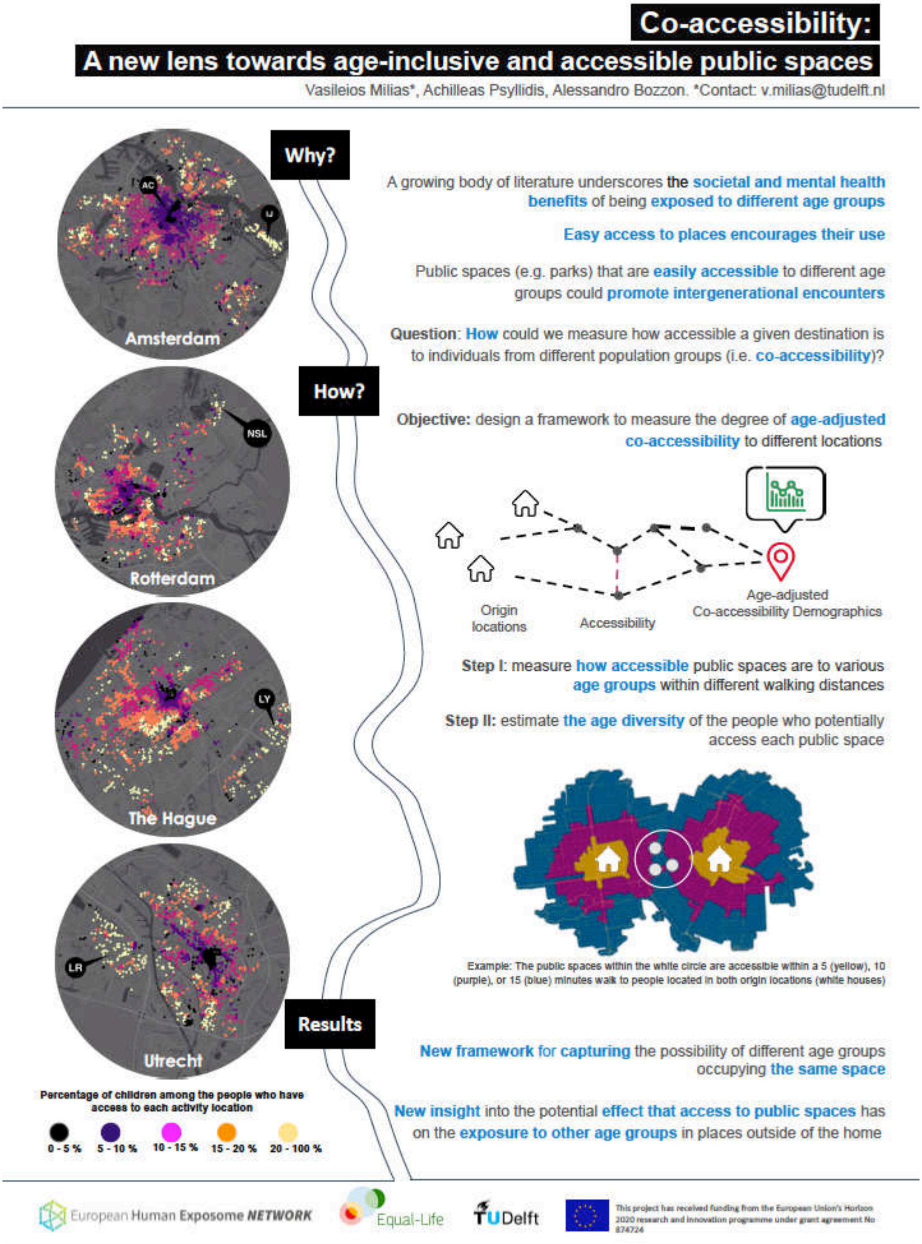

Figure B.2.: Poster exhibited at the EHEN 2022 Conference, Barcelona, Spain, May 2022.

Accessibility is a widely employed concept across a variety of disciplines to evaluate the degree to which individuals can reach a desired destination. Conventionally, accessibility is determined by the attractiveness of a destination and the associated travel cost to reach it. However, existing place-based accessibility measures do not differentiate between destinations accessible to individuals from a single demographic group and those accessible to individuals from diverse demographic groups. This hinders our ability to discern the encounter potential of different destinations. This dissertation introduces co-accessibility as a measure of a destination's potential to bring together different individuals and individuals from diverse demographic groups.