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Roos Teeuwen

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Dissertation

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by

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"And then came the grandest idea of all! We actually made a map of the country, on the scale of a mile to the mile!" "Have you used it much?" I enquired. "It has never been spread out, yet," said Mein Herr: "the farmers objected: they said it would cover the whole country, and shut out the sunlight! So we now use the country itself, as its own map, and I assure you it does nearly as well."

Lewis Carroll
excerpt from *Sylvie and Bruno Concluded*, Chapter XI, London, 1895

Contents

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Summary

Access to urban greenspace, i.e., space characterized by vegetation, is crucial for children's health and well-being, for example by providing space for socialization, physical activity, and personal development. Children's access is influenced by a variety of factors that differ from those influencing adults, including children's limited routine activity space, reduced autonomy, and physical and perceived barriers in urban space. Studies in environmental epidemiology, spatial equity, and urban planning typically evaluate children's access to urban greenspace by utilizing methods designed for the general population. That is, they overlook the distinct factors determining children's access.

In this dissertation, we introduce and evaluate novel methods for assessing urban greenspace accessibility that integrate the factors influencing children's access. We scope to children aged approximately 6 to 11 years old, and contribute methods for measuring access during two routine outdoor activities of children: commuting to school, and playing outdoors without adult supervision. We focus on methods that serve *across scales* (e.g., per single street and entire city) and *geographical contexts* (e.g., for cities dispersed throughout Europe), and we adhere to open science principles to allow replication and adaptation of our methods. We conduct this research in the context of the Horizon 2020 project named "Equal-Life: Early environmental quality and life-course mental health effects", studying the *exposome* (i.e., the totality of physical, social and internal exposures during lifetime) for a healthier future for all children.

We begin our research by identifying the *factors* that influence children's access to urban greenspace, drawing on the literature and generative workshops with researchers and practitioners (chapter 2). We synthesize these factors, both physical and social, into a *conceptual model*, contributing a comprehensive visual overview of factors. Our model shows how access to greenspace depends on a trade-off between how reachable and how attractive a greenspace is to a child and whoever may accompany them. Reachability concerns the route connecting a child's starting setting to greenspace, while attractiveness concerns how the greenspace suits the child's (and potentially their companions') motivations to visit. Perceptions of safety play an important role throughout, and interrelations between factors are prevalent. Throughout this dissertation, this conceptual model serves to position the studies that follow into their wider context.

We continue with delving into one of the clusters of factors in our conceptual model, specifically *greenspaces*, and how they can be recognized in *data* when measuring greenspace accessibility (chapter 3). We study how two widely used greenspace data sets, i.e., OpenStreetMap and Normalized Difference Vegetation Index maps (NDVI), correspond to human perceptions of greenspace collected through crowdsourcing. When analyzing places in three cities across Europe (i.e., Gothenburg, Rotterdam and Barcelona), we find an overall match between perceived greenspaces and places tagged as such in OpenStreetMap, and that pocket-size greenspaces and play spaces are often perceived

green as well. Between people's perceptions of vegetation and NDVI values, we find a moderate correlation, contrasting with two related studies that did not identify any significant association. Greenspace characteristics underlying the deviations between people's perceptions and greenspace data include vegetation variety and configuration, and proximity to other natural (e.g., water) or built-up elements (e.g., concrete).

With our improved understanding of key factors and data, we proceed with developing two novel *methods* for measuring children's access to urban greenspace. We first address the lack of methods for measuring access from *en route settings*, e.g., during children's daily trips between home and school (chapter 4). We use the *patronage betweenness* accessibility measure, estimating pedestrian flows per street in entire cities, to capture commuting children. Our novel *on-the-move* accessibility measure overlays these commuting patterns with the aforementioned OpenStreetMap greenspaces to calculate how each greenspace is traversed by children. When we implement our measure in three major Dutch cities (i.e., Amsterdam, Rotterdam, and The Hague), we discover that expansive greenspaces wider than 500 meters appear to be poorly accessible to commuting children, as are greenspaces located near other greenspaces or urban open space.

Finally, we address the lack of greenspace accessibility methods incorporating factors associated to *unsupervised outdoor play*, such as children's autonomy, parental safety perceptions, and spatial barriers (chapter 5). Together with experts on children's health and urban environments, we iteratively co-design a novel *child's play* accessibility method. We unpack the factors our method should incorporate, discuss how to recognize them in geospatial data such as OpenStreetMap, and assess prototypes of our method, using neighborhoods in three cities across Europe as case studies (i.e., Utrecht, Milan, and Ljubljana). We operationalize our method by adapting the *walkshed buffer zone* accessibility measure such that it determines where children can access (green) play space within a short 300-meter walk along the street network without crossing barriers. Barriers include major roads, public transport infrastructure, waterways, and greenspaces over 5 hectares in size. In such large-size greenspace, passive surveillance is limited and children may get lost, causing parental safety concerns, as opposed to small-size greenspaces that typically serve well for unsupervised play.

When developing our novel accessibility measures, employing participatory research methods and integrating measures from diverse disciplinary domains proved highly advantageous (chapter 6). Our comprehensive visual overview of factors serves not only to communicate the intricate nature of the subject, but also facilitates contextualizing existing research within these factors. This dissertation contributes to the study of children's access to urban greenspace and the development of measurement methodologies, but also bears implications for collaboration with the public health sector and the advancement of initiatives aimed at creating greener and healthier urban environments for all residents. Promising directions for future research include investigating the relations between our measures and behavioral and health outcomes, and expanding the scope to encompass other demographic groups and public spaces. Yet complementing our measures with field work and engagement of local (children's) communities remains essential in further refining our understanding of urban greenspace accessibility.

Samenvatting

Toegang tot stadsgroen, plekken gekenmerkt door vegetatie, is cruciaal voor de gezondheid en het welzijn van kinderen, bijvoorbeeld door ruimte te bieden voor sociaal contact, fysieke activiteiten en persoonlijke ontwikkeling. De toegankelijkheid voor kinderen wordt beïnvloed door een verscheidenheid aan factoren, die verschillen van de factoren die volwassenen beïnvloeden, zoals de beperkte omgeving waar kinderen hun tijd doorbrengen, hun geringe autonomie en barrières in de stad, zowel fysiek als gevoelsmatig. Onderzoeken in milieu-epidemiologie, ruimtelijke rechtvaardigheid en stadsplanning evalueren de toegang tot stadsgroen voor kinderen doorgaans door middel van methodes ontwikkeld voor de algemene bevolking. Dat wil zeggen, ze gaan voorbij aan de afwijkende factoren die de toegankelijkheid voor kinderen bepalen.

In dit proefschrift introduceren en evalueren we nieuwe methodes om de toegankelijkheid van stadsgroen te bepalen, die de factoren van invloed op kinderen meenemen. We beperken ons tot kinderen van grofweg 6 tot 11 jaar oud en introduceren methodes om toegankelijkheid te bepalen tijdens twee veelvoorkomende buitenactiviteiten: naar school gaan en buitenspelen zonder toezicht van volwassenen. We richten ons op methodes die toepasbaar zijn op verschillende *schaalniveaus* (bijvoorbeeld individuele straten en hele steden) en *geografische gebieden* (bijvoorbeeld steden verspreid over Europa). We volgen de beginselen van open wetenschap om onze methodes reproduceerbaar en aanpasbaar te maken. Dit onderzoek maakt deel uit van het Horizon 2020 project genaamd “Equal-Life: Early environmental quality and life-course mental health effects”. Dit project onderzoekt het *exposoom* (de totaliteit van fysieke, sociale en interne factoren waar een mens tijdens het leven aan wordt blootgesteld), ten behoeve van een gezondere toekomst voor alle kinderen.

We beginnen dit onderzoek door de factoren te identificeren die toegang tot stadsgroen voor kinderen beïnvloeden, op basis van de literatuur en generatieve workshops met onderzoekers en praktijkdeskundigen (hoofdstuk 2). We combineren deze factoren, zowel fysiek als sociaal, tot een *conceptueel model* dat een uitgebreid visueel overzicht van factoren toont. Ons model maakt inzichtelijk hoe toegang tot groen bepaald wordt door een wisselwerking van bereikbaarheid en aantrekkelijkheid van een groene plek voor kinderen en hun eventuele begeleiders. Bereikbaarheid betreft de route die de startplek van het kind verbindt met het groen, terwijl aantrekkelijkheid gaat over de aansluiting van het groen bij de motivatie van het kind (en eventuele begeleiders) om het te bezoeken. Ervaringen van veiligheid spelen hierin een belangrijke rol en veel factoren zijn onderling verbonden. In dit proefschrift gebruiken we dit conceptuele model om de studies die volgen te plaatsen in hun bredere context.

Vervolgens focussen we op één van de clusters van factoren in ons conceptuele model, namelijk *groene plekken* en hoe we die in *data* kunnen herkennen wanneer we toegankelijkheid meten (hoofdstuk 3). We bestuderen hoe twee veelgebruikte datasets, Open-

StreetMap en *Normalized Difference Vegetation Index* kaarten (NDVI), corresponderen met menselijke percepties van groen, verzameld door middel van *crowdsourcing*. Wanneer we locaties analyseren in drie Europese steden (i.e., Göteborg, Rotterdam en Barcelona), vinden we veel overeenkomsten tussen de perceptie van groen en de bijbehorende labels in OpenStreetMap. We zien bovendien dat ook postzegelparken en speelplekken vaak als groen worden ervaren. Tussen de perceptie van groen en NDVI-waardes vinden we een matige correlatie, in tegenstelling tot twee gerelateerde studies die geen enkel significant verband vonden. Onder andere de variëteit en configuratie van de vegetatie, alsook nabijheid tot andere natuurlijke of bebouwingselementen (zoals water of beton), lijken aan de verschillen tussen menselijke perceptie van groen en de data ten grondslag te liggen.

Met dit vernieuwde inzicht in de relevante factoren en de data, ontwikkelen we twee nieuwe *methodes* om toegang tot stadsgroen voor kinderen te meten. Eerst pakken we het gebrek aan methodes aan voor het meten van toegang *onderweg*, bijvoorbeeld tijdens het dagelijkse pendelen tussen huis en school (hoofdstuk 4). We passen het *patronage betweenness* principe toe op pendelende kinderen, dat een inschatting maakt van voetgangersstromen in de stad. Onze nieuwe *onderweg*-meetmethode legt deze voetgangersstromen over de eerdergenoemde OpenStreetMap groendata heen om te bepalen hoe iedere groene plek doorkruist wordt door kinderen. Als we onze methode implementeren in drie grote Nederlandse steden (i.e., Amsterdam, Rotterdam en Den Haag), ontdekken we dat uitgestrekte groene gebieden van meer dan 500 meter breed relatief slecht op de route liggen voor kinderen, evenals groen in nabijheid van andere groene of open ruimtes in de stad.

Tot slot richten we ons op het ontwikkelen van een methode die de toegankelijkheid tot groen meet voor kinderen die buitenspelen zonder toezicht, gerelateerd aan de autonomie van kinderen, ervaringen van veiligheid onder ouders en ruimtelijke barrières (hoofdstuk 5). Samen met experts in jeugdgezondheid en stedenbouwkunde, co-creëren we iteratief een nieuwe *kinderspel*-meetmethode. We benoemen de factoren die de methode mee zou moeten nemen, bespreken hoe we die in ruimtelijke data zoals OpenStreetMap kunnen herkennen en beoordelen prototypes van onze methode toegepast op buurten in drie Europese steden (i.e., Utrecht, Milaan en Ljubljana). We implementeren onze methode door de *walkshed buffer zone* toegankelijkheidsmaat aan te passen zodat die bepaalt waarvandaan kinderen binnen 300 meter lopen zónder barrières te doorkruisen toegang hebben tot een (groene) speelplek. Zulke barrières zijn bijvoorbeeld grote wegen, infrastructuur voor openbaar vervoer, waterwegen en groen groter dan 5 hectare. In zulk groot groen is weinig passieve surveillance en kinderen zouden er de weg kwijt kunnen raken, wat resulteert in veiligheidszorgen onder ouders. Daarentegen is klein groen doorgaans goed geschikt is voor buitenspelen zonder toezicht.

Participatieve onderzoeksmethodes en meetmethodes uit andere domeinen bleken zeer waardevol voor het ontwikkelen van onze nieuwe meetmethodes (hoofdstuk 6). Ons complete visuele overzicht van factoren dient niet alleen om het ingewikkelde samenspel van factoren inzichtelijk te maken, maar ook om bestaand onderzoek aan deze factoren te relateren. Dit proefschrift draagt bij aan de studie van toegang tot stadsgroen voor kinderen, alsook aan de ontwikkeling van nieuwe meetmethodiek. Daarbij heeft het implicaties voor samenwerking met het volksgezondheidsdomein en de bevordering van initiatieven om groenere en gezondere stedelijke ruimte te creëren voor alle inwoners. Veelbelovende richtingen voor toekomstig onderzoek zijn onder andere het bestuderen van de relaties tussen onze metingen en waargenomen gedrag en gezondheid, evenals het uitbreiden van onze methodes naar andere bevolkingsgroepen en publieke ruimtes. Uiteindelijk blijft het essentieel om onze methodes aan te vullen met veldwerk en lokale (kinder)gemeenschappen te betrekken om het begrip van de toegankelijkheid van stadsgroen verder te verfijnen.

1

Introduction

In this dissertation, we propose innovative approaches for assessing urban greenspace accessibility with a specific focus on factors affecting children's access. Access to quality greenspaces in urban areas is crucial for fostering the health and well-being of children and providing spaces for recreation, socialization, and personal development. Unlike adults', children's access to greenspaces is influenced by factors such as their daily activity patterns, levels of autonomy, and various physical and perceived barriers. While many studies in epidemiology, spatial equity, and urban planning aim to evaluate access to greenspaces for children across different urban scales and geographical contexts, they often utilize methods designed for the general population, overlooking the distinct factors affecting children's access. Our research addresses this gap by developing tailored methodologies that account for the specific needs and experiences of children in urban environments.

1.1. Background

Greenspace for health and well-being. Urban greenspaces are urban spaces characterised by vegetation of any kind, according to the World Health Organization Regional Office for Europe [1] definition. Especially in urban environments, greenspaces have great potential to increase public health and well-being [2]. They are generally found to positively affect human health and well-being in multiple ways [3, 4]. For example, they mitigate human exposure to environmental harms, such as air pollution, noise, and heat [5, 6, 7], support people's restoration capacities, such as attention restoration, coping behavior, and stress recovery [6, 8, 9], and help people to build capacities, for example by encouraging physical activity and facilitating social interactions, especially when incorporated into people's daily routines [8, 10, 11, 12, 13, 14].

A growing body of literature highlights the importance of direct exposure, i.e., by using greenspace and spending time in them, as opposed to indirect exposure by the mere presence of greenspace in a person's surroundings [11, 12, 13, 15, 16, 17]. Examples of health-promoting use of greenspace include making purposeful visits to greenspace on a regular basis [10, 13, 16], or passing through them while travelling to other destinations [18, 19, 20].

Children's access to greenspace. For children in particular, using greenspace can improve attention and decrease stress [8], and health care providers advise to play outdoors in nature to combat obesity [8] and enhance mental health [13, 21]. Children visiting greenspace are frequently engaged in physical recreation and interacting with peers [22]. Furthermore, traversing greenspace on a daily basis has been associated with children's cognitive development [19].

The evidence on the value of children's use of urban greenspace has not remained unnoticed. Use of greenspace is found to be primarily encouraged by easy access [22, 23]. The World Health Organization Regional Office for Europe [24] has therefore mandated specific guidelines based on the evidence on the benefits of children's access to greenspace, agreeing "...to provide each child with access to healthy and safe environments and settings of daily life in which they can walk and cycle to kindergartens and schools, and to green spaces in which to play and undertake physical activity". In addition, the United Nations [25] formulated the goal to "provide universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities" by 2030.

In this dissertation, we focus on children in middle childhood, i.e., roughly 6 to 11 years old as defined by the World Health Organization [26] — a phase in which children start to gain *some* freedom from adults, depending on the concerns of their parents [27]. Examples include increasing independent mobility, increasing privacy from parental surveillance, and a widening range of destinations to visit, all depending on the cultural and geographical context, and the spatial surroundings.

Factors affecting children's access. Ensuring access to greenspace by children, however, is not trivial. Research indicates that the factors at play are plentiful, and not the same as factors affecting access by adults.

Children are drawn to places where they can interact with their peers [28], without parental supervision [29, 30], and engage in diverse and challenging play [29, 30], possibly with natural objects [28, 31]. Furthermore, parents appreciate landscaped or open greenspace where children can be active, with a pleasant general atmosphere, and facilities such as variety of play equipment and toilets [32, 33, 34].

Limiting factors include children's restricted independent mobility, their routine activity-space being largely bound to locations near their home, school, and homes of friends and family [30, 35, 36], and their dependence on the time and motivation that their parents or caretakers have to accompany them on outdoor trips [31, 32, 37, 38]. Parents or caretakers may impose rules on children, defining how and where they may go, given physical barriers and social safety concerns relating to traffic danger [39, 40, 41] or incidents involving strangers [30, 32, 39, 40].

Measuring access across scales and geographical contexts. While the terms *access* and *accessibility* are often used interchangeably, they refer to different concepts. In our case, children can have access to greenspaces, and these greenspaces thereby become accessible to them. *Accessibility measures* allow to study the accessibility of greenspaces among communities (of children) in a given area, assessing how accessible greenspaces are, and how communities have access to them. Accessibility depends on "the spatial distribution of potential destinations, the ease of reaching each destination, and the magnitude, quality, and character of the activities found there" [42], i.e., an interplay between places, people, and how they are connected.

A multitude of methods for measuring access has been designed over the past decades [2, 4, 15, 42, 43]. Such methods are typically based on distance or proximity, the temporal or monetary costs of getting to a destination, and their trade-off with its attractiveness, for instance defined by the greenspace's size or presence of desirable facilities. No single method for measuring access, however, serves to measure access by all demographic groups, i.e., for both children in specific, and the population in general [44]. Furthermore, quality of outcomes regarding the level of access that people are deemed to have depends on how accurately input data represent the real-world situation [44], and little adaptations when operationalizing methods can have "dramatic impacts" on their outcomes [45].

Throughout this dissertation, we focus on methods that can quantify children's access to greenspace across scales and geographical contexts (figure 1.1). *Across scales* refers to methods that quantify access at a granular scale, e.g., per street, but that can simultaneously be applied to identify patterns in neighborhoods, districts, and entire cities. *Across geographical contexts* refers to methods using principles that extend beyond a single place, neighborhood, city, or country. That is, principles that can be applied to multiple cities spread over the European continent — e.g., not only for Amsterdam but also for other Dutch cities such as The Hague, and for other European cities such as Barcelona.

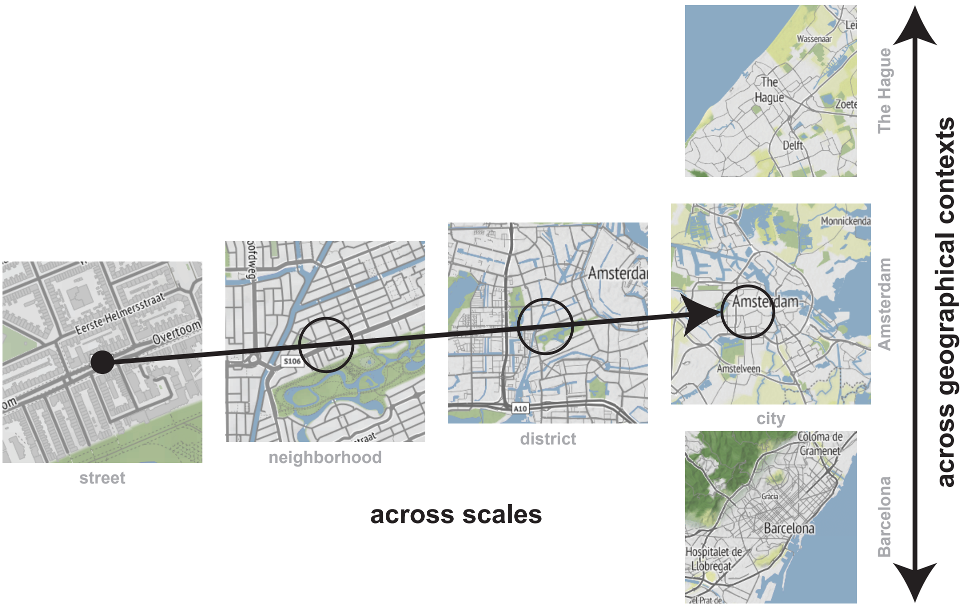


Figure 1.1.: Examples of scales (horizontal axis, i.e., individual streets up to entire cities) and geographical contexts (vertical axis, i.e., in multiple cities spread over the European continent. Maps by Stamen Design and OpenStreetMap.

As such, the methods that we focus on can serve to study not only *if* greenspace is needed, but also *how much*, *where*, *when* and of *what type* [2], to study how equitable access to greenspace is distributed within and between cities [46, 47], for implementation in large-scale epidemiological studies [48], and to benchmark progress towards a better future.

1.2. Problem statement

While access to urban greenspace has been measured in a variety of manners, we observe that methods for measuring access by children (1) that account for *key factors* affecting children's access, and (2) that serve *across scales and geographical contexts*, remain lacking. In the following paragraphs, we discuss how methods for measuring children's access do or do not account for the factors affecting children's access to urban greenspace, thereby motivating what it is that remains lacking before articulating the research gap that we address in this dissertation.

Measuring children's access? In section 1.1, we elaborated on the factors affecting children's access to urban greenspace, including restrictions and low autonomy, limited activity-space and mobility, and the particular preferences that children have. Yet, we observe a mismatch between the factors that affect children's access to greenspace, and the factors methods for measuring children's access account for.

Despite focusing on children, *many studies modelling children's access to greenspace use the same methods as used to measure access by the general population*, for example based on presence or availability of greenspaces, shortest distance to greenspace, or access within administrative areas or within a given proximity threshold distance [49, 50, 51, 52]. That means these methods ignore, for example, the restricted nature of children's independent mobility, as opposed to adults'.

Other studies make limited adaptations to the way in which they measure children's access, for instance by explicitly motivating chosen distance thresholds and greenspace types with respect to access by children, thereby acknowledging that children's independent mobility is bound to smaller areas, while they may feel particularly attracted to greenspace with a playground [53, 54, 55, 56]. Few studies measure access from both home and school settings [57, 58], or (most recently) during study participants' commutes [59], thereby accounting for a larger share of children's routine activity-space. However, spatial barriers imposed by parents or caretakers remain unaccounted for, and the methods used for modelling access from commuting settings remain limited to the level of individual study participants, rather than applicable to discern patterns across urban scales (i.e., for single streets and entire cities).

A limited number of studies tailor their methods to the children's age group. Examples include studies scoring greenspace destinations according to specific features relevant for children as captured in map or audit data [37, 60], calculating access via dedicated walking or cycling infrastructure [61], or measuring various greenspace indicators around the school environment, such as canopy cover, street trees that may be passed en-route to school, and greenspace for recreation within walking distance [47]. Also these approaches, however, do not address the physical and perceived barriers that children may face, or are not applicable across scales and geographical contexts.

Yet another set of studies do not model access to greenspace, but use questionnaires [16, 23, 62, 63, 64] or interviews [22, 28] to collect data from children or their parents, or perform observations of their behavior [22]. While such methods account for children's and parents' perceptions, and realized behaviors, they are not generalizable to other geographical contexts. Instead, they rely on participation of the local population or in-situ field work: a costly and time-consuming data collection process, thereby challenging to conduct across scales and geographical contexts [65, 66].

Research gap. The research gap we aim to address in this dissertation is twofold. First, there is a lack of methods for measuring access to urban greenspace that account for the factors affecting children's access. In this dissertation, we focus on the following factors: access during routine outdoor activities such as commuting to school or playing outdoors, and accessibility barriers that children without adult supervision may face. We argue that studies measuring access to urban greenspace among children should acknowledge the factors that limit or promote children's access in particular, incorporate them where relevant, and be transparent about the limitations in accounting for those factors that remain. By providing researchers and professionals with novel methods to quantify access, we aim to support greenspace accessibility assessment in a manner that is closer to children's day to day realities.

Second, there is a lack of methods for measuring access to urban greenspace that can operate across scales and geographical contexts. Recent increase in (open) data availability and computing power open up possibilities to incorporate a growing amount of factors in methods to quantify access, or to implement them on more granular scales (i.e., for every single street within a city) and across geographical contexts (i.e., for multiple cities in various countries).

To address this research gap, we break our research down into three levels. We arrange the multitude of *factors* affecting children's access to urban greenspace into a conceptual model — which remains lacking to date — and study how existing methods for measuring access account for these factors. Furthermore, we study how to systematically recognize these factors in large-scale geospatial *data* that such methods can build upon — including fundamental questions on how to recognize (child-friendly) greenspaces, routine activity-patterns, and spatial barriers in these data. Additionally, we explore how to transform or adapt existing *methods* so that they incorporate factors previously uncovered, design and implement these new methods, and evaluate the insights they bring and the limitations that remain.

1.3. Research objective and questions

The main research question this dissertation aims to answer is:

> **How can the factors influencing children's access to urban greenspace be integrated into methods for assessing access across scales and geographical contexts?**

In answering this main research question, we identify four challenges.

1. First of all, knowing what *factors* affect children's access to urban greenspace is key to be able to integrate them into accessibility measures. A comprehensive overview of factors and their high-level relationships can provide thorough understanding of the mismatch between (clusters of) factors that matter, and the factors that methods for measuring children's access to urban greenspace account for. Thereby, it can serve as a foundation for future research. Additionally, when presented visually, such an overview can serve to communicate with, and support awareness among, a wide audience as to what the scope and focus of each method is, and what remains unaccounted for. Such a comprehensive and visual overview of factors, however, is lacking to date.

2. One of the clusters of factors influencing children's access to urban greenspace concern the *greenspaces* themselves (challenge 1). When measuring greenspace accessibility, it is thus essential to be able to recognize greenspaces in *data*. Methods in literature applicable across scales and geographical contexts typically use two types of greenspace data: vegetation indices derived from satellite imagery, and land use / land cover maps. Research indicates, however, that for access to greenspace, people's subjective perceptions of greenspaces prove especially important, but may not be mirrored by greenspace data. Understanding how well people's perceptions of greenspace are captured in greenspace data, and in what cases they deviate, is key for interpreting the outcomes of accessibility measures that use these data as input. However, such knowledge remains lacking.

3. Another cluster of factors concerns the *settings* from which children may start a visit to greenspace (challenge 1). In addition to access from home or school, children may access greenspace while *en route*, for instance while commuting between home and school. Such routine en route access is deemed important for children's cognitive development. However, a *method* for measuring greenspace access en route — serving across scales and geographical contexts, and building upon the greenspace data mentioned in challenge 2 — remains lacking. As a result, it is unknown how accessibility outcomes differ when measuring access from home, school, or en route.

4. Fourth, we focus on children's access to urban greenspace *for unsupervised play*. Such access also promotes children's routine use of greenspace, and contributes to their physical, mental and social health. It is associated to the child's autonomy, parental restrictions related to perceived safety, spatial barriers along the route, and opportunities to play within the greenspace, amongst others (challenge 1).

Yet, a *method* for measuring greenspace access that incorporates these factors is lacking. Questions remain how we can systematically recognize these factors in data, and how we can integrate them into methods for assessing children's access to urban greenspace, building forth upon existing data and methods (challenge 2 and 3).

To address these four challenges, we pose four research sub-questions:

RQ1. What factors affect children's access to urban greenspace, and how are these accounted for in accessibility measures?

RQ2. How well do greenspace data capture people's perceptions of urban greenspace?

RQ3. How can we assess children's access to greenspace from residential, educational, and commuting settings?

RQ4. How to design a greenspace accessibility metric that considers factors associated with children's unsupervised play?

1.4. Approach and contributions

To answer our four research sub-questions and, consecutively, our main research question, we perform four studies. Each chapter in this dissertation describes one study. Throughout these studies, we explore the balance between *scales* and implementation across *geographical contexts* in methods and associated data, and the level of *depth* with which they account for relevant factors. In the following subsections, we explain the focus, scale, and the geographical context to each study, elaborate on the research methods, and state how these studies relate to each other.

We start with two studies to generate deeper understanding of the factors affecting children's access that methods could account for, and the greenspace data typically used as a basis for such methods to date.

Study 1. Factors and measures (RQ1)

With study 1 we answer to RQ1 by generating theoretical understanding of *factors* affecting children's access to greenspace, and assessing how these are accounted for by methods for measuring access available to date. We use conceptual framework analysis [67], performing a scoping review of academic and policy-making literature, [68] and conduct two workshops with researchers and practitioners to identify factors that affect children's access to urban greenspace. Using reflexive thematic analysis [69] and visual mapping techniques, we synthesize these factors into a conceptual model. Subsequently, we identify methods for measuring children's access to urban greenspace in literature, and apply deductive coding to assess which factors of our model these methods account for, which factors workshop participants find meaningful to measure, and which of those remain unaccounted for to date.

Described in:	Chapter 2, published as: R. Teeuwen, A. Bozzon, and A. Psyllidis. “Children’s access to urban greenspaces: A survey of factors and measures”. In: Cities & Health (2024).
Focus on:	*Factors* and *methods*
Main contribution:	Conceptual model
Scale & context:	Through literature and workshops with European researchers and practitioners

Study 2. Greenspace data (RQ2)

With study 2 we answer to RQ2 by delving into *data* typically used when measuring greenspace accessibility, and how well they capture what people perceive as greenspace. Such subjective perceptions are found to be essential when investigating human activities in greenspace. We focus on two widely used greenspace data sources that are openly available world-wide and serve as a basis for many methods for measuring access to greenspace: land use / land cover data such as OpenStreetMap, and satellite-based indices such as Normalized Difference Vegetation Index (NDVI) maps. We generate empirical understanding on how well these data capture people’s visual perceptions of greenspaces, and where and why deviations remain. We sample locations in three case-study cities spread over Europe, and crowdsource people’s visual subjective perceptions of these places, by showing them panoramic street-level imagery and asking them how vegetated they perceive the place in the image, and why. We then statistically assess how well these perceptions align with the OpenStreetMap and NDVI data, and explain notable deviations that occur using reflexive thematic analysis [69].

Described in:	Chapter 3, published as: R. Teeuwen, V. Milias, A. Bozzon, and A. Psyllidis. “How well do NDVI and OpenStreetMap data capture people’s visual perceptions of urban greenspace?”. In: Landscape and Urban Planning 245 (2024).
Focus on:	*Data* on greenspaces
Main contribution:	Insights on agreement between greenspace data
Scale & context:	Data available world-wide, through analyzing places in three European cities

We continue our research by designing two novel methods for measuring access that (a) incorporate factors that remain unaccounted for to date, according to study 1, and (b) are based on OpenStreetMap greenspace data, studied in study 2.

Study 3. Measuring access from daily settings (RQ3)

With study 3 we answer to RQ3 by designing a novel method for measuring access to greenspace by children commuting between home and school. Such routine access while being en route is important for children’s cognitive development. We complement existing approaches to map children’s routes by contributing a *more scalable* method that can identify patterns across all streets within cities. We build upon principles of patronage betweenness, estimating the flows of people that are en route from one place to another [70]. We apply this principle to children commuting between home and school for three Dutch case study cities, generating heat maps of commuting children, and quantify per greenspace how many children are estimated to commute through it on a daily basis, resulting in an on-the-move accessibility measure. We statistically compare these outcomes to the outcomes of methods that measure children's access for dedicated trips from home or school, respectively, and qualitatively explore spatial patterns underlying the most notable differences between the methods.

Described in:	Chapter 4, published as: R. Teeuwen, A. Psyllidis, and A. Bozzon. "Measuring children's and adolescents' accessibility to greenspaces from different locations and commuting settings". In: Computers, Environment and Urban Systems 100 (2023).
Focus on:	*Methods* to measure access from various *settings*
Main contribution:	On-the-move measure
Scale & context:	Per street in entire cities, implemented on three Dutch cities

Study 4. Measuring access for unsupervised play (RQ4)

With study 4 we answer to RQ4 by designing a novel *method* to measure access to greenspace by children that go out to play without adult supervision. Children value natural features for play, and express the desire to play without supervision. Furthermore, unsupervised access enables routine use of greenspace, and contributes to children's health, development, and interaction with peers, amongst others. However, despite knowing about the importance of exposure to nature, parents restrict their children's opportunities to visit greenspace without adult supervision because of perceptions of safety. In study 4, we go *into depth* on access for unsupervised outdoor play, exploring what *factors* influence such access, how to recognize them in *data*, and how to integrate them into accessibility *measures*. We focus on three urban neighborhoods spread over Europe, while ensuring potential future transferability to (other) cities. We iteratively co-design our method [71] in two interactive workshops with European experts on children's health and the built environment. In preparation to the first workshop, we adapt an existing *walkshed* accessibility measure, informed by an exploratory literature review. During the workshops, we delve further into what factors promote or limit access to play space for children without adult supervision, how these factors can be recognized in data on the urban environment, and how our method currently reflects these factors. After every workshop, we perform reflexive thematic analysis [69] to analyze the participants' input, and revisit our prototype with the knowledge generated. We then apply our final method to urban environments in the three case study cities, and quantitatively compare outcomes of our novel method to the outcomes of the original.

Described in:	Chapter 5, published as: R. Teeuwen and A. Psyllidis. "Easy as child's play? Co-designing a network-based metric for children's access to play space". In: Proceedings of the 18th International Conference on Computational Urban Planning and Urban Management (CUPUM 2023) (2023).
Focus on:	*Methods* to measure access for *unsupervised play*
Main contribution:	Child's Play metric
Scale & context:	Per street in urban neighborhoods, implemented on three European cities

Finally, in chapter 6, we revisit our conceptual model, contributed in study 1, with the knowledge generated throughout studies 2, 3 and 4, and reflect on our findings by means of this model.

Figure 1.2 shows an overview of our four studies and how they relate to each other. Each study is visualized in a separate rectangular box, stating the associated sub research question and research methods. On the left side, input data or methods are shown, with an arrow towards the main contribution on the right side of the box, as well as side contributions in italics outside of it. Arrows between the boxes show how outcomes from one study feed into others. Additionally, one grey dashed arrow ties all studies together, leading to a revisited conceptual model.

Open science principles

Throughout our studies, we adhere to *open science* principles. This means that we make our research publications publicly available, contribute open-source Python code to operationalize our two novel methods on various case study cities, and base our methods on open data wherever possible. Additionally, we make data resulting from our studies openly available as well, specifically data on people's visual perceptions of greenspace, and greenspace accessibility maps of various urban environments across Europe. Doing so, our work can be reused, replicated, or adapted by other researchers and practitioners. Our research data and code are available at the 4TU.ResearchData repository via the following DOI's:

- **Study 1.**
  10.4121/1e3643a6-effc-4d90-8948-115904cc524d
- **Study 2.**
  data: 10.4121/5c3ad699-5ed4-4e91-8435-fb537e01f325
  code: 10.4121/558f6150-a3e9-4960-82b2-cd2115c070d4
- **Study 3.**
  data: 10.4121/ac5073de-34cb-4e71-a9b2-6e2d65e7ae72
  code: 10.4121/7422a6cf-ec0e-42c5-9ceb-55d7c886bc4d
- **Study 4.**
  data: 10.4121/0ec69d2a-d966-4dcd-a415-f05d756636d6
  code: 10.4121/2e16ff97-dabb-421f-803d-d05fd3204959

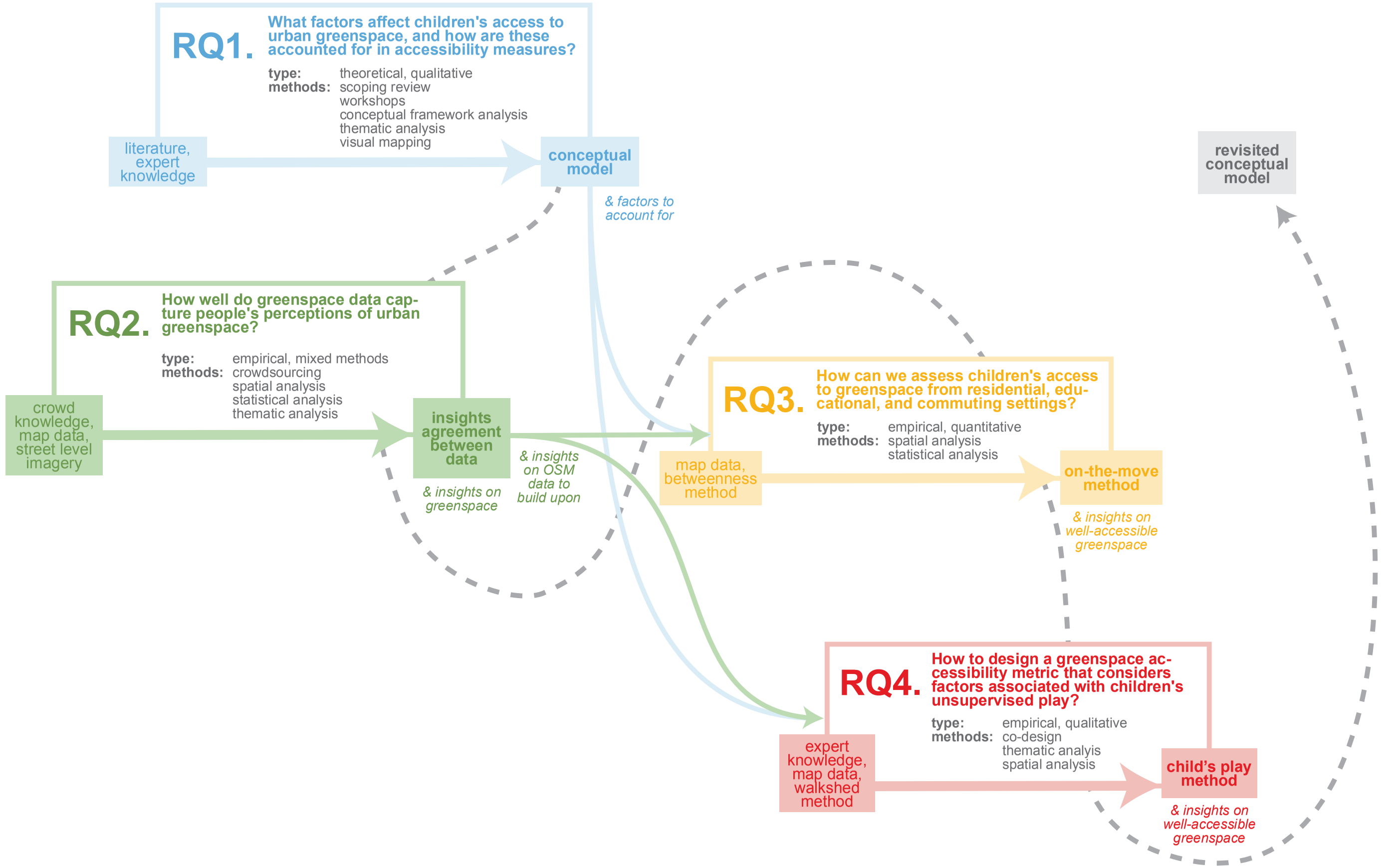
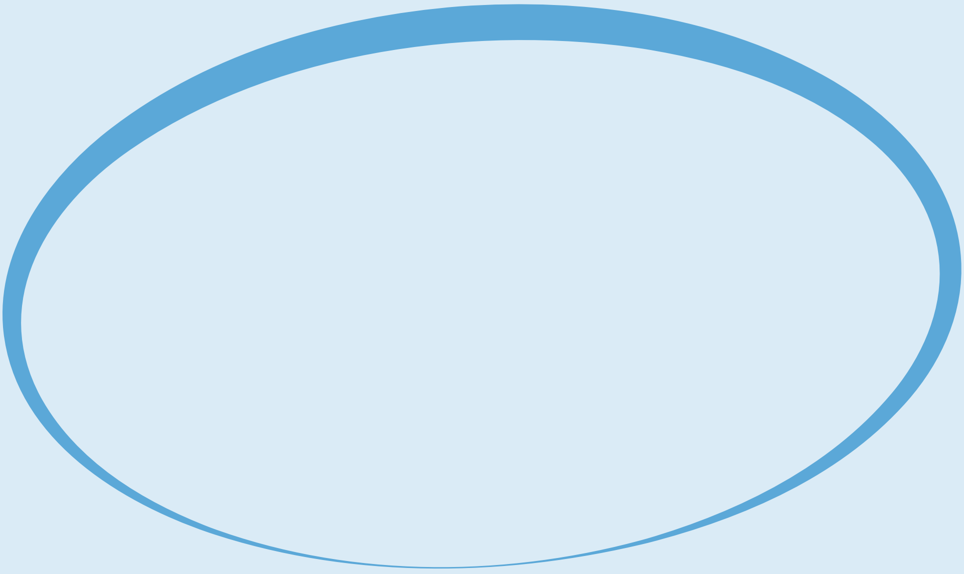


Figure 1.2.: Methodological overview of four studies with their research question, methods, and input and output data, as well as relationships between studies, and synthesis of results into a revisited conceptual model. Each chapter in this dissertation describes one study.



2

A conceptual model of factors

In this chapter we explore what factors affect children's access to urban greenspaces, synthesize them into a conceptual model, and assess how generalizable accessibility measures implemented in literature address these factors. We first conduct a scoping review and workshops with researchers and practitioners to identify factors affecting children's access to greenspace. Using conceptual framework analysis and visual mapping techniques, we iteratively synthesize the literature and workshop transcripts into a conceptual model. Subsequently, we use deductive coding to identify what factors generalizable accessibility measures implemented in literature account for, what factors workshop participants deem important to measure, and which of these factors remain unaccounted for. Based on our findings, we identify potential future research directions to develop methods for measuring children's access to greenspace, while our conceptual model can help in making informed decisions when selecting measures, and in fostering a shared understanding of children's access to urban greenspace. By the end of this dissertation, we will revisit the conceptual model contributed in this chapter with the knowledge generated throughout the remaining chapters of this dissertation.

This chapter is published as: R. Teeuwen, A. Bozzon, and A. Psyllidis. "Children's access to urban greenspaces: A survey of factors and measures" In: Cities & Health (2024). DOI: 10.1080/23748834.2024.2387931

2.1. Introduction

Methods for measuring children's access to urban greenspace can help in understanding the links between greenspace and children's health and well-being [2, 48], yet two issues remain. First, existing accessibility metrics often employ the same principles for both children and the general population, ignoring factors such as parental restrictions and children's preferences, which are important determinants of children's access to greenspace. Instead, these metrics predominantly capture the mere presence of greenspace in a given environment [49, 50, 51] or the distance to the nearest greenspace [52]. Second, the lack of a comprehensive assessment of factors influencing children's access to urban greenspace highlights the limitations of the existing metrics. During an exploratory literature review, we identified one conceptual framework on *planning* greenspaces for and with children [72]. While this framework regards accessibility as important, and may serve well in urban planning processes, it does not unpack in further detail what it entails for a greenspace to be accessible to children, nor did we identify any other reviews, frameworks, or models that do so. Yet, a comprehensive overview of what determines children's access could provide valuable insight into what factors remain unaccounted for by accessibility measures, support the design of measures that better account for these factors, and help communicate the coverage and limitations of measures available to date.

In this chapter, we introduce a conceptual model of what factors affect children's access to urban greenspace and present an overview of how these are, or are not, accounted for in accessibility measures implemented in literature. Doing so allows us to identify promising lines for future work on designing measures for children's access to urban greenspace. We collect data from two sources: a scoping review of scientific and policy-making literature identifying factors affecting children's access to urban greenspace, or implementing measures thereof, and generative workshops with researchers and practitioners as participants to elicit their ideas and needs for measures. We then analyze all data and synthesize our findings into two contributions: (1) a conceptual model of factors affecting children's access to greenspace, and (2) an overview of accessibility measures implemented in literature, positioned in relation to these factors and participants' needs. We scope to access by children in so-called middle childhood [26], i.e., roughly six to eleven years old, a phase in which children start to gain *some* freedom from adults [27], depending on the cultural and geographic context. By positioning existing measures into our conceptual model of factors, we provide insight into promising lines for future development of accessibility measures that account for factors previously uncovered.

In the remainder of this chapter, we define key terms and set our scope and detail our approach. Then, we present our two contributions: a conceptual model of factors affecting children's access to urban greenspace, and an overview of how measures implemented in literature account for them. Lastly, we interpret our results and their implications, before concluding with our key findings.

2.2. Definitions and scope

Before delving into how we conduct our data collection and analysis, we define key terminology and set the scope of our study.

The definition of *greenspace* varies per discipline and study. Generally, two types of definitions can be distinguished, referring to either an overarching concept of nature (and thus an antonym to urbanization) or to urban vegetation, in interaction with humans [73]. We focus on the latter, specifically, urban vegetation open for activities by the general public. The World Health Organization (WHO) defines *urban greenspace* as "urban space covered by vegetation of any kind" [74]. We adapt this definition to "*public* urban space *characterized* by vegetation of any kind", including "smaller green space features (such as street trees and roadside vegetation), and larger green spaces that provide various social and recreational functions (such as parks, playgrounds or greenways)". Contrary to the WHO definition, however, we exclude "green spaces not available for public access or recreational use (such as green roofs and facades, or green space on private grounds)".

Accessibility can be defined as "the ease of reaching a destination" [42], affected by the amount, variety and spatial distribution of potential destinations, the magnitude, quality, and character of activities that can be performed in them, and the travel costs and modality associated to getting there. A multitude of *measures* have been designed to quantify access to greenspace [2, 4, 15, 43], including measures of straight-line or network distance, or temporal or monetary costs of getting to a greenspace, potentially differentiating between greenspace class, size, and presence of desirable facilities.

Throughout this chapter, we focus on *generalizable accessibility measures* quantifying access to greenspace in entire cities, building upon principles that can transcend to other geographical contexts. This means we exclude studies relying on the participation of local populations (e.g., by conducting questionnaires or tracking GPS coordinates) or in-situ field work (e.g., observations or audits). Instead, we scope to approaches that use geographical data, such as land use and land cover data, street networks, satellite imagery, and population data, to model access within a city. Such generalizable measures can serve to study not only if greenspace is needed, but also how much, where, when and of what type [2], to perform large-scale epidemiological studies [48], or to assess how equitable access to greenspace is distributed over cities [46, 47].

We scope further down to generalizable accessibility measures *tailored to the children's age group*: We solely consider measures that adapt their design to, or motivate their design choices with respect to, the children's age group. We exclude measures applying the same principles to the children's group as to any other population group without explicitly motivating why the same principles hold for children as well. For instance, we exclude measures quantifying access as the presence of greenspace within a given distance, without explaining why the chosen distance suits for access by children, while we do include measures that apply similar principles, but explicitly motivate their proximity threshold as the distance *that can be traversed by children*, or that motivate chosen greenspaces as *suitable for children* because playing equipment is present.

Lastly, we scope to access by children in so-called *middle childhood* [26], i.e., roughly six to eleven years old. In this age group, depending on parental concerns and the cultural and geographical context, children may start to gain their first independence from adults [27]. This choice has further been determined by the European Horizon 2020 research project this study is part of: Equal-Life [75].

2.3. Methods

In this section, we describe how we collect data, compose a conceptual model of factors, and create an overview of measures in relation to these factors. Figure 2.1 illustrates our workflow. We follow the conceptual framework analysis methodology by Jabareen [67] to build our conceptual model. Informed by an initial exploratory literature review, we collect two types of data: first, literature from academia and policy-making practice (section 2.3.1), and second, ideas and needs for measures from researchers and practitioners articulated during two workshops (section 2.3.2). Combining knowledge described in literature with knowledge stemming from researchers and practitioners allows us to gain a more holistic understanding of our topic. Using thematic analysis [69] and visual mapping techniques, we iteratively compose our conceptual model, before applying deductive coding to position measures in relation to the identified factors (section 2.3.3).

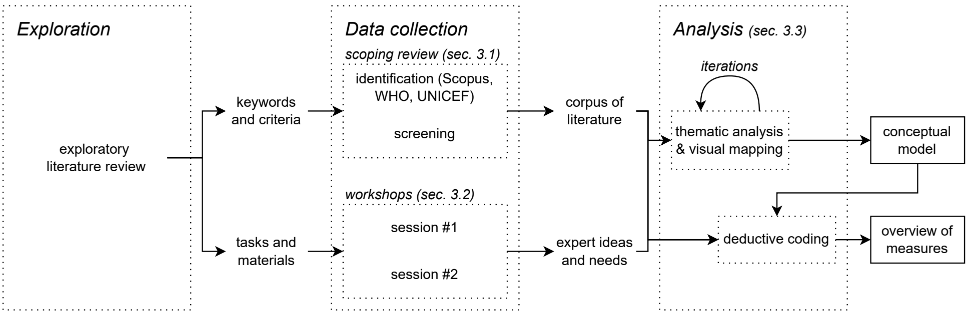


Figure 2.1.: Research workflow: exploratory literature informing review keywords and criteria, and workshop tasks and materials; data collection through scoping review and two workshops; iterative thematic analysis and visual mapping resulting in a conceptual model of factors; and deductive coding resulting in an overview of measures positioned in relation to these factors.

2.3.1. Identifying relevant literature

We perform a scoping review to identify relevant literature from academia and policy-making practice. We structure our review in four phases, following an adaptation of the PRISMA statement [76] (figure 2.2).

Academic literature. We use *Scopus* to identify academic literature: a multidisciplinary database integrating content from various specialized databases [77]. We filter for journal articles and conference papers in English, published no later than October 2023 (i.e., until we conducted our analysis) mentioning in their title, abstract, or keywords “urban”, “greenspace”, “access”, and “child”, or synonyms thereof, as defined based on the authors’ best judgment, using in the following Scopus search query:

```
TITLE-ABS-KEY (
( urban* OR "city" OR "cities" OR metropol* ) AND
( "greenspace" OR "green space" ) AND
( access* OR reach* ) AND
( child* OR "youth" OR "young people" OR "young person" ) ) AND
( LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT-TO ( DOCTYPE , "cp" ) )
AND ( LIMIT-TO ( LANGUAGE , "English" ) )
```


We then assess the identified literature on eligibility. In line with definitions and scope set in section 2.2, we use the following exclusion criteria: (a) the *greenspace* criterion, excluding studies that do not focus at least partly on public urban greenspace (but instead, e.g., hospital gardens, or nature reserves far from cities); (b) the *age* criterion, excluding studies that do not focus at least partly on children between six and eleven years old; and (c) the *accessibility* criterion, excluding studies that do not study the concept of greenspace accessibility (but instead, e.g., "bioaccessibility" in soil, or having "far-reaching" implications). We also exclude study protocols, editorials, and opinion statements, and entries to which we cannot obtain the full text. Lastly, we exclude literature implementing measures that are authored by the authors. The first and last author formulate the query parameters and exclusion criteria together. The first author performs the screening, while iteratively consulting with the last author to discuss considerations made and to decide on particular cases. After excluding literature that does not meet our criteria, 45 academic full texts remain (figure 2.2).

Policy-making literature. We also collect policy-making literature from two organizations operating world-wide to improve, among others, children's health and well-being: the *World Health Organization* (WHO) and the *United Nations Children's Fund* (UNICEF). We query the WHO *Institutional Repository for Information Sharing* (IRIS) for English publications mentioning our keywords "urban" and "greenspace", or their synonyms, as of October 2023, resulting in 80 technical documents, governing documents, periodical articles, and other publications. We query the topic-based *UNICEF publications* search engine, focusing on the topics "urbanization", "environment", "sustainable development goals", "data and reports", and "health", and search for publications mentioning "greenspace" or its synonyms. After excluding documents that do not meet our criteria, eleven policy-making full texts remain (figure 2.2).

2.3.2. Two generative workshops

Following Jabareen [67], we also collect data from researchers and practitioners, complementing knowledge described in literature with knowledge on what practitioners deem meaningful to measure. The workshop activities have been reviewed and approved by the Human Research Ethics Committee at the authors' institute: Delft University of Technology.

Participants. We recruit a total of 27 participants. For the first workshop, we recruit researchers and practitioners (n=17) on children's health and well-being through a stakeholder network of the European Horizon 2020 research project this study is part of: Equal-

2

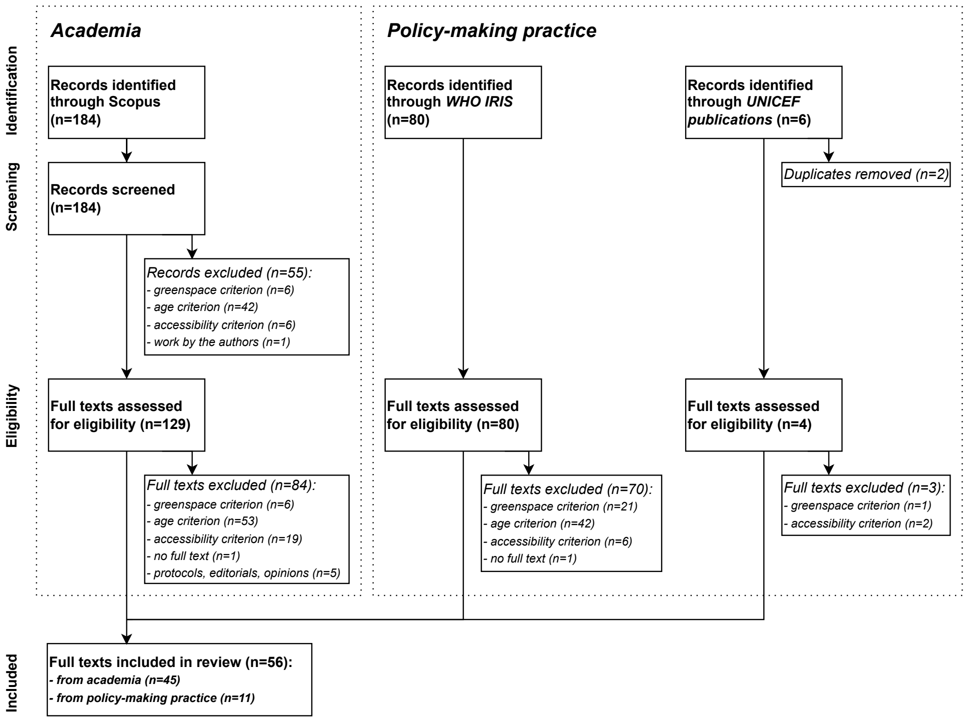


Figure 2.2.: Information flow throughout the phases of the scoping review.

Life [75]. For the second workshop, we recruit practitioners (n=10) working on green urban development for children at regional authorities in the region of The Hague, the Netherlands. We obtain informed consent from all participants.

Procedure. Both workshops follow the same three-round structure: introduction of the topic and participants, sharing ideas and needs for measures, and a plenary discussion. Table 2.1 details the tasks and materials we gave participants in each round, including filling a form and pitching ideas, and figure 2.3 shows an impression of the workshop setup. Both workshops took place in September 2023, the first in English and the second in Dutch. The English workshop materials are included in appendix A.

Figure 2.3.: Three participants filling the forms during the first workshop, with the card deck lying on the left.

2.3.3. Synthesizing findings into a model, and positioning measures against it

We analyze our data to make two contributions: (1) a visual conceptual model of factors affecting children's access to urban greenspaces and (2) an overview of how measures implemented in literature and proposed by participants relate to these factors, and which factors remain unaccounted for.

Conceptual model. By means of reflexive thematic analysis [69] on the identified literature and data gathered during the workshops, i.e., transcripts and forms, we identify themes covering factors that affect children's access to urban greenspace. To each theme, we formulate a key question based on which we report our results. Using visual mapping techniques, we then synthesize the identified clusters and factors into a visual conceptual model. We iterate on this process several times until we finalize our conceptual model.

2

Table 2.1.: Workshop structure in three rounds: (1) introduction of topic and participants, (2) sharing ideas and needs for measures, supported and inspired by a form and card deck, and (3) pitching ideas and plenary discussion.

Round	Tasks and materials
1. Introduction	We introduce the topic and the research context and ask participants to introduce themselves and how they work on children's access to urban greenspace.
2. Ideas & needs	We ask participants to generate and share ideas for meaningful ways to measure children's access to urban greenspace, individually or in small groups, without briefing them on existing measures beforehand. We encourage free thinking and creativity, and ask participants suggest whatever could support them in their work, and not to constrain themselves to what they perceive is feasible to implement. For support and inspiration, we provide participants with: • **A form** with guiding questions: what would they like to measure, why, on what scale, using what information? We also invite them to illustrate their idea in any way suitable (e.g., a schematic map, diagram, or drawing). • **A card deck** in which we introduce various potentially relevant information types, informed by the exploratory literature review: green- and bluespace data (e.g., from imagery, land use and land cover data [2, 3, 78]), locations where children perform activities (e.g., homes, schools [2, 36]), (slow) traffic infrastructure (e.g., sidewalks, main roads [30, 40, 41]), people's judgment of greenspace (e.g., through questionnaires, audits, and children's participation [2, 3, 29, 79, 80]), and a joker card to remind participants to bring up any other potentially relevant information type.
3. Discussion	We ask participants to pitch their ideas to each other, opening the floor for a broader discussion on what they deem relevant to measure, why that, and what such a measure could look like.

Overview of measures. We then delve further into how children's access to urban greenspace is measured. From our corpus of literature, we identify implementations of generalizable accessibility measures that are tailored to the children's age group, as defined in section 2.2. We apply deductive coding, using the factors from the conceptual model as codes, on the identified measures from literature, and the needs for measures collected during the workshops, to identify (1) which factors participants deem meaningful to measure, and why; and (2) which factors are accounted for by generalizable accessibility measures in literature to date, and how.

The first author performs the coding and identifies the initial themes while iteratively consulting and refining with the last author. We document our analysis in Microsoft Excel and Atlas TI. The authors acknowledge their perspectives are grounded in the European geographical context and their background in spatial and urban analysis. Workshop transcripts are analyzed in their original language. We report evidence stemming from the workshops in "quotes" (Pn.m) with *n* depicting the workshop, and *m* the participant. Quotes from the second workshop are translated into English for reporting purposes.

2.4. Conceptual model of factors

Based on our corpus of literature (n=56) and workshops (n=2), we build a conceptual model of factors affecting children's access to urban greenspace, presented in figure 2.4: Within an encompassing ellipsoid, depicting the context, we present five clusters of factors, each relating to a key question: *(With) whom* does the child access? *From where*? *How*? *To where*? And *why*? Arrows depict key relationships, and overarching factors are placed in the center. In the following subsections, we explain and exemplify our model, emphasizing terms from figure 2.4 in *italics*.

2.4.1. (With) whom? The *child*, and their *household* and *network*

Not every *child* is the same. Opportunities to access greenspace depend on a child's *age*, affecting their preferred activities [27, 81]. *Character* plays a role too, as every child is different [72, 82]. On *gender*, results are mixed. Some studies observe behavioral differences between boys and girls [74, 83] or report less experience with nature among girls [84], while others find no differences [85]. For children living with certain *conditions*, these play a major role [72, 82, 86, 87], for example autism spectrum condition [33, 88]. Throughout, the level of *independence* granted to the child by adults is key, primarily in terms of autonomy. Some children are allowed and able to access greenspaces without adult supervision "so they can just do it by themselves" (P1.16), or with peers [27, 35, 37, 89, 90], while others are accompanied by adults [22, 27, 33, 34, 89, 90, 91, 92, 93].

These adults are often members of the *household*, typically *family* (e.g., (grand)parents), or *guardians* [82, 89, 90], setting *restrictions* on the child's independence, defining which routes they can take, or what greenspace they can go to. Restrictions may conflict with children's wish for freedom and challenge [27, 82, 85, 94, 95]. Restrictions can be imposed by parents [27, 33, 35, 37, 85, 96], teachers [81], greenspace managers [97], or other adults: "what other people find what is and isn't allowed" (P2.8). The *housing* situation

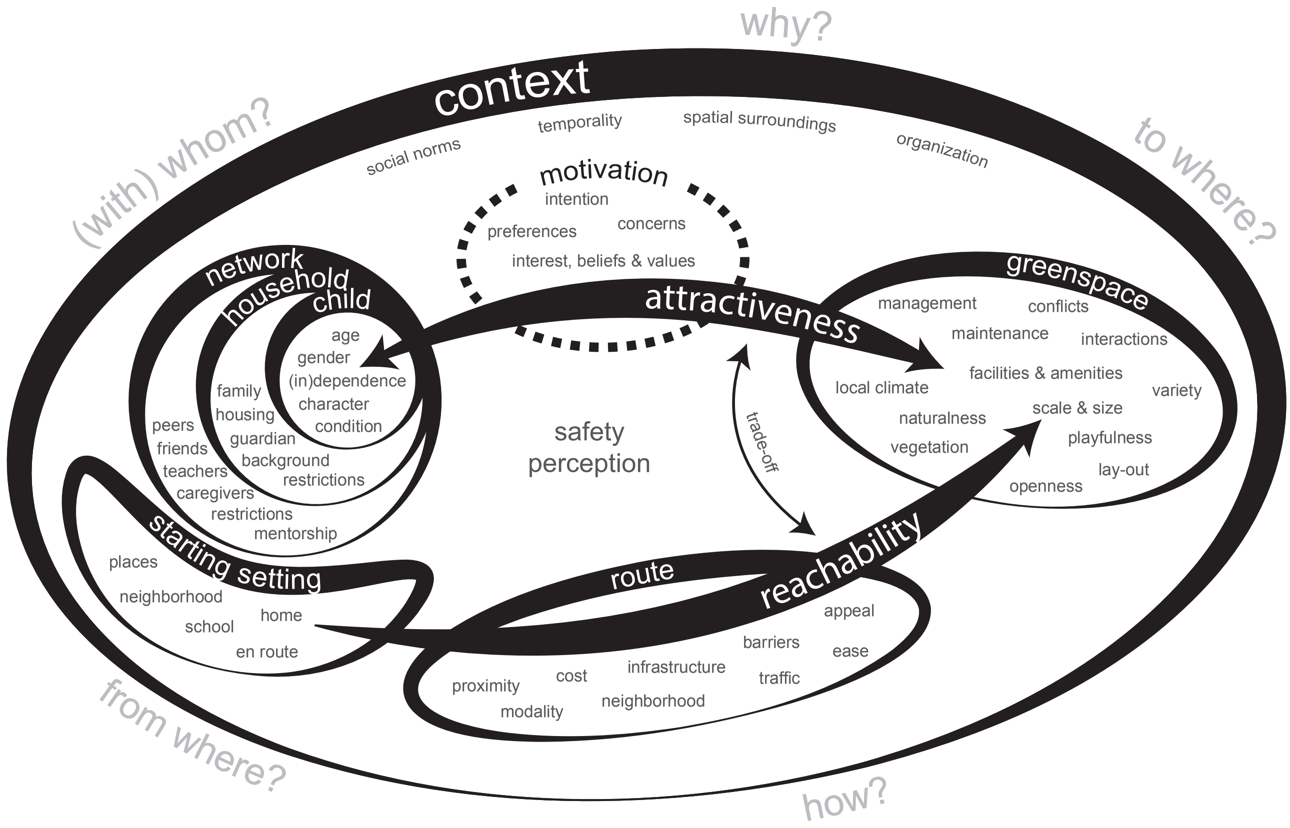


Figure 2.4.: Conceptual model of factors affecting children's access to urban greenspace, organized into five clusters, with overarching factors and key relations depicted in the middle. Key question to each cluster stated outside the encompassing ellipsoid: Access *with and by whom*? *From where*? *How*? *To where*? And *Why*?

may also affect access. A garden may serve as play space and catalyst for visiting public greenspaces [33, 90], while for other people “the park is your garden” (P1.13). Children living in gated communities visit greenspace more frequently [86]. On the socio-economic *background* of the household, results are mixed [98]. Family finance may affect type and location of housing, and access to transport means [82, 87, 93], while migration status [99] or ethnicity [22, 91] can play a role too. Furthermore, spatial inequalities in provision, quality and funding of greenspaces may correlate with demographics [82, 87, 91, 93, 97]: “in [neighborhood A] you obviously have more greenery for children anyway than in [neighborhood B]” (P2.10).

A wider social and support *network* around the child may also be involved, including *peers* and *friends*. With other children nearby, adults grant children more freedom and autonomy [35, 90], and children enjoy themselves: “often it is not at all the greenery itself, but simply that your friends are there” (P2.2). Adults from the network can accompany children too, for example *teachers* or *caregivers*, or may set *restrictions*, similarly to adults within the household. Sometimes, the social network provides *mentorship*: community workers or others providing information or practical support for accessing greenspace [99].

2.4.2. From where? The starting *setting*

Children may access greenspace from various *starting settings*. Most typical are the *home* [22, 27, 86, 98, 100] and *school* [22, 27, 33, 72, 97, 101, 102], either during school hours [74, 82, 90, 101], depending on the school’s budget and schedule, and teacher’s confidence or concerns [101], or after school with school mates or adults picking children up from school: “perhaps they can go before or after school and make use of those spaces because they’ve been brought there during their school day to learn how to use and interact in that space and may feel welcome” (P2.15). The *neighborhood* around the starting setting matters too, e.g., neighborhood greenness, deprivation, safety, or crowdedness [35].

Another possible starting setting is while being *en route* between home and school: “greenery is also important in the every-day life of children so simply on your route for example to school” (P2.5) [37, 85, 103]. Lastly, other *places* where children perform routine (extra-curricular) activities can serve as starting settings [72, 82, 91], particularly when houses are mixed with other places: “the physical network of those children, school, sports club, the stores where you go to” (P2.2).

2.4.3. To where? Characterizing child-friendly *greenspace*

Children’s access also depends on *greenspace* characteristics and quality [86, 91]. Good quality *vegetation* makes a greenspace suitable for children, sparse vegetation is often preferred [81, 89], and *openness* is valued, allowing good visibility and space to be active [27, 81, 92]. On greenspace *scale and size*, evidence is mixed. Some studies stress large area does not imply satisfaction [33], while others find large-size greenspaces to promote accessibility [91, 95]. Several studies highlight how small, local, or informal greenspaces are essential to complement larger ones: “that is of course especially important for the children” (P2.10) [37, 85, 89, 90, 96, 102]. Regarding *lay-out*, people prefer open and landscaped greenspaces for children [22, 27, 34, 81, 83, 92], compartmentalized in various inter-connected areas [72, 82, 88].

Opposed to landscaped greenspace, *naturalness* is valued less for children's activities [22], especially when wild animals or poisonous planting (so-called "ecosystem disservices" [96]) are present [85, 96, 104], while some studies do report preference for less manicured and more wild greenspaces [85, 89]. Children dedicate value to vegetation [74, 82, 95, 96], and biodiversity has "value as well" (P1.1). The *local climate* may make a greenspace more suitable, e.g., with shade [33, 83, 91], and without environmental pollution: "air pollution, water appropriateness, and so on" (P1.5). During the workshops, attractive soundscapes were mentioned: "the idea of that a place is also characterized by the acoustics, if you have a spring water, it has an acoustic, traffic roads is another, acoustic birds in the park" (P1.3). Greenspace *playfulness* encompasses various aspects. Natural elements serving for play, such as trees for climbing or natural or hilly terrains promoting adventure and exploration [81, 82, 92, 97]. Additionally, playgrounds may be linked "to the greenery that is already there" (P2.8) [47, 102], and playful furniture and art may be present [82], or recreational water for "swimming in nature" (P1.5) [22].

When accessing greenspace, *conflicts* with other users may occur, including older children or teenagers perceived as intimidating [27], dogs perceived intimidating, and their poo [94], homeless people living there occasionally [85], and people who intimidate, harass, beg, shout, or otherwise induce fear among children or their companions [27, 82, 93]. Yet, children do value *interactions* with peers [22, 72, 90], other generations [22, 72, 82], or animals inhabiting the greenspace [72], and accompanying adults value interactions with each other [33]. Perceived social safety further encourages access, promoted by good visibility and presence of people [27, 33, 97].

Facilities and amenities may further induce such interactions, and access in general [74]: e.g., safe play and sports equipment concentrated in one place [33, 34, 82, 91, 94], seating for accompanying adults [82], lighting to ensure visibility during dark hours [82, 96, 105], and provisions such as drinking water, electricity, and Wi-Fi [22, 34, 82]. Having a *variety* of options is important "because the wishes of everyone is different" (P1.4) [33, 82, 83, 88, 92]. Variety also makes greenspaces suit multiple generations, encouraging adults to accompany their children more often: "it should be attractive for their guardians as well" (P1.4) [82, 84, 89]. Both children and adults value good *management* and *maintenance*, e.g., spaces without damaged or excessive vegetation [81, 87, 96], or spaces with proper hygiene and cleanliness, without litter lying around [82, 85, 87, 96]. Poor upkeep may cause parents to regard greenspaces off-limits [87].

2.4.4. How? Barriers and encouragement along the *route*

Regarding the *route* to greenspace, *proximity* is key: the greenspace should be reasonably nearby the starting setting [27, 33, 35, 37, 72, 82, 85, 89, 93, 97, 98, 99, 101, 106]. The distance a child can travel depends on age, restrictions [35, 37, 97], and company [89]. Proximity, however, is not the only thing: "sometimes it is nearby, but it does not feel nearby" (P2.9) [88, 90, 101]. *Modality* plays a role too, depending on the distance [90, 107]. Access on foot is mentioned often [33, 89, 93], while biking is an option as well, especially when children are older: "they are then allowed to cycle in the streets" (P1.3) [33, 90, 91, 93]. Adult company opens up possibilities to travel further by car or public transport [33, 88, 89, 90, 93]. Such modalities, however, come at a *cost* [87, 99], e.g., of owning and maintaining a vehicle, buying fuel or using public transport. Modalities further depend on the *infrastructure* connecting the starting setting to greenspace. Walking and biking infrastructure are important "so that you can get to a place via decent sidewalks" (P2.8) and should be perceived safe [82, 100, 103].

Along the route, children may encounter *barriers*, either spatial, e.g., major public transport infrastructure [33], or physical, e.g., uneven surfaces or narrow passages, especially for children living with mental or physical health conditions [82, 108]. A particular type of barrier is *traffic*: "so I think that one of the big barriers is traffic" (P2.9). Traffic may cause safety concerns [82, 91, 105] restricting independence [27]. Children should be kept away from traffic [33] and should not have to cross busy streets to get to greenspace [33, 82, 93].

The route's *neighborhood* can increase opportunities to access greenspace, for instance when it is walkable, with a high land use mix [82, 91], where multiple trips can be combined, e.g., to cafes, shops, and greenspaces. However, when public school grounds are near, parents are less inclined to let children visit greenspace further away without supervision [37], and where public transport is close, fewer children are observed in urban parks [91]. Access increases when a route is *easy* to traverse, especially for children with certain conditions [88, 105], e.g., with clear signage, a smooth surface, and without difficult crossings. Routes may even have *appeal* in themselves: "attractive routes" (P2.2) enhance accessibility further.

2.4.5. Why? *Motivations* to visit

Understanding *motivations* of children, and their companions, to visit greenspace is key: "the question of, yeah, why does someone want to go somewhere is quite important" (P2.4). Motivations is driven by the *intention* to perform activities, and how well the greenspace suits those activities, e.g., playing, including exploration, seeking adventure, pretend play, and learning through play: "they like to play, this is all the most important differences from we, adults" (P1.11) [27, 72, 81, 82, 83, 84, 90, 96, 97, 106]. Physical activity is mentioned as well: "to feel free, be free, and move around" (P2.8) [22, 82, 83, 93, 95, 102]; as are social interactions [82, 83, 95, 97, 102], enjoying privacy [85], and relaxation [81, 85, 90]. *Preferences* may simply vary from person to person and motivation is also influenced by *interests, beliefs, and values*, for example parental interests in nature [33, 84], parental wishes to enjoy time with their children [22, 33, 34], parental beliefs regarding healthy activities and environments [33, 87], feelings of attachment to certain places [34], or personal receptivity by previous good experiences with greenspace [99]. Children or adults may also assign educational, provisional, or socio-cultural value to nature in general [104]. Safety *concerns* may limit motivations to visit [27, 87, 96], caused by fear of hazards [96], crime [91], injury [85, 94], traffic safety [85, 96], water banks and steep hills, or high voltage electricity [82].

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2.4.6. Overarching and contextual factors

A key overarching relationship is the trade-off between reachability and attractiveness: *Reachability* depends on the route connecting the starting setting to the greenspace, while *attractiveness* is determined by how greenspace characteristics match the motivations of children and their companions to visit: “the more attractive the space is, the more the people go” (P1.16). Access depends on a *trade-off*, i.e., whether visiting is worth the effort, depending on how easy and pleasant, or dangerous and difficult reaching the greenspace is, and how well it appeals to the child and their companions: “if it’s attractive they go across the city” (P1.17) [33, 87, 89].

Contextual factors play a role too. *Social norms* define how important people find children’s visits to greenspace [87] and the level of independence they can be granted [37]. *Temporalities* include effects of seasonal variance (e.g., heat, cold, ice, flooding) [82, 91, 96], the type of day (e.g., weekdays, weekends, holidays) [91], and the time of day (e.g., darkness, or need for shade) [27, 33, 82, 83, 87, 91]. Additionally, children need sufficient free time to visit [72, 89], and particular time periods, such as the COVID-19 pandemic, may have effects [90, 109]). Differences in *spatial surroundings* may exist between geographic regions [33, 85], e.g., in deprivation [91] and urban density [91]. *Organized* programs and activities in greenspace can promote children’s visits further [34, 74, 82, 87, 91].

Last but not least, *safety perception*, of both the child and their companions, relates to many aforementioned factors: e.g., how independently children may operate [27, 35, 37], through what neighborhood and via what route they may go [72, 82], and what greenspace they want, or are allowed, to spend time in [33, 34, 72, 82, 87, 90, 105].

2.5. Overview of generalizable accessibility measures

We identify 21 articles, all academic, that implement a measure of children’s access to urban greenspace. Additionally, 25 workshop participants share ideas and needs for such measures. In this section, we position all measures and needs as an extra layer to our conceptual model in figure 2.5: In bold, we emphasize what factors participants find meaningful to measure, and in blue, we highlight factors that measures in literature account for. We differentiate between factors directly accounted for (dark blue, e.g., measuring distance to greenspace from houses directly accounts for factors *proximity* and *home*) and those only indirectly accounted for (light blue, e.g., a chosen distance threshold motivated as the distance children can traverse *independently*). In the following subsections, we explain and exemplify this overview of measures. Additionally, we provide two summary tables in appendix A: table A.1 reporting factors accounted for in literature, and table A.2 reporting what factors participants propose to measure.

2.5.1. The child as the true expert

Concerning the *child* participants emphasize the need to measure *independent* access to greenspace: “the principle is that children should be able to meet friends on their own” (P1.16). In literature measures, however, independence is only touched upon. Various studies motivate their distance threshold as “the area a child could be expected to be able to use independently” [35], with distances varying between 300 meters and a

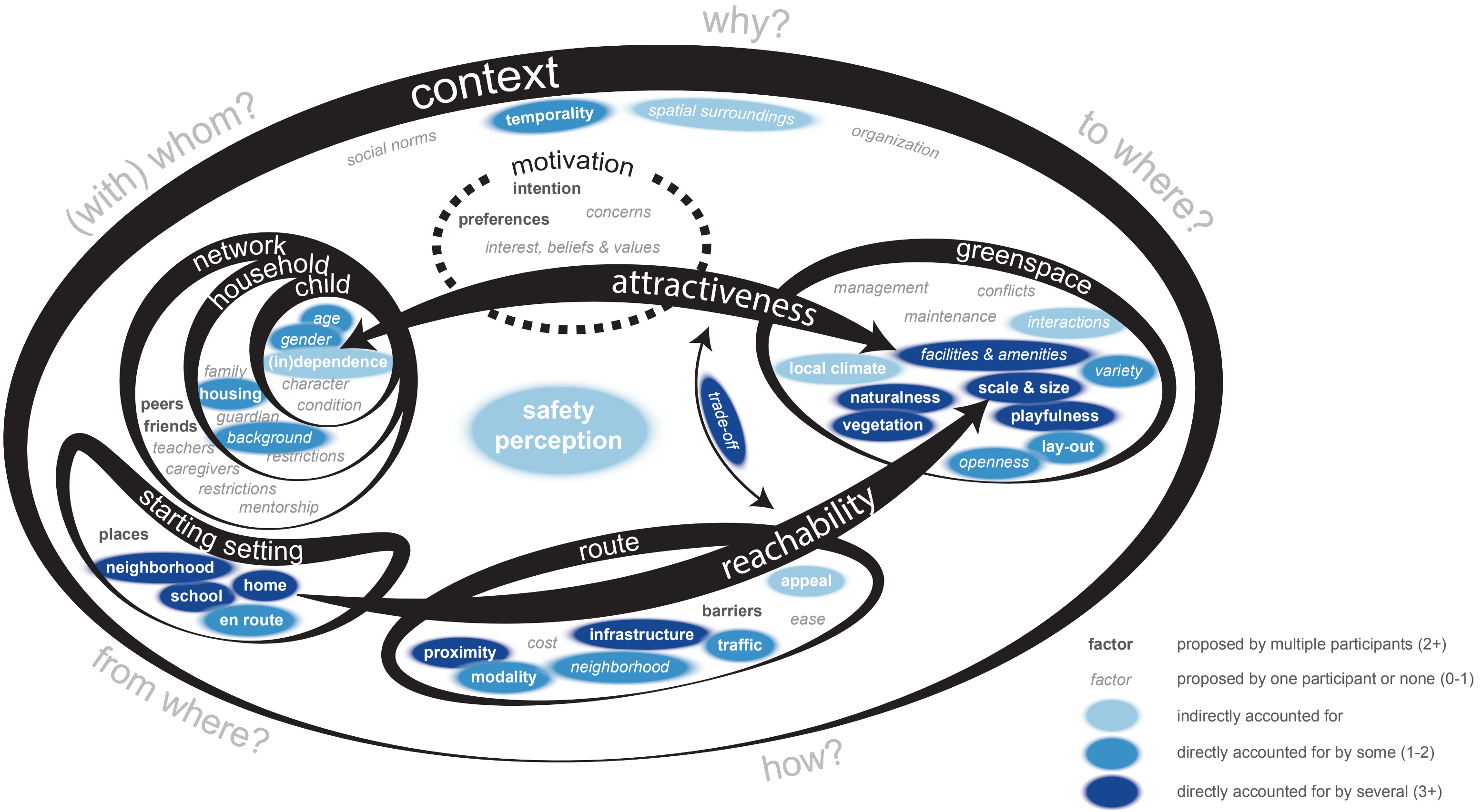

Figure 2.5.: Overview of measurement needs and implementations: Factors of the conceptual model that are accounted for by measures implemented in literature highlighted in dark blue (accounted for by several, 3+), medium blue (accounted for by some, 1-2), and light blue (indirectly accounted for). Factors deemed meaningful to measure by multiple workshop participants emphasized in **bold**.

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kilometer [35, 47, 53, 55, 110]. Reyes, Páez, and Morency [107] use *age* and *gender* to determine the distance a child may travel to access greenspace, while Ghale, Gupta, and Roy [111] and Iraegui, Augusto, and Cabral [46] touch upon *age* by differentiating between greenspace types for different age groups and corresponding distance thresholds. We identify no measures accounting for *character* and *conditions*, and neither are these emphasized by participants. Yet, participants do emphasize needing information on children's views on access: "the true experts" (P1.12); "what do those children think themselves" (P2.7); while other participants comment that "sometimes children don't know exactly what good is for them" (P1.13).

Regarding the child's *household* participants emphasize housing: "it should start with a nice play space near the house, so a garden or something" (P.2.10); "but not everybody has a garden, so the park is your garden" (P1.13). In literature, Mears *et al.* [53] account for housing by measuring garden size as one of their indicators. Reyes, Páez, and Morency [107] account for the household's *background* (e.g., income class) as a determinant for distance, and La Rosa *et al.* [60] touch upon background by stating how their measure can adapt to different social groups. We do not identify any measures that account for *family*, *guardians*, or *restrictions*.

Regarding the child's social and support *network* participants emphasize needing information about access with *peers* and *friends*, but we do not identify measures accounting for those factors in literature, and neither for *teachers*, *caregivers*, *restrictions*, and *mentorship*.

2.5.2. Starting settings and missing places

All *starting settings* in our conceptual model are also emphasized by participants. The *home* is often mentioned: "where does this target group live?" (P2.9); and accounted for by over half of the literature measures [35, 37, 53, 56, 57, 58, 59, 61, 105, 112, 113, 114]. Several studies measure access from residential *neighborhoods*, such as census or postal code areas [53, 55, 60, 110], and others measure access from *schools*: some to complement measuring access from home [57, 58, 59, 105, 114], while others focus on schools in particular. Examples include Walker, Bormpoudakis, and Tzanopoulos [101] studying greenspaces near schools, and Baró *et al.* [47] studying greenness on school premises, in surrounding streets, and nearby greenspaces. Measuring access *en route* is also emphasized by participants "so we know where do we invest our money to make spaces better, to adjust the environment because we now know where children move" (P1.14). In literature, Ye *et al.* [59] model home-to-school routes and assess how vegetated these are. Baró *et al.* [47] touch upon access *en route* as a motivation to measure street trees surrounding schools. Other *places*, such as sports clubs or shops, remain unaccounted for in literature measures, while participants do emphasize them: "the sports club, the shops where they go to [...] schools and play spaces are part of the total network that they use" (P2.2).

2.5.3. The route: broad needs, narrow implementation

Regarding the *route*, literature gravitates towards measuring *proximity* and *infrastructure*. Participants emphasize a broader range of factors, but also stress proximity and infrastructure: "it would be interesting to know how far a child of 6 to 12, what is the range of such a child" (P2.8); "and what the sidewalk there is like to get there" (P1.15). All literature measures operationalize some indicator of *proximity* [35, 37, 46, 47, 53, 54, 55, 56, 57, 58, 59, 60, 61, 101, 105, 107, 110, 111, 112, 113, 114, 115]: Studies deem anything within a given distance accessible [112], identify the nearest greenspace [37], or use distance as one of many parameters [56]. Distances are measured as straight-line distance [35, 47, 53, 55, 59, 101, 105, 107, 113, 115], or along the street network, thereby also accounting for the *infrastructure* [46, 47, 53, 58, 60, 61, 111, 112, 114].

Participants also emphasize *traffic*: "if I want to know how children can easily reach greenspace then I actually want to know how much traffic there is for the accessibility" (P2.9); and to a lesser extent *modalities*: "by foot by bike or by tram" (P1.16). Purwohandoyo *et al.* [105] use distance to high-traffic roads as an indicator promoting accessibility, indirectly touching upon *ease* in their motivation, and Gupta *et al.* [54] touch upon *traffic* and its effect on walking speed. Robillard, Boisjoly, and Waygood [61] also account for traffic by identifying children's infrastructure, e.g., by excluding high-speed streets, or solely including streets with sidewalks. Robillard, Boisjoly, and Waygood [61] also account for *modality* by differentiating between walking and cycling infrastructure, and Reyes, Páez, and Morency [107] by using the traffic modes available to a family, e.g., cycling or driving, as indicator for distance travelled. Several other studies touch upon modality by differentiating between walking and driving distances and infrastructure [59, 111].

Participants also emphasize needing information on *barriers*: "next to distance of course the physical barriers" (P2.2); while such barriers remain unaccounted for in literature. Two participants refer to the *appeal* of a route, which remains unaccounted for in literature. Reyes, Páez, and Morency [107] account for the route's surrounding *neighborhood* by considering land use and built environment as indicators for distance travelled. *Costs* remain unaccounted for.

2.5.4. Diversity in measures of greenspace

Measures in literature account for a variety of *greenspace* characteristics — most often scale and size, playfulness, vegetation, naturalness, or facilities and amenities.

Regarding *scale and size*, participants stress the need to measure small-scale greenspace, as "we have neighborhood greenspace and that is of course mostly important for children" (P2.10), and connectivity between greenspaces: "how is that connected neighborhood level up to city level" (P1.1). In literature, measures categorize greenspaces based on size or scale [37, 46, 54, 60, 111, 113, 115]. Xing *et al.* [56] include area as one of many parameters in their accessibility formula, and Janssen and Rosu [55] quantify the percentage of land covered by vegetation. Several studies touch upon size by including greenspaces of a certain size [53, 101, 114], while others explicitly include greenspaces of any size [57, 58].

Regarding *vegetation*, participants mention the need to measure, for instance: "the area of green per inhabitant" (P2.10); or "streets without trees" (P1.13). Studies quantify tree or vegetation cover, e.g., within a greenspace, [55, 56, 105], on school premises [47], or within an area [53]. Other studies use satellite-derived vegetation indices to quantify vegetation within an area [58, 59] or to distinguish between densely and sparsely vegetated greenspace areas [111]. Weber, Haase, and Albert [113] analyze, among others, greenspaces classified as "lush".

Concerning *playfulness*, participants emphasize interest in "how many play spaces there are", and in playful natural elements, e.g., "bushes that we [adults] overlook" (P2.8). Measures typically focus on playground presence [37, 53, 112, 113] or count [56] within the greenspace. Some studies consider playgrounds to be a type of greenspace as they "are generally located within greenspaces (or tree-covered public spaces such as squares) in Barcelona" [47], or classifying "tot lots" as the smallest greenspace type [54, 111]. Purwohandoyo *et al.* [105] touch upon playful nature by motivating measuring green waterfronts as "space for children to play".

Some participants connect playfulness to *naturalness*, needing to know "whether it's really a nature place because in my opinion, a nature play area, it's green, it's soft, it has a soft on the ground, it has enough light, water, sand, trees, natural things" (P1.10). Other participants express interest in measuring naturalness as "birds in the park" (P1.3), "green and blue infrastructure, so how is it performing and how is it connected?" (P1.1) and "biodiversity value as well" (P1.1). Measures in literature account for naturalness through water bodies [56, 105, 111], biodiversity or bird counts [35, 111], greenspaces "having a predominantly natural feeling" [53], or by studying "wild", "soughing" and "serene" greenspaces [113], or, indirectly, by assuming large-size greenspaces are natural [46].

Facilities and amenities are not particularly emphasized by participants, yet studies account for e.g., toilets [56, 112], walking paths within the greenspace [56], sports facilities [56, 113, 115], social or commercial facilities [105], swimming pools, benches, and picnic areas [56], and terraces [46]. Conversely, local climate and lay-out were emphasized by participants, but measured by few. Participants need information about the *local climate*, including air quality, light and shade, sound and noise, and water quality: "what quality of air, what noise you have in that" (P1.5). In literature, Baró *et al.* [47] touch upon the local climate, motivating measuring canopy cover as an indicator of good air quality and heat mitigation. Participants also emphasize *lay-out*, specifically in relation to other greenspaces: "you do not only want to know the greenspace but also the green structures" (P2.10). In literature, Ghale, Gupta, and Roy [111] account for layout of individual greenspaces through a measure of spaciousness, with highest values for greenspaces with a relatively large area given their perimeter.

While *openness* is not emphasized during the workshops, measures account for it by measuring the presence of green open space [105] or studying greenspaces characterized by "soughing openness" [113]. As to *interactions*, one participant expresses the need to understand where children "can meet each other" (P2.8). Studies touch upon such interactions as motivation for measuring presence of play and sports facilities [53], or for focusing on neighborhood- and community parks as places where children interact [111]. Xing *et al.* [56] account for *variety* within greenspaces through a multi-component attractiveness score, including indicators of playfulness, facilities and amenities, naturalness, and vegetation, where only greenspaces scoring well on all indicators achieve a maximum score. Christian *et al.* [37] touch upon variety by assuming large greenspace size implies a variety of attractive characteristics. We identify no measures that account for management, maintenance, or conflicts, and neither are they emphasized by multiple participants.

2.5.5. Motivations: important yet uncovered

Children's *motivations* are important to participants: "the question like motivation, why, why do you want to be there at all?" (P2.2); "I think the question like yeah, why does someone want to go somewhere, is quite important" (P2.4). Participants particularly stress *preferences* and *intentions*: "which greenspace do they find interesting, do they want to use?" (P2.1). However, we do not identify any measures implemented in literature that indirectly or directly account for any motivation-related factors.

2.5.6. About the context

Several participants emphasize the key overarching factor *safety perception*: "[it should be] safe enough that the parents would let them go" (P1.17). In literature measures, however, safety perception is only touched upon by Robillard, Boisjoly, and Waygood [61], measuring access to greenspace via pedestrian infrastructure to reflect "a safer way to travel by foot".

Only one participants mentions the need to measure *trade-off* between a reachability and attractiveness, while multiple measures in literature account for this trade-off, typically differentiating between greenspace size, scale, or type, and a corresponding distance visitors would be willing to travel [46, 54, 111, 115]: for instance, residential greenspaces serving local populations located within hundreds of meters, opposed to city-level greenspaces serving populations within kilometers. Xing *et al.* [56] quantify a greenspace's accessibility as a function of attractiveness (e.g., size, facilities, natural qualities) and reachability (e.g., travel time from surrounding populations).

Regarding contextual factors, participants express interest in accounting for *temporalities* in several ways. Participants stress the difference between moments in time: "spring and summer and autumn and yeah winter because it's going to differ ... at school time, not school time, weekends, vacation time, holidays" (P1.15). In literature, Ye *et al.* [59] combine measures for access from various starting settings, weighted by the (daylight) hours children spend at these settings, i.e., during weekdays, eight at school, one commuting, and three at home. Other studies measure access during both school and leisure time [47, 111], or quantify duration of greenspace traversal [114]. Participants also emphasize need for repeated measurement as "this relationship will be constantly different (P1.2)". In literature, studies consider using greenspace data from several years, but merge them given strong collinearity [57, 58]. Participants further wish to account for future scenarios "in spatial planning process that are about long-term reservations of space and about the arrangement and actual use not yet in sight" (P2.4); which we do not find implemented in literature. Lastly, several studies touch upon *spatial surroundings* by stating parameters can be adapted to the geographical context [46, 60, 61], while *social norms* and *organization* remain unaccounted for.

2.6. Discussion

In this section, we interpret our main findings, discuss implications for future work, and consider the limitations of our approach.

2.6.1. Interpretation of main findings

As to our conceptual model of factors, we observe that the characteristics of the child can hardly be separated from those of the people in its direct social surroundings, such as parents and peers. In our model, we materialized this entanglement through various nested circles — depicting the child, their household, and the wider network — inspired by the ecological model by Bronfenbrenner [116].

Many other factors in our conceptual model cannot be seen in isolation either. Key relationships concern the relationship between the starting settings, route, and greenspace that constitutes reachability, and the relationship between the greenspace, child, and motivations, constituting attractiveness. Yet these are not the only relationships, as can also be understood from the accompanying descriptions in section 2.4: Traffic relates to restrictions and reduced independence, and concerns may be caused by conflicts, and mitigated by openness for good visibility. We chose to keep our model clean and clear, by materializing only the most key relationships, while we do emphasize that relationships are prevalent. As such, our model can be interpreted with respect to the concept of the *exposome* — i.e., the totality of exposures during lifetime from conception onward, complementing the human genome [117] — and the inherent inter-linkages between the multitude of factors affecting a child's well-being [118].

Additionally, in line with recent conceptualizations of the (children's) exposome [118, 119], the factors we identified are not only physical (e.g., proximity, starting settings, greenspace scale and size), but also social (e.g., interactions, conflicts, social norms), or on the intersection between physical and social (e.g., safety perceptions, playfulness).

As to accessibility measures, we identified only one measure that indirectly accounts for safety perception [61], while safety perception is a key overarching factor in our model. One could hypothesize that, in the case of children, links between safety perception and other factors are so apparent that safety perception as a factor is no longer explicitly articulated, or approximated through other factors, e.g., traffic or independence, instead.

Other notable clusters that remain unaccounted for are motivations, the child's network, an several other factors related to the child and their household. Participants, however, emphasized interest in understanding the child and their motivations, or to assess accessibility in collaboration with them: "we need the children for this" (P1.12). As such, our findings align with literature calling to integrate subjective with objective data for most valuable insights [23]. Other participants, however, highlighted the value in measures that can be applied at large scale: "data we can access in the country level [...] the world level" (P1.2); for instance for epidemiological research on levels to which subjective data collection methods do not scale easily.

A factor often accounted for in literature, but emphasized by only one participant, is the trade-off between attractiveness and reachability. We observed that measures typically operationalize this trade-off by assigning different distance thresholds to different greenspace scales. A possible explanation could be that participants, during the workshops or their work in general, scope to one particular scale, and thus distance threshold, at a time.

Lastly, while our conceptual model focuses on *children's* access to urban greenspace, many factors may also apply to the general population: While some factors may be child-specific (e.g., restrictions, playfulness, and schools), other factors may affect children more strongly than the general population, but are not unique to them (e.g., traffic, openness). Conversely, also within the children's age group, differences between subgroups remain. Our corpus included studies on children with autism spectrum condition [88] and children from immigrant families [99]. One could expect that each subgroup of children may come with its particular barriers and preferences.

2.6.2. Implications and future work

A challenge for future work is how to design measures that put the factors center stage that remain, to date, unaccounted for or only touched upon. Examples include independence, company of peers and friends, intentions and preferences, the local climate of the greenspace, the appeal and ease relieving the burden of traversing the route, barriers along the route other than traffic, and the places that children routinely spend time at and may access greenspace from, other than home and school.

A *low hanging fruit* may be to account for missing spatial factors, such as these other places, the greenspace's local climate (e.g., noise and air quality), or other physical barriers along the route. Measuring social or perceived factors, often less directly linked to the spatial surroundings, has great potential, but comes with practical challenges to be addressed in future work: How to account for such factors in generalizable measures, and how well are they captured in data? Furthermore, one could argue that accounting for such oftentimes sensitive factors, for instance family background, the child's condition, or parental beliefs and values, could raise ethical concerns when implemented at scale and taken out of context.

Our overview of measures may provide researchers and practitioners with guidance in selecting measures for children's access to urban greenspace, for instance when studying spatial equity, urban planning, or environmental health. The possibilities are numerous and depend on the aims and context of the study at hand. We do, however, emphasize that our overview should not be treated as a rating, ranking, or advice on which measures to use. Instead, we argue that for measuring children's access to urban greenspace, or access in general, no *one-size-fits-all* solution exists. All measures remain a simplification of reality, in which choices on what to represent should consciously be made. One could also consider, as several studies already do, to complement various measures with each other.

Lastly, our model aims to support the design and evaluation of urban planning policies and interventions by highlighting how interlinkages between factors may cause changes directed at one factor to spill over to others. Furthermore, policies and interventions, as well as exogenous processes such as climate change, may have long-term or delayed effects. While presenting prototypes of our conceptual model, we observed it helped to illustrate the complexity of children's access to urban greenspace, sparking discussions and exchange of experiences and advice among researchers and practitioners as to how to enhance or measure children's access to urban greenspace.

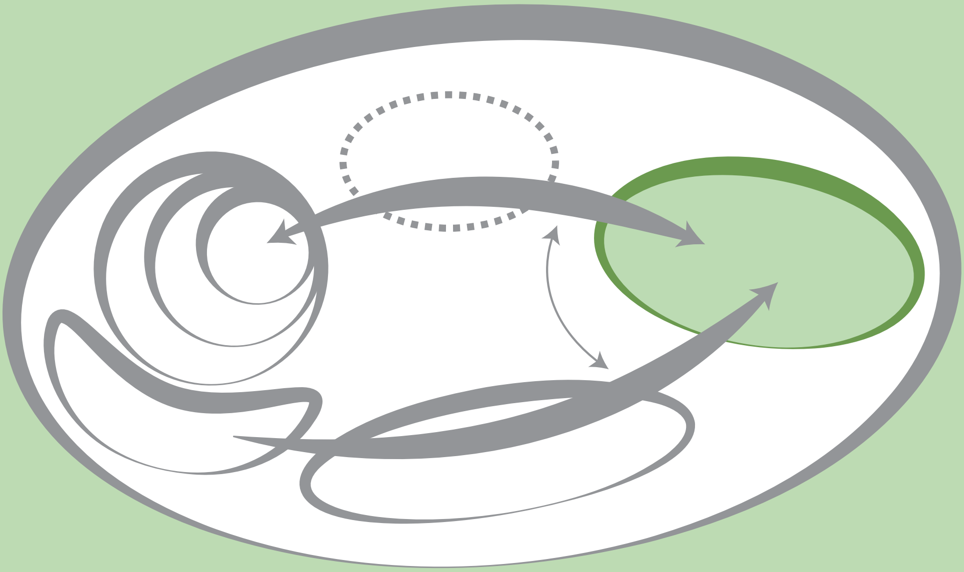
2.6.3. Limitations

Several limitations remain in this study. First, not all relevant literature used in our scoping literature review may have been indexed in Scopus. We complemented the literature sourced from Scopus – a multidisciplinary database that integrates content from various other specialized databases [77] – with literature from the policy-making domain and conducted complementary workshops with researchers and practitioners. This approach is what sets our work apart. Although our results may not be all-encompassing, we did experience reaching a level of saturation while identifying factors, that may indicate our results are rather complete. Furthermore, with developing the first version of our conceptual model of factors, a process of rethinking and revising starts, depending on new insights, comments, and literature [67]. Regarding measures, we acknowledge more measures may exist. Yet, we are confident that the overall patterns we identified hold. Second, the academic literature in our corpus largely stems from contexts in the Global North (77%), opposed to the Global South (23%), and our workshops participants all work within Europe, which may bias our results towards the European geographical and cultural context. Third, we note that academic literature may not explicitly mention all considerations made when describing their measure for children's access to urban greenspace: We may have missed factors implicitly accounted for *behind the scenes*. Fourth, one could argue that some factors extend broader than the indicator measured to account for it, e.g., playfulness may encompass more than just the presence of playgrounds that studies measure. We aimed to provide insight into *how* measures account for such factors, without judging on quality or completeness, but do note this could be interesting future work. Fifth, some generalizable measures in our overview incorporate a manual step in their workflow, e.g., by using data from earlier audits, or from manual interpretations of imagery. As these measures remain largely generalizable, we did choose to incorporate them. One could argue that data without any manual component are scarce, with satellite index or object detection data sets as exceptions, while many widely used data sets such as land use data and local data registries depend on manual work by someone. Moreover, by incorporating these measures, we aim to exemplify the value of such data in future research, and we call upon both researchers and practitioners to open their data for reuse wherever possible.

2.7. Conclusion

In this chapter, we contributed (1) a conceptual model of factors affecting children's access to urban greenspaces and (2) an overview of how generalizable accessibility measures account for these factors. Children's access to greenspace is determined by a tradeoff between greenspace reachability and attractiveness. Reachability concerns the route connecting the child's starting setting with the greenspace, whereas attractiveness is determined by how well the characteristics of the greenspace suit the child, their companions, and their motivations to visit. Perceptions of safety play a role throughout. While researchers and practitioners wish to understand the child and their motivations to visit greenspace, measures implemented in literature typically ignore these factors, or only touch upon them. Measures do account for a variety of greenspace characteristics that make it attractive, including scale and size, playfulness, vegetation, naturalness, or facilities and amenities, and the route's characteristics that make the greenspace reachable, gravitating towards proximity and infrastructure.

Future work could explore how factors ignored or only touched upon to date can be put center stage in novel accessibility measures. Our overview of measures may support researchers and practitioners to make better informed decisions, selecting measures depending on the factors they aim to capture, while our conceptual framework may foster common understanding among disciplines about the multitude of factors affecting children's access to urban greenspace.



3

Data and perceptions of greenspace

In the previous chapter, we identified factors affecting children's access to greenspace. Amongst others, we identified how perceptions of adults (e.g., parents or other caretakers) influence children's access, either when accompanying children on visits to greenspace, or by setting restrictions on where children may go. In this chapter, we dive into perceptions of the *vegetation* that characterize greenspaces, and how we can recognize them in spatial data. People's subjective perceptions are typically collected through questionnaires, and while such perception data are essential when researching human activities, they scale poorly. Large-scale studies into greenspace typically rely on two types of spatial data: vegetation indices derived from satellite imagery, such as the Normalized Difference Vegetation Index (NDVI); and land use or land cover maps, such as OpenStreetMap (OSM). These datasets are both freely available worldwide and thus valuable for assessing cities at scale or prioritizing locations for interventions. We study how effectively NDVI and OSM data capture people's visual perceptions of urban greenspaces. We collect people's visual perceptions of public spaces in Gothenburg (Sweden), Rotterdam (the Netherlands), and Barcelona (Spain) through crowdsourcing, quantitatively compare them to NDVI and OSM data, and qualitatively investigate causes of remaining disparities, including interrelations with other factors. With our findings we aim to help researchers and practitioners in making more informed decisions when collecting greenspace data, as we will do as well when designing and operationalizing our novel greenspace accessibility measures in the upcoming two chapters of this dissertation.

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3.1. Introduction

Depending on the discipline, pathway, and context, greenspaces are typically examined using one of three types of data sources [2, 3, 17, 23]. First, data collected through large-scale questionnaires that reflect individual people's perceptions of greenspace, for example of their residential neighborhood, are typical of environmental psychology research [23, 62]. Second, vegetation indices derived from satellite imagery, such as the Normalized Difference Vegetation Index (NDVI), are commonly employed in epidemiological studies to study the abundance of vegetation around people's homes [19, 20, 48, 120]. Finally, Land Use / Land Cover (LULC) maps that describe the land surface in distinct categories, such as OpenStreetMap (OSM), are frequently used in city planning or policy assessment to quantify the availability, accessibility, or size of formal greenspaces [23, 48, 121, 122, 123].

While environmental perceptions from questionnaires are essential when investigating human activities [124, 125], such data scale poorly due to time, costs, geographical coverage, and spatial extent constraints. NDVI and LULC maps such as OSM, on the other hand, are freely available worldwide and routinely updated over time, making them valuable to assess the availability or accessibility of greenspaces at scale, or to prioritize locations for interventions [2, 3, 17, 48]. Even though LULC maps often only represent formal greenspaces such as parks and urban forests, informal and small-scale greenspaces or green streets have also been found to benefit people [3, 10, 126, 127]. Furthermore, while both NDVI and LULC maps are essential in greenspace studies, they may not mirror subjective human perceptions [3, 17, 23, 128, 129]. Although recent works have attempted to incorporate the human perspective into large-scale greenspace studies using street-level imagery [48, 130, 131, 132], to the best of our knowledge, these have primarily employed computer vision techniques such as automated object detection and scene recognition, which do not acknowledge the subjectivity of human perception.

We aim to contribute to a better understanding of how well large-scale open datasets, specifically NDVI and OSM LULC maps, capture people's visual perceptions of urban greenspace. Our goal is to evaluate how well these datasets match with each other, and where they deviate, and to explain such disparities using the spatial features of investigated locations, to inform the design of future greenspace studies.

To that end, we follow a two-step approach. First, we collect large-scale open-source NDVI and OSM data for three major European cities. We apply a crowdsourcing approach to obtain people's visual greenness perceptions of various sorts of public spaces. Second, we assess how well these visual perceptions correspond to or diverge from the information included in NDVI and OSM data. We hypothesize that: (H1) there is a strong positive correlation between NDVI values and perceived greenness, as these are both commonly used to quantify environmental greenness; (H2) perceived greenness is higher for regular-size OSM greenspaces than for pocket parks, play spaces, open public spaces, and streets, as definitions of greenspace are often limited to greenspaces larger than a certain threshold area, whereas pocket parks, play spaces, open public spaces, and streets can also be perceived as (informal) greenspaces, as other studies suggest; and (H3) perceived greenspaces are better reflected in data when they are selected using a combination of OSM categories and NDVI values, rather than simply OSM categories or just NDVI values. To test our hypotheses, we employ statistical analyses, followed by a qualitative thematic analysis to discover which spatial qualities explain differences between NDVI and OSM data and people's visual perceptions.

In the remainder of this chapter, we explore greenspace data sources used in related work, detail what data sources we collect and how we analyze them, present and discuss our findings and their implications, and conclude with our key conclusions and future lines of research.

3.2. Greenspace data sources

In this work, we adapt the definition of greenspace by the World Health Organization Regional Office for Europe [1] to "urban space characterized by vegetation of any kind", including street trees and roadside vegetation, green roofs and facades, greenspace on private grounds, and parks, playgrounds, or greenways. We narrow our focus to greenspaces that are publicly accessible, thereby allowing people to engage in outdoor activities.

To study greenspaces, researchers use data of varying types and scales, depending on hypotheses and outcomes of interest [3]. Examples include measures of availability, accessibility, visibility, and use of greenspace [3, 17]. Large-scale data are essential for informing policy, measuring how well cities adhere to such rules, and studying the epidemiological consequences of greenspace [3, 48, 121].

Other studies collect data on people's perceptions regarding greenspaces, which are critical when studying people's behavior in greenspaces [3], for instance through questionnaires among residents or interviews with park visitors [22, 28, 121]. In this work, we focus on people's visual subjective perceptions, which we define as perceptions generated by visual stimuli, such as a photo of a place, and further influenced by the individual's experiences, preferences, emotions, and context.

The following subsections go over various data sources and collection methods and discuss their differences and similarities that motivate our study.

3.2.1. Objective measures of greenspace using spatial data

Among all vegetation indices derived from satellite imagery, the Normalized Difference Vegetation Index (NDVI) is the most widely used [3]. NDVI is an objective remote sensing index that captures vegetation by calculating the difference between red and near-infrared light reflected by the land surface. NDVI maps are often obtained from Landsat or Sentinel satellite missions. Both of these missions provide open data at regular intervals worldwide, with the European Sentinel-2 mission providing data at a high resolution of 10 meters [3, 17]. Alternatives to NDVI include the Green Ratio Vegetation Index (GVRI) [133], Soil-Adjusted Vegetation Index (SAVI) [134], and Enhanced Vegetation Index (EVI) [135]. Indices such as NDVI are particularly relevant for studying the presence or availability of greenspace, for instance around people's home locations or along the routes they take as captured in GPS tracks [3, 20, 136, 137].

Land Use / Land Cover (LULC) maps represent the land surface in distinct classes, such as buildings, roads, parks, and forests, allowing to study the size, shape, kind, accessibility, or spatial layout of designated greenspaces [2, 3]. LULC maps are commonly utilized for greenspace accessibility studies; they account for a large share of objective studies on greenspace for human activities [17]. OSM, in particular, is a type of LULC map that is increasingly being used in academic studies as an open-source and global alternative to local commercial or authoritative LULC datasets [138] and is an effective alternative to local data in terms of its accuracy and precision [139]. Alternative LULC maps include, for example, the Urban Atlas in Europe (e.g., used by Turunen *et al.* [64]) and local data registries (e.g., municipal canopy cover and street tree data used by Baró *et al.* [47]).

Geo-located street-level imagery is gaining importance for urban analyses, including studies on urban greenery [17, 131]. Examples include measuring the Green View Index in images [78, 132], detecting vegetation objects through computer vision [140, 141], or merging street-level imagery with LULC data [23]. Lastly, various studies make use of social media data, such as the frequency of *Flickr* photos and *Tweets* posted per location [142], the contents of *Tweets* [143], and the categories of objects detected in *Instagram* photos [140].

3.2.2. Capturing subjective perceptions through interviews, questionnaires, and audits

People's subjective environmental perceptions are typically obtained through interviews or questionnaires [2, 3]. Examples include in-situ interviews with park visitors. For instance, Talal and Santelmann [22] conduct interviews with park visitors to understand their motivations for visiting, experiences, perceptions of accessibility, and suggestions for improvements, and Sundevall and Jansson [28] conduct walking interviews with greenspace users to learn about their desired use, content, atmosphere, inclusivity, and management of a greenspace.

Questionnaires often employ Likert scales to obtain quantified subjective measurements, for instance asking respondents to rate the perceived quality and amount of greenspace in their surroundings [18], the perceived amount of greenness, and how satisfied people are with its quality, amount, maintenance, and safety [62], or the perceived quantity and usage quality of greenspaces near their homes [23].

Alternatively, researchers conduct audits to measure the quantity and quality of greenspace [2]. A subset of greenspace studies employs street-level imagery to elicit perceptions or to conduct audits, such as assessing the existence of features in greenspaces through street-level imagery [130]. Other examples include work by Du *et al.* [144], who provided park visitors with photos of park scenes to help them recall their visiting experience while answering a questionnaire about their health and well-being, or van Vliet *et al.* [145] who conducted a video-based choice experiment on park attributes such as trees, furniture, cleanliness, facilities, and biodiversity.

Although subjective data prove important when studying use of greenspace [124, 125], their collection is typically constrained by time, money, and geographical extent.

3.2.3. Capturing subjective perceptions through crowdsourcing campaigns

To address these temporal, monetary or geographic limitations, researchers collect people's visual environmental perceptions from many people through crowdsourcing campaigns, typically elicited through street-level imagery. Crowdsourcing is a method of recruiting a group of participants to execute a task online, i.e., ex-situ or remotely, whereas street-level imagery allows to remotely mimic at scale what pedestrians may observe [3, 48, 132]. As such, street-level imagery-based crowdsourcing campaigns enable researchers to source perceptions from a vast and diverse number of places and individuals worldwide in a time- and labor-efficient manner [146].

Examples include studies that collect perceptions by asking their participants in questionnaires to choose which location they prefer or to rate places on a Likert scale and then inviting them to explain their responses by selecting options from a list or inputting keywords. Examples include asking people to choose the most safe, upper-class, or unique-looking place out of two places presented in imagery [147]; or the most happy, beautiful, or quiet place [148]; letting participants select the least and most safe or attractive looking place out of four images [65]; and by asking people to virtually navigate city streets while rating how safe and attractive they perceive their path in various places [146].

3.2.4. Differences and similarities between subjective and objective greenspace data

Few studies have investigated the extent to which large-scale spatial data and people's perceptions of greenspaces match. These studies suggest, however, that consistency is limited. Leslie *et al.* [128] discovered a lack of agreement with overall perceived greenness and a significant but modest correlation only for greenness expanse and not for street greenness, green sports facilities, and green amenities when comparing NDVI maps with people's perceptions of their residential surroundings captured in four greenspace components. Zhang, Tan, and Richards [23] found no correlation of people's perceived quantity and usage quality of greenspaces near their homes with canopy cover and at best very weak correlation with park area, vegetation cover, and Green View Index. Kothencz and Blaschke [129] assessed park visitors' ratings of greenness, accessibility, and functions of parks, and found no correlations with NDVI or park area, while they did find a moderate correlation of people's impression of greenness with the percentage of vegetated surface. Hyam [149] discovered a correlation between the author's rating of perceived naturalness, and natural components in street-view imagery detected through computer vision. Helbich *et al.* [120] found no correlation between NDVI and deep-learning-based metrics of street-view greenness.

Our study aims to add to our understanding of the previously reported (lack of) associations between large-scale greenspace data, such as NDVI and LULC maps, and people's visual perceptions of greenspaces. That is, we do not necessarily presume that these data are comparable, but rather seek to provide evidence on their differences and similarities, as well as in which circumstances substantial differences arise. Three factors distinguish our work. First, we include in our study a diverse range of public spaces that differ in terms of type, geographical setting, and vegetation level. Second, we collect multiple people's perceptions on the same locations. Third, we investigate potential causes of dataset differences by qualitatively analyzing the reasons people give for their assessments and the spatial characteristics of each location to further strengthen our quantitative findings.

3.3. Methods

We collected and analyzed greenspace data in three European cities: Barcelona, Rotterdam, and Gothenburg. We used Python to collect NDVI data and LULC data from OSM, and we used a crowdsourcing approach with Google Street View (GSV) imagery to collect people's visual perceptions of greenspaces. We then tested our hypotheses and conducted additional exploratory and sensitivity analyses, and qualitatively investigated what spatial characteristics explain deviations between people's perceptions of greenspace and what is captured in the map data. Figure 3.1 shows a summary of our steps and figure 3.2 depicts the data we collected for each location: median NDVI values, OSM categories, and people's visual perceptions of greenness. Links to repositories containing our code and (pseudonymized) data are provided in section 1.4.

3.3.1. Three case-study cities

We selected three case-study cities in Europe: Gothenburg (Sweden), Rotterdam (the Netherlands), and Barcelona (Spain). OSM data in Europe is found to be relatively complete [150]. The selected cities are all major cities in their respective countries, with Gothenburg and Rotterdam having comparable populations of approx. 583,000 (in 2021) and approx. 592,000 (in 2022), respectively, while Barcelona has a substantially larger population of over 1,640,000 (in 2022) [151, 152, 153]. All three cities have an important harbor. By selecting case-study cities from Northern, Western, and Southern European regions [154], different vegetation zones [155], and diverse coverage of green land [156], we account for varying environmental qualities. Barcelona is situated between a seaside with beaches and a forested mountain range inland, with a variety of parks, including historic parks such as the Montjuïc hill and architect Antoni Gaudí's Park Güell, complemented by trees distributed along its streets. Gothenburg is strategically placed at a river outlet into the sea, and it has several greenspaces within its borders, including parks such as the centrally located Kungsparken, nature reserves such as Änggårdsbergen, and other types of greenspaces. Rotterdam is distinguished by modern morphology and architecture resulting from the city's reconstruction following significant bombing during World War II. It has several well-known parks such as the Kralingse Bos forest and lake, and The Park located on the Meuse riverside. Both Rotterdam and Gothenburg have temperate maritime climates, while Barcelona has a warmer Mediterranean climate.

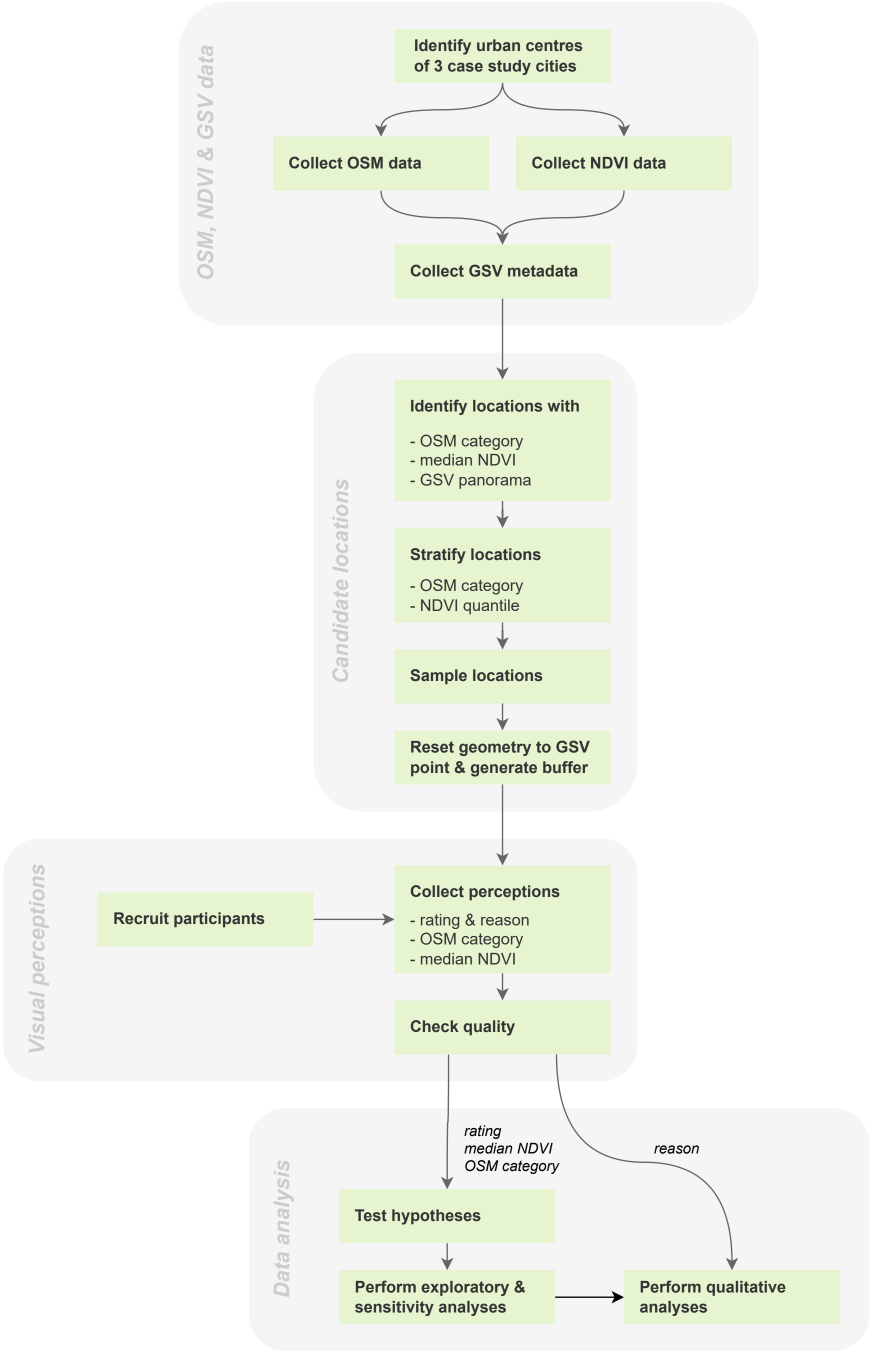

Figure 3.1.: Overview of methodological steps.

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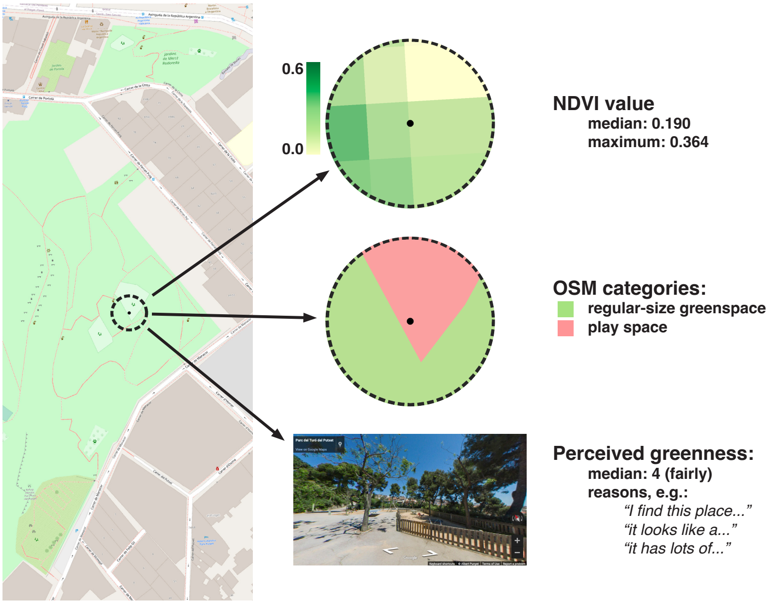


Figure 3.2.: Collected data per sampled location: NDVI values and OSM categories within radius distance, perceived greenness, and reasons. Example in Parc del Turó del Putxet, Barcelona.

3.3.2. Collecting OSM, NDVI, and GSV data

As candidate locations for analysis, we identified urban public spaces with relevant OSM categories, NDVI values, and GSV imagery available. We scoped to public spaces located within walking distance from the urban centers of these case-study cities, based on the European Commission's Human Settlement Layer models and guidelines [157, 158].

OSM data. We collected public space and pedestrian street network data from OSM using the Overpass API and the Osmnx library [159]. We collected a variety of public spaces, represented as polygons: vegetated spaces, typically referred to as greenspace; and other spaces that may — depending on their character — be perceived as such according to the WHO definition [1]. We excluded spaces that are inaccessible via the pedestrian street network or that are smaller than 200 square meters (i.e., the size of a typical tennis court). For vegetated spaces, we merged overlapping or adjacent spaces into one, such as shrubbery adjacent to a forest, and differentiated between different sizes. As a result, we obtained OSM polygons of five OSM categories: regular-size greenspaces (specifically parks, nature reserves, forests, woods, scrubs, shrubbery, heath, meadows, grass(lands) village greenery, and fells, at least 0.5 hectares in size [160]); pocket-size greenspaces (same categories, up to 0.5 hectares in size [17, 122, 161]); public open spaces (specifically squares, pedestrian areas, marketplaces, and common grounds); play spaces (specifically playgrounds and public schoolyards); and streets accessible to pedestrians (i.e., for walking as defined by Boeing [159]).

NDVI data. We used Google's Earth Engine API to collect high-resolution satellite vegetation indices from the Copernicus Sentinel-2 mission [3, 17]. We used all imagery between May and September 2021, i.e., the growing season for vegetation in Europe [20], and calculated the average NDVI value per raster cell. We then calculated the average NDVI value per OSM polygon, while ignoring values less than 0 (i.e., water) [3].

GSV metadata. Using Google's Street View Static API, we looked for the nearest GSV imagery for up to 10 random points within each OSM polygon, with a maximum search radius of 15 meters [162]. When we found an image captured from 2018 to 2022 in May to September (i.e., the vegetation growing season [20, 64]), we stored its metadata. We considered imagery sourced by Google, and 360-degree panoramas uploaded by GSV users, as particularly in green urban areas that are inaccessible by car, user-contributed imagery is a widespread alternative to imagery sourced by Google.

Identifying candidate locations. Our candidate locations are OSM polygons of various categories for which we have both an NDVI value and GSV imagery available. We then took a random sample of 140 candidate locations per case-study city, while ensuring equal spread between both OSM categories (i.e., sampling equal numbers of regular-size greenspaces, pocket-size greenspaces, public open spaces, etc.) and NDVI-value quarters. We manually checked if their associated GSV imagery is suitable for collecting visual perceptions: we excluded images captured indoors or underground, during nighttime or events, of poor image quality, taken from bird's or frog's view perspective, or when sight to the location they were sampled for was obstructed (e.g., by a wall). We replaced these locations with another randomly sampled candidate from the same OSM category, NDVI quartile, and city, until all sampled locations passed the check.

Finally, we reset the geometry of these sampled locations to the point from which the GSV image was taken. We recalculated the median NDVI and determined which OSM place categories were located within 15 meters buffer zone around this point [162]. By doing so, we ensured that people's perceptions, NDVI values, and OSM categories all referred to the same location. We also investigated buffers of 25, 29, 43 and 100 meters to define a location's immediate surroundings to assess the sensitivity of our results to the radius distance chosen. In related studies, 25 meters were found to be relevant for capturing greenery visible from a location [163]; 29 and 43 meters for observing events in urban environments [162]; and 100 meters for representing the individual human scale in greenspace health research [17].

3.3.3. Collecting people's visual perceptions

We then collected people's visual perceptions of the sampled locations through a questionnaire on Prolific: an online crowdsourcing platform designed for academic research [164]. We recruited participants who currently live in Europe and are proficient in the English language. We ensured diversity in age and gender and paid participants minimum wage in the Netherlands, the country of the authors' affiliation. Participants provided informed consent to participate and could only submit a single questionnaire.

Crowdsourcing task. Our questionnaire, implemented using the Qualtrics platform, took about fifteen minutes to complete. On average, we expected each location to be rated by five people. We formulated our questions based on related questionnaires used in environmental health research [18, 62], while keeping them simple and straightforward for crowdsourcing [65, 146, 147, 148]. Figure 3.3 depicts an impression of the interface. First, we introduced the topic and asked participants to provide some demographics. Second, for each participant, we randomly sampled five locations from the same case-study city. For each location, we showed them the panoramic GSV image and instructed them to pan around for at least 10 seconds. We then collect participants' visual perceptions of greenness by asking them to indicate to what extent they find the place vegetated (on a 5-point Likert scale: not at all (1) to very (5)); and what characteristics of the location motivated their choice (in open text). We included quality checks consisting of a reCAPTCHA bot test and an attention check and collected the number of panning clicks participants made. Finally, we asked participants some more demographics and asked how clear they found the crowdsourcing tasks.

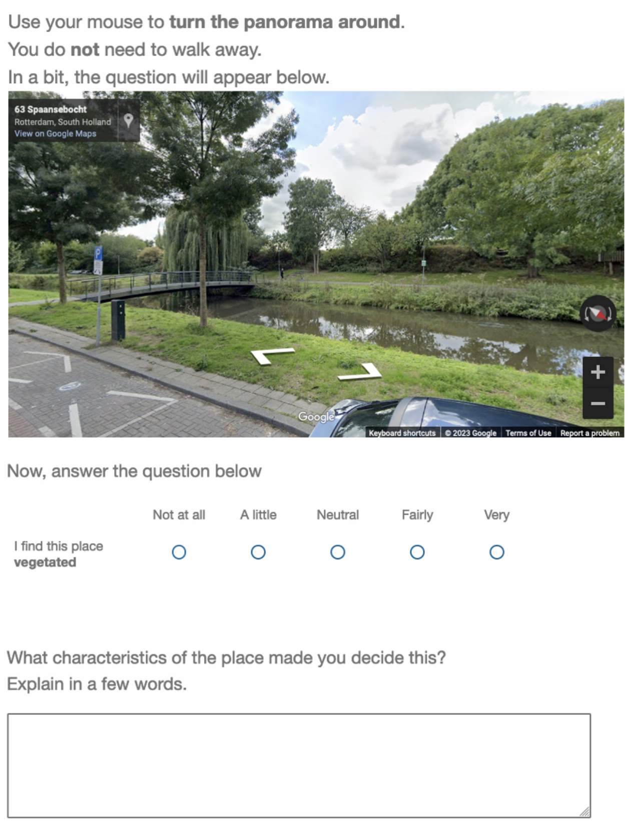


Figure 3.3.: Impression of crowdsourcing interface to collect people's perceptions on greenness of public urban space.

3.3.4. Data analysis

After collecting all necessary data (see figure 3.2), we could assess how well NDVI and OSM capture people's visual perceptions of greenspaces.

Quantitative (statistical) analysis. First, we filtered out participants or visual perceptions that did not meet our quality standards (e.g., through bot detection and an attention check, and checking if participants panned around in the panorama). We then calculated descriptive statistics based on the NDVI value, OSM category, and perceived vegetation level of each location, and aggregated ratings into a median value per location for further analysis. To compare perceived vegetation levels to the binary OSM data categories (i.e., something either is tagged as a greenspace, or not), we also converted perceived vegetation levels into binary values, by defining perceived greenspaces as locations with a median perceived vegetation level of 4 (fairly) to 5 (very) vegetated [18]. We statistically tested our hypotheses and conducted several exploratory analyses. Table 3.1 summarizes our hypotheses (H1-3) and the non-parametric methods we used to test them. First, we tested for correlations between visual perceptions (on a 5-point Likert scale) and NDVI data using Spearman's ρ (H1). Second, we compared the perceived greenness distributions (on a 5-point Likert scale) of various OSM categories using the Mann-Whitney U and Kruskal-Wallis tests (H2.1); and calculated the percentage of OSM regular-size greenspaces that are perceived as greenspaces (in binary values) (H2.2). Third, we implemented three algorithms to select greenspaces from the different data sources and compared them on how well they captured perceptions of greenspace using McNemar's test. We also performed sensitivity analyses to identify how our results change when we increase the buffer zone radius from which we identify the median NDVI value and the presence of OSM greenspaces. Given that we performed 8 different significance tests (i.e., 1 for H1, 5 for H2, and 2 for H3), we applied a Bonferroni correction to our significance threshold of $0.05/8 = .006$. We used the same cutoff for exploratory analyses.

Qualitative analysis. To understand potential causes of differences between visual perceptions and map data, we conducted a reflexive thematic analysis [69]. Based on our quantitative findings, we identified the places for which perceptions notably deviated from NDVI and OSM map data and analyzed the spatial characteristics of these places that participants mentioned as reasons. We used Atlas TI to conduct our thematic analysis, employing inductive coding and iterative identification of themes.

3.4. Results

This section describes the number of perceptions we collected, the number of places we included in our analysis, and the number of people who participated in our study.

Between March and May 2023, 423 Prolific participants, living in 21 different European countries, completed our crowdsourcing task. Of these people, 409 passed our quality checks and were therefore included in our study. A majority found the tasks clear (100%), panned the panoramas around as requested (93%), did not move away to adjacent places (71%) and were not familiar with the places presented (95%). Participant genders vary

Table 3.1.: Overview of hypotheses and statistical methods.

	Hypothesis	Method
H1	There is a strong positive correlation between NDVI and perceived greenness.	Spearman's ρ
H2.1	Perceived greenness is higher for OSM regular-size greenspaces than for pocket parks, play spaces, open public spaces, and streets.	Mann–Whitney U & Kruskal-Wallis
H2.2	Pocket parks, play spaces, open public spaces, and streets can be perceived as greenspaces.	Descriptive statistics (percentages)
H3	Perceived greenspaces are better captured in data when selecting them based on a combination of OSM categories and NDVI values, opposed to only OSM categories, or only NDVI values.	Descriptive statistics (true positives and negatives) & McNemar's test

3

(49% female, 49% male, and 2% non-binary, third gender, or prefer to self-describe or not to say), as well as ages (12% age 18-24, 19% 25-34, 20% 35-44, 20% 45-54, 18% 55-64, and 10% 65 years or older). Most participants are city dwellers (61%). When testing differences in perceptions among pairs of demographic groups using the Mann-Whitney U test, we did not find any statistically significant differences.

From these 409 participants, we obtained a total of 1956 perceptions on greenness, after filtering out data in case of technical issues (e.g., the panorama did not load in time) or in case the participant did not interact at all with the panorama (i.e., made no clicks to pan the panorama around or zoom in).

Out of 420 places, 413 received valid perceptions from our participants. On average, each place was rated on greenness by 5 people. Table 3.2 shows descriptive statistics on the places, their NDVI values and OSM categories, and associated perceptions per city. People perceived 180 of the places (44%) as green.

Table 3.2.: Descriptive statistics of places and associated perceptions per case-study city.

case	**places**	**NDVI [0-1]**			**OSM category [%]**					**percep.**
city	**n**	**med.**	**min**	**max**	**reg.s. greens.**	**poc.s. greens.**	**open space**	**play space**	**street**	**n**
Barcelona	139	0.139	0.017	0.379	30.9%	20.1%	31.7%	20.1%	28.1%	647
Rotterdam	137	0.188	0.023	0.539	26.3%	21.9%	21.9%	19.7%	27.0%	645
Gothenburg	137	0.140	0.019	0.492	24.1%	20.4%	20.4%	16.8%	22.6%	664
total	**413**	**0.151**	**0.017**	**0.539**	**27.1%**	**20.8%**	**24.7%**	**18.9%**	**25.9%**	**1956**

3.4.1. Quantitative analyses

H1: Perceived greenness in relation to NDVI values

Hypothesis and outcome. We hypothesized to find a strong positive correlation between NDVI and perceived greenness. Using Spearman's ρ, we tested the correlation between how green places are perceived to be, and their NDVI values, and found a statistically significant correlation of moderate strength (ρ: .459, p-value < .006), thus *not* supporting our hypothesis.

Exploratory analyses. No apparent NDVI value threshold that differentiates greenspaces from other spaces could be identified. When comparing correlations between cities, we found that correlation is much weaker in Barcelona (ρ:.269, p-value < .006) than in Rotterdam (ρ: .540, p-value < .006) and Gothenburg (ρ: .570, p-value < .006) Furthermore, we did not find stronger correlations when using the maximum NDVI value in a place's proximity, as opposed to the median (i.e., ρ: 0.47, p-value < .006).

Sensitivity analyses. To analyze how sensitive our correlation results are to the radius distance used to calculate a place's NDVI value, we found that by increasing the radius distance to 25, 29, and 43 meters, correlation strengths increase from .459 to .556, .585 and .600 (all p-value < .006), while decreasing again for larger distances. Furthermore, from 25 up to 100 meters, the differences in correlations among case-study cities largely disappeared.

H2: Perceived greenness in relation to OSM categories

Hypothesis and outcome H2.1. We hypothesized (H2.1) that perceived greenness is higher for OSM regular-size greenspaces than for pocket-size greenspaces, play spaces, open public spaces, and streets. Using the Kruskal-Wallis test, we found significant difference in perceived greenness occurs between OSM categories (H: 107, p-value < .006). Using a one-tailed Mann-Whitney U test, with the alternative hypothesis that regular-size greenspaces are perceived more green than others, we found that regular-size greenspaces (median perceived greenness: 4.0, n: 112) are indeed perceived greener than: pocket-size greenspaces (median: 4.0, U: 5878, n:86, p-value<.006); open public spaces (median: 2.0, U: 9723, n: 102, p-value<.006); and streets (median:3.0, U: 8741, n: 107, p-value < .006); while no significant difference was found with play spaces (median: 4.0, n: 78); showing that OSM regular-size greenspaces are only perceived greener than pocket-size greenspaces, open public spaces, and streets.

Hypothesis and outcome H2.2. We further hypothesized (H2.2) that also pocket-size greenspaces, play spaces, open public spaces, and streets can be perceived as greenspaces, as some literature suggests. We considered a place to be perceived as greenspace when it was rated on median 4 (fairly) or 5 (very) vegetated. We found that 70% of all OSM regular-size greenspaces are perceived as greenspaces. Furthermore, 47% of pocket-size greenspaces, 11% of open public spaces, 36% of play spaces, and 23% of streets (all excluding those that also lie within direct proximity of a regular-size greenspace) are perceived as greenspaces. Thus, we can confirm that not only regular-size greenspaces, but also pocket-size greenspaces are perceived as green more often than 40% of times (i.e., if greenness ratings were distributed equally over our 5-point scale, 2/5 or 40% would be considered green).

Sensitivity analyses. When we gradually increased the radius distance which we use to define if a place lies in proximity to an OSM greenspace, we observed that results for H2.1 remain rather stable up to 43 meters. Yet for H2.2, we observed that percentages decline: with a radius of 15 meters, 70% of places located near OSM greenspace are indeed perceived by people as green; while with 25, 29, and 43 meters, the percentages declined to 67%, 66%, and 63%, respectively.

H3: Perceived greenness in relation to both NDVI values and OSM categories

Hypothesis and outcome. We hypothesized that if perceived greenspaces are selected using a combination of OSM categories and NDVI values, they are better recorded in data than when only OSM categories or only NDVI values are used. To test our hypothesis, we implemented three greenspace selection algorithms based on our findings in H1 and H2: 1) OSM-based, selecting all locations near OSM regular-size greenspaces; 2) NDVI-based, selecting places with an NDVI value larger than the median NDVI value of all sampled locations in the same city; and 3) combination-based, selecting locations near OSM regular-size greenspaces, and pocket-size greenspaces and play spaces with an NDVI larger than the median. We compared their results to the crowdsourced perceptions of greenspace. In 67.8% of cases, the OSM-based algorithm correctly captured perceptions of greenspace, compared to 65.6% for the NDVI-based algorithm, and 71.8% for the combination-based algorithm. McNemar's one-tailed test revealed that the combination-based algorithm performed significantly better than the NDVI-based algorithm (n: 401, p-value < .006), while no significant difference was found with the OSM-based algorithm.

Sensitivity analyses. When we repeated our analysis with NDVI values and OSM categories within larger radius distances, we discovered that the percentages of the OSM-based and combination-based algorithms gradually decreased with distance, while they increased for the NDVI-based algorithm, which is consistent with the findings in H1 and H2 (see table 3.3). Regardless of radius distance, the combination-based algorithm outperformed the OSM-based algorithm, while at a 43-meter radius distance, the NDVI-based algorithm achieved the highest score of 72.3%. Using McNemar's test, we observed the NDVI-based algorithm outperforms the OSM-based algorithm significantly (n: 412, p-value < .006), while the difference with the combination-based algorithm was not statistically significant.

3.4.2. Qualitative analyses

The following paragraphs present qualitative findings following up on testing hypotheses H1 and H2. Exemplary quotes denoted as Q-i are included in the appendix B, as is exemplary street-level imagery.

Table 3.3.: Quantitative results per radius distance. Per row, highest scores are highlighted in green.

		radius distance [m]			
		15	**25**	**29**	**43**
H1	correlation perception & NDVI	.459	.556	.585	.600
H2.2	percentage OSM greenspaces perceived as such	69.6%	66.9%	66.4%	62.9%
H3	correctness OSM-based algorithm	67.8%	67.0%	66.8%	65.3%
	correctness NDVI-based algorithm	65.6%	69.7%	70.8%	72.3%
	correctness combination-based algorithm	71.8%	70.2%	70.0%	68.2%

Deviations between perceived greenness and NDVI values (following H1)

To understand deviations between perceived greenness and NDVI values, we explored why people regard places green, while NDVI values are low, and vice versa. We selected places for analysis based on our quantitative results, using a 43-meter radius distance, i.e., where correlations were strongest.

Regarding places that do have a high surrounding NDVI value but are not deemed green (n=6, see table B.1 and figure B.1 in appendix B), we identified that these are typically characterized by the place being in between two distinctive sides, resulting in mixed opinions among participants (Q-1). Specifically, these places are characterized by greenness on one side, with grass, trees, and occasionally other vegetation or natural features. However, the other side is generally dominated by built-up elements (e.g., buildings, concrete, and infrastructure) or, when there is some vegetation present (e.g., trees, grass, greenery, or private gardens, sometimes located further away or combined with other natural features), it remains too little or too barren (Q-2, Q-3). Less often, we observed that greenery may be present, but is physically inaccessible, for instance due to height difference (Q-4).

Regarding places that are perceived by people as green but have a low NDVI value (n=10, see table B.2 and figure B.2 in appendix B), first, we identified that vegetation is often present and varying in type, but only on a low level (e.g., only grass, other ground-covering greenery, or low-level bushes), still young (e.g., tiny trees), or scattered around in small bits (e.g., stand-alone trees, some vegetation in every garden) (Q-5). We also observed that vegetation may be lush, but only on a limited area, in private gardens, or located further-on (Q-5). Second, participants also mentioned other natural features: riverfronts, sand or small tiles on the ground, wooden fences, or a seemingly good local climate (e.g., shaded, clean air) (Q-6, Q-7). Third, we observed spaces are characterized by a lack of features, for example: distant from traffic, secluded, or quiet (Q-8). We do note, however, that some participants still characterized places dominated by built-up elements as “green for an urban environment” (Q-10), in which cases the judgment seemed contextual rather than absolute (Q-9). Lastly, mentions of attractiveness were more prevalent among places perceived as green, than vice versa (Q-11).

Deviations between perceived greenness and OSM categories (following H2)

Subsequently, we explored why people regard places green, while OSM does not tag them as such, and vice versa. Again, we selected our cases based on quantitative results, now using the 15-meter radius distance at which OSM performed best.

As to places tagged by OSM as greenspaces, but not perceived as such by people (n=12, see table B.3 and figure B.3 in appendix B), we identified two main reasons. First, despite being tagged in OSM as green and seemingly equipped for use by people, e.g., with benches or an elevated pedestrian walkway, some places were not perceived by people as green (Q-12). People state vegetation is too low, young (e.g., tiny trees), scattered, dry, constrained, located too far away, or only on one side, or the space is too open and empty (Q-13, Q-14, Q-15, Q-16). In these cases, the vegetation was overruled by built-up structures: major roads or tramways, high building blocks, concrete and other paved areas, and associated sense of a bad local climate (Q-17, Q-18, Q-19). Second, again, we observed that some places are characterized by two distinct sides: major apartment buildings on one side, versus a natural rock landscape with vegetation on the other; concrete and constructions works, versus a carefully designed green-looking space; and a major road, versus an extensive vegetated area. These differences sometimes caused disagreement among people, depending on what attracted their attention the most (Q-20 versus Q-21).

Places that are not tagged as greenspaces of regular size in OSM, but still are perceived as green by people, outnumbered all other qualitative cases: 102 places. We identified two main themes (see table B.4 and figure B.4 in appendix B). First, presence and number of trees, other greenery such as bushes, shrubs, and smaller plants, and to a lesser extent grass played a major role, while people also mentioned variation in vegetation, flowers, and fields (Q-22, Q-23, Q-24). We also observed vegetation configuration was explicitly or implicitly referred to (Q-25): vegetation on different heights (e.g., grass fields, tree canopies, and vegetated walls) (Q26); and places that are spacious or have vegetation all around and far extending (Q-27). Second, we see again that people judged urban greenspace contextually rather than absolutely: they are green “for an urban setting” (Q-28). These included residential neighborhoods with lots of private greenspace and natural buildings materials (Q-29); and regular or dense road-side vegetation (Q-30). Also, other qualities were associated with greenness: water, shade and fresh air, and quietness, attractiveness, and safety (Q31, Q-32, Q-33). Yet we do note that the conflict between built-up and greenspace remained, with people motivating their greenness by the lack or presence of built-up elements, such as buildings, traffic, concrete, and parking lots (Q-34, Q-35, Q-36, Q-37).

Table 3.4 summarizes the outcomes of our hypothesis tests and exploratory, sensitivity, and thematic analyses.

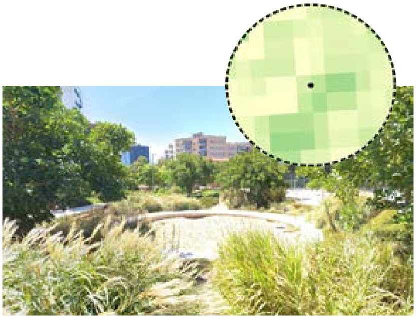
Table 3.4.: Summary of quantitative and qualitative findings.

H1	**Perceived greenness in relation to NDVI**	
	hypothesis test	No evidence for a strong correlation with median NDVI.
	exploratory analysis	Significant moderate correlation instead; weak correlation for Barcelona, while moderate for Rotterdam and Gothenburg; and moderate but less strong correlation with maximum NDVI.
	sensitivity analysis	NDVI within 43m radius distance yields strongest correlation.
	qualitative analysis	Places perceived not-green, but with high NDVI: have two distinctive sides; or the greenspace is physically inaccessible. Places perceived green, but with low NDVI: have varying vegetation; other natural features nearby; absent built-up features; are rated in context.
H2	**Perceived greenness in relation to OSM**	
	hypothesis tests	Regular-size greenspaces are perceived as greener than pocket-size greenspace, open public spaces, and streets, but not greener than play spaces. Pocket-size greenspaces are oftentimes perceived as greenspaces.
	sensitivity analysis	OSM within 15m radius distance yields best outcomes.
	qualitative analysis	Places perceived not-green, but in OSM: are still equipped for people; have dominant built-up features; or two distinctive sides. Places perceived green, but not in OSM: have large amount and good configuration of vegetation; are rated in context; have other natural and soft features.
H3	**Perceived greenness in relation to NDVI and OSM**	
	hypothesis test	Algorithm combining OSM and NDVI data yields better results than NDVI-based algorithm, but no significant difference with OSM-based algorithm.
	sensitivity analysis	Combination- and OSM-based algorithm perform best with 15m radius distance, while NDVI-based algorithm with 43m radius distance scores highest overall.

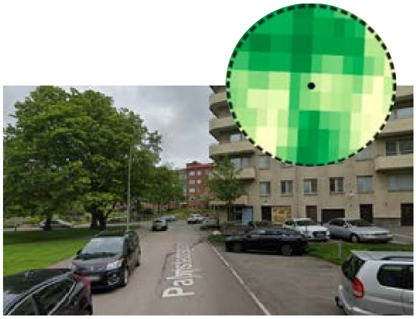
3.5. Discussion

3.5.1. Interpretation of results

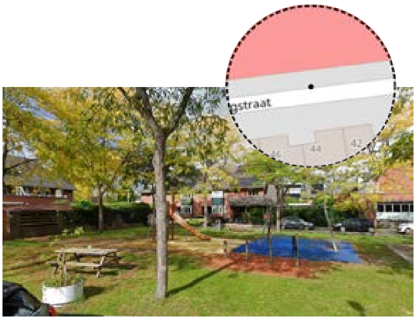
Our findings suggest that NDVI and OSM data capture how green people find places to be rather well, yet significant discrepancies remain. Figure 3.4 shows exemplary locations where perceptions of greenspace deviate from NDVI and OSM map data.



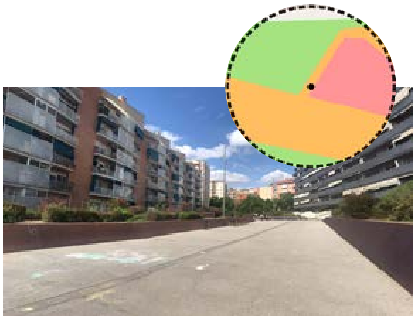
A. Perceived on median very green (5/5) by 6 participants who rated it, but with a low median NDVI of 0.076 (Barcelona).



B. Unanimously perceived a little green (2/5) by 3 participants who rated it, but with a high median NDVI of 0.296 (Gothenburg).



C. Perceived green by 6 out of 7 partici pants who rated it, but surround ings not tagged in OSM as green-space, tagged as play space (colored pink) instead (Rotterdam).



D. Not perceived green by any of the 5 participants who rated it, but surroundings tagged in OSM as regular size greenspace (colored green, specifically, a park), as well as open public space (orange) and play space (pink) (Barcelona).

Figure 3.4.: Exemplary locations where perceptions deviate from NDVI or OSM data.

We found no evidence for a strong correlation between how green places are perceived and the NDVI values in their immediate vicinity. However, we did discover a significant moderate correlation. Our findings of a significant correlation contrast with those of Kothencz and Blaschke [129] and Leslie *et al.* [128], who found no significant correlation of NDVI values with park visitor's perceptions of greenspace, or with people's perceptions of their home environment. What distinguished our method from Leslie *et al.* [128]

is that we collected data for one single point in place, rather than an entire residential neighborhood, and unlike Kothencz and Blaschke [129], we collected data for a broader range of public spaces, potentially with a wider range of NDVI values.

When we investigated the influence of radius distances, we discovered that the strongest correlation was .600 when using median NDVI values within a 43-meter radius distance. We saw the greatest change in correlation strength with increasing radius distance in Barcelona, rising from .269 to .577, implying that perceptions of places in Barcelona are based on greenery located further away: One could hypothesize that Barcelona's public spaces are more spacious or have more mature trees that can be seen from a distance, as opposed to grasslands or small vegetation that is more evenly distributed in space.

We found evidence to support our hypothesis that OSM regular-size greenspaces are perceived significantly greener than pocket-size greenspaces, streets, and public open spaces, while OSM seems to use open space tags almost exclusively for places where vegetation is not dominant. We also discovered that nearly half of OSM pocket-size greenspaces are perceived as green, adding to the body of evidence that pocket-size greenspaces are important for green cities as well [17, 122, 161]. Surprisingly, no significant difference in greenness perception was found between OSM regular-size greenspaces and play spaces. We discovered that many play spaces are unanimously perceived by people as green, even though OSM does not provide any indication of the presence of greenery. Furthermore, examples of greenery that are unexpectedly missing from OSM include forests and groves located on the outskirts of cities that are not represented in OSM. Other deviations were not due to a lack of greenery in OSM data, but rather to how we filtered our greenspaces. That is, we selected greenspaces of significant size based on a minimum size of 0.5 hectares of adjacent green land [160]. Some greenspaces, however, are mapped in such granularity in OSM — for example, every individual patch of grass separated from others by narrow footpaths — that our algorithm filtered them out.

We also observed that some places in OSM are labeled as green but are not perceived as such. When we look at these places in OSM, we see that half of them are tagged as parks. The term park is explicitly included in the WHO definition of greenspace that we used [1], and many other definitions of greenspace in the literature [73], and participants often seemed to regard parks equivalent to greenspaces. According to OSM, a park is "an area of open space for recreational use, usually designed and in semi-natural state with grassy areas, trees and bushes" [165]. As this definition and our findings suggest, OSM parks are typically *but not always* vegetated.

We demonstrated that combining OSM categories and NDVI values can help to better select perceived greenspaces from these data in many cases, providing an answer to the question raised by Liao, Zhou, and Jing [139] whether combining multiple datasets improves performance. Surprisingly, we observed that the NDVI-based selection algorithm outperformed all others at a 43-meter distance. Qualitative results suggested refining these algorithms with information on other spatial characteristics from OSM has great potential, such as proximity to water or presence of greenery in all directions; proximity to traffic infrastructure or high-rise buildings; and presence of private gardens. Other qualities, such as vegetation variety, quietness, attractiveness, and safety, may be more difficult to capture in large-scale data, but are studied in related work [65, 146, 147, 148].

Our qualitative findings indicated that people seem to judge the greenness of a place contextually rather than absolutely. Specifically, people stated, for example, that "for an urban setting, more trees than I would have expected" (Q-28), suggesting that people have different expectations of greenspaces within cities opposed to outside of them. Furthermore, they stated "considering it's in the middle of a man made square it seems quite green" (Q-9), indicating that within the constraints of the type or function of a given urban space (e.g., a crossroads or a major road), people sometimes simply considered a place as green as can be.

3.5.2. Implications for research and practice

According to our findings, NDVI maps are only moderately associated with how green people perceive places to be. For optimum results, perception data should only be exchanged for NDVI maps while keeping this limitation in mind, ideally utilizing median NDVI values within 43 meters. When using OSM data, similar limitations arise, but we suggest using a short radius distance of 15 meters instead.

Our results further suggest that incorporating NDVI data into OSM-based analyses produces more accurate results. In the case informal and small-scale greenspaces are of interest, NDVI values may help to filter out those parks that are not perceived green, or to identify pocket parks and play spaces that are often perceived as green.

Our qualitative findings suggest that when identifying locations for greenspace interventions, urban planners could consider prioritizing greenspaces that appear in large-scale data but are not perceived as such, e.g., where built-up features are too dominant.

Our findings could also serve as guidance when aiming to make cities "just green enough": greenspace strategies that limit adverse effects of interventions to make neighborhoods healthier and more attractive, such as increased property values, so-called green gentrification, and displacement of the residents in whose interests these interventions were originally designed [127, 166]. Potential solutions are green interventions that are small-scale, in scattered locations, and evenly distributed rather than concentrated projects in one focal place that may kick-start gentrification [127]. Our qualitative findings regarding what it is that makes a location be perceived as green, while not formally tagged or depicted as such in data registries, may inspire such interventions. Examples include selecting varying vegetation extending in multiple directions; combining vegetation with other natural features such as water fronts or pervious surfaces; greening roadsides or traffic squares that may be perceived as green within their specific urban context; and limiting concrete or hiding built-up structures from view by tree canopies and hedges.

3.5.3. Limitations and future work

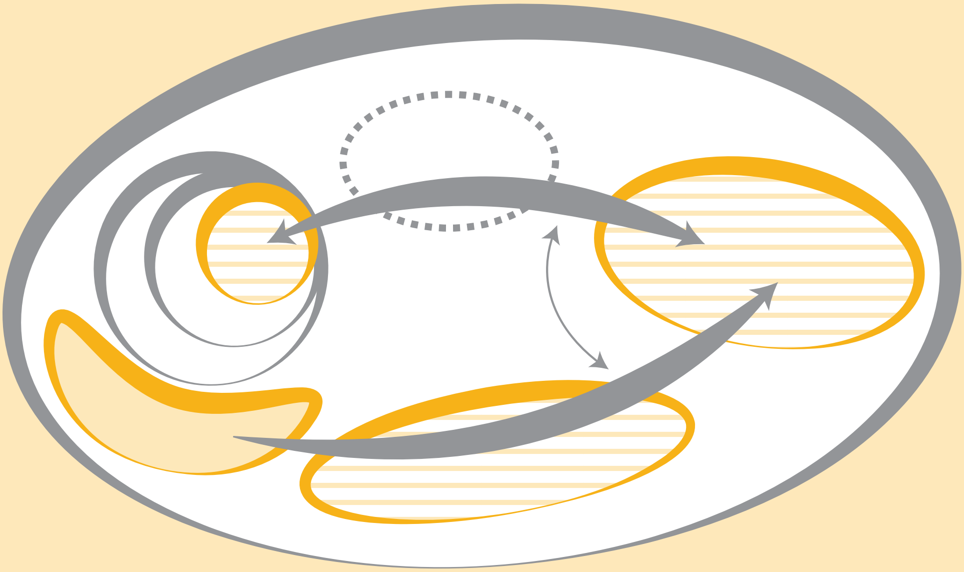
Several remaining limitations in this study could be addressed in future research. First, we collected only visual perceptions using street-level imagery, which should be interpreted as a proxy for perceptions in real urban environments [147]. Nonetheless, street-level imagery is becoming more important in urban analyses and is a promising source for efficient urban environment auditing [130, 131]. Second, the participants of our study cannot be considered a representative sample of the general population or of the case-study cities. We did, however, recruit European participants, balanced in age and gender, and found no significant differences in greenness perceptions among different groups. Third, regarding our questionnaire implementation, due to random chance, not all locations were rated as often as others. Furthermore, participants' perceptions may be influenced by the locations they have previously seen, or the places they are familiar with [167], although we expect the effect of familiarity bias to be small given that less than 5% of participants reported knowing some places from personal experience. Fourth, we limited our study to three European cities, but our method can be applied to any city in the world. We did notice some differences between Barcelona, and Rotterdam and Gothenburg. Future work could research how our findings hold across continents, climates, and cultures [3, 150, 168], for LULC maps other than OSM, and for case-study cities dominated by hills and viewpoints. Fifth, NDVI values are subject to change over time [120], and the lushness of vegetation in street-level imagery is only a snapshot in time. While we used NDVI data and street-level imagery from similar years and months, we cannot rule out the effects of temporal changes. Sixth, we only analyzed places that were at least 200 square meters in size, which means that places smaller than approximately the size of a tennis court were not studied. Finally, future work could assess how people's visual perceptions are captured in other quantitative data, such as the Green View Index or computer-detected objects in street-level imagery; or to develop refined algorithms to select potential perceived greenspaces by combining NDVI and LULC maps, potentially using viewsheds and incorporating other spatial characteristics.

3.6. Conclusion

In this chapter we looked at how well NDVI and LULC data captured people's visual perceptions of urban greenspaces. While NDVI and LULC data are widely used in greenspace studies and planning, insight into their representation of visual perceptions has remained lacking to date.

We crowdsourced perceptions of public spaces in three European cities and quantitatively compared them to NDVI and to LULC data sourced from OSM, and qualitatively explored reasons for deviations. Although we discovered an overall match between NDVI and OSM data and people's perceptions of greenness, notable deviations remain. NDVI values moderately correlate with perceived greenness, and OSM greenspaces are perceived to be greener than other types of public spaces except for play spaces, while pocket-size greenspaces are frequently perceived to be green as well. Selecting perceived greenspaces based on both OSM and NDVI yields better results in many cases. Furthermore, built-up elements may overpower the presence of vegetation, while a space may still be considered green given its urban context. Not only the amount of vegetation but also its configuration and variety influence people's perceptions of greenness, as do other natural features and perceptual qualities.

Our findings can help researchers and practitioners to make more informed decisions when collecting data for greenspace studies and planning. Future work could improve greenspace data collection by including more qualities that influence greenspace perception or test the transferability of our findings to other geographical contexts around the world.



4

Access by children en route

In this chapter, we study how to measure access from various starting settings, as identified in chapter 2, building upon one of widely used greenspace datasets that were subject of study in chapter 3, namely OpenStreetMap. Existing approaches for measuring greenspace accessibility focus predominantly on areas surrounding home locations, or to a lesser extent from origins such as the school, disregarding access while *en route* between places, for instance while commuting between the home and school. In chapter 2, we identified only one accessibility method that measures access en route, yet in a way that does not scale to entire cities. In this chapter we introduce a novel method for measuring greenspace accessibility that considers access by children that are on the move between home and school, revealing patterns for multiple entire cities. We compare its outcomes to the outcomes of measuring access from home or from school, and further explore variation in outcomes when applying these methods to the children's age group, opposed to for example adolescents, or the population in general. We use Amsterdam, Rotterdam, and The Hague in the Netherlands as case study cities to illustrate the utility of our novel accessibility measure. Our method can be replicated in other cities worldwide, with the aspiration to provide researchers and practitioners with a novel method to help in evaluating children's access to greenspace from specific settings, complementing the existing body of accessibility measures.

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4.1. Introduction

A growing body of literature demonstrates the importance of greenspace use in maximizing exposure over other determinants such as the percentage of greenness in an area [11, 12, 13, 15, 16, 17]. Greenspace use primarily manifests itself in two ways. First, by making *routine purposeful visits* to greenspaces for leisure or physical exercise [10, 13, 16]. Second, in the form of *regular traverse movement* through greenspaces, involving serendipitous walking when commuting to school, work or other activities [18, 19, 20].

Evidence suggests that greenspace use is primarily encouraged by accessibility [23]. Specifically, easy access emerges as the main motivating factor in studies investigating what encourages people to visit a greenspace such as a park [22].

Even though a large number of methods for measuring accessibility have been developed over the past decades, it remains a challenging undertaking. In the context of greenspace access, in particular, the complexity is further induced by the trade-offs between aspects of proximity, configuration, size, spatial distribution across neighborhoods, level of greenness, and quality of provided facilities, among others [15]. Moreover, greenspace access may vary by age [14] or socioeconomic status [169]. Existing approaches to measuring greenspace accessibility present several limitations. First, the majority of accessibility metrics focus solely on the areas surrounding home locations, using administrative areas or arbitrary buffers of different sizes around residencies, thereby ignoring other routine activity settings such as schools and commuting routes [2, 36, 170, 171]. Second, the dependency of human access on the road network is often disregarded, as is the chosen transport modality, relying primarily on Euclidean distance-based proximity measures [2, 172]. Third, the entrances connecting the greenspace to the road network are frequently overlooked, measuring access on the basis of centroids or park edges instead [43, 172].

In this chapter, we propose a new method to measure greenspace accessibility that simultaneously accounts for (1) road network proximity to various routine activity places such as home and school, (2) both purposeful visits and traverse movements (e.g., while commuting), and (3) different population age groups (i.e., children between the ages of 0 and 14, and adolescents between the ages of 15 and 24). To the best of our knowledge, such a multidimensional measure for capturing the various aspects pertaining to greenspace access is currently lacking.

To demonstrate the utility of our greenspace accessibility measurement method, we apply it in the three largest Dutch cities — namely, Amsterdam, Rotterdam, and The Hague. We collect data about the road network, the distribution and configuration of greenspaces, population demographics and home locations, and the distribution of educational facilities. We, further, calculate greenspace accessibility for three settings: (1) relative to the home location, (2) from various educational facilities (e.g., kindergarten, primary school, secondary school, higher education institution), and (3) on the move from home (i.e., origin) to educational facility (i.e., destination). We generate these measures for three walking trip durations, namely 5, 10, and 15 minutes. Finally, we conduct a correlation analysis to identify differences between our proposed measures and a conventional baseline measure (i.e., buffer zones around homes of people of any age), and perform a qualitative evaluation to explore what characterises the greenspaces where differences occur.

What sets our approach apart is the simultaneous consideration of different human activity settings (i.e., home, school, and commuting routes), while accounting for the characteristics of two – often underrepresented – population age groups; that is, children and adolescents. In this way, we aspire to provide planners, public health experts, and policy-makers with a methodological tool that can help in evaluating access and use of greenspaces when designing health-promoting interventions. Unlike unitary greenspace accessibility measures, our method does not only account for different settings of daily human activity, but also stresses the importance of embracing and addressing the differences between population age groups.

The remainder of this chapter is structured as follows. First, we review the related research on approaches to measuring greenspace accessibility. Second, we detail the data sources, explain how we extract and calculate indicators pertaining to greenspace access, and describe how we integrate the indicators in different accessibility measures (i.e., home-based, school-based, and on-the-move). Next, we present the analysis results on the assessment of greenspace accessibility in the three case-study cities. We then discuss the outcomes of our analyses, showcase the utility of our method for assessing greenspace accessibility, and outline the limitations of our approach. Finally, we summarize the conclusions and suggest future lines of research.

4.2. Related work

4.2.1. Greenspace exposure and health benefits

Recent evidence shows accessibility is a main condition for greenspace use [22, 23]. Access to green open space can promote daily routine activities, such as physical exercise, and further allows for informal social interactions, thereby increasing mental well-being [10]. Children visiting greenspaces are largely engaged in physical recreation and interacting with other children [22], which may in turn affect their health, and visits to greenspaces are positively correlated with mental health and physical activity [13, 16]. College students' mental health is positively associated with perceived greenness at university, independent from perceived greenness at home [173]. Commutes through green environments benefit the cognitive development of children [19] and the mental health of adults, especially when active [18], and being on the move through green environments is negatively correlated with depression [20].

4.2.2. Greenspace accessibility measures

Greenspace accessibility has been studied in various ways. It primarily depends on the number, spatial configuration, and spatial distribution of greenspaces [15]. However, the choice for the most suitable measure for greenspace accessibility depends on the context [43]. In line with the works of Zhang, Lu, and Holt [15] and Wang, Wang, and Liu [43], we first distinguish four types of greenspace accessibility measures: *travel cost*, *statistical index*, *buffer zone*, and *spatial interaction*. In the next subsection, we discuss *betweenness*; an accessibility metric that remains untapped in greenspace accessibility studies to date.

Travel cost measures quantify accessibility by measuring Euclidean distance, network distance, or time to the nearest greenspace (see e.g., Higgs, Fry, and Langford [45] and Shackleton and Blair [174]). It assumes people will choose a greenspace to visit by proximity, for example the closest greenspace to their home. Travel cost measures are widely used in greenspace accessibility studies within a public health context [2, 17]. Even though travel cost metrics are intuitive and convenient to implement, they oversimplify reality by, for instance, assuming that people exclusively visit the greenspace that is closest to them [15].

Statistical index measures use predefined areas as units of analysis, such as administrative neighborhoods or census tracts (see e.g., Taubenböck *et al.* [123] and Spotswood *et al.* [137]). They quantify the number, total area, or density of greenspaces within the area at hand [43]. A main shortcoming is that predefined areas are prone to the Modifiable Areal Unit Problem [175]. That is, outcomes are dependent on the size and boundaries of the arbitrary and modifiable areal unit of analysis. Additionally, administrative boundaries may fail to capture the spatial context of people's activities [170].

4

Buffer zone measures quantify accessibility based on a zone around the location of interest. They involve the calculation of often a Euclidean or network distance area around a greenspace centroid, edge, or entrance (see e.g., Zhang, Tan, and Richards [23], Kabisch and Haase [121], and Wood *et al.* [122]). Network buffer zones are also referred to in literature as *walksheds* (see e.g., Adhikari *et al.* [176] and Goldenberg, Kalantari, and Destouni [177]). That is, the areas that can be reached within e.g., a 15-minute walk, or an equivalent 800m network distance. The buffer zone measure is another proximity-based measure that is widely used in public health oriented greenspace accessibility studies [17]. A main advantage of buffer zones is that they are as intuitive as travel costs measures, but use a limited spatial radius instead, thereby avoiding oversimplification or ecological fallacies [15]. Wang, Wang, and Liu [43] recommend to use network distance buffer zones around greenspace entrances to measure their accessibility, as they provide more realistic results than the other measures discussed in this subsection.

Spatial interaction measures use demand, attractiveness and distance between two locations to quantify accessibility (see e.g., Park and Guldmann [178] and Chen *et al.* [179]). It is assumed that people are more likely to access locations that are close by or more attractive, given their size or diversity of offered facilities. Spatial interaction is also referred to as *gravity*, by analogy with the gravitational force between two objects in physics [15]. However, Wang, Wang, and Liu [43] state that by adjusting the attractiveness parameter under the assumption that a greenspace can host a maximum number of people may cause biased outcomes.

4.2.3. Betweenness

Betweenness measures capture accessibility for unplanned visits by estimating the flows of people that are on the move from one place to another. The main assumption is that people who pass by a place are more likely to visit it, as they do not need to initiate a separate trip. This is especially the case in dense urban environments, where people often visit their destinations on foot [180]. Betweenness, originally proposed by Freeman [106], is defined as the fraction of shortest paths between any pair of nodes in a network. Porta *et al.* [181], Sevtsuk [182], and Buzzacchi *et al.* [183] use betweenness to study the accessibility of retail locations, and Psyllidis *et al.* [184] demonstrate its utility in the context of infectious diseases. In addition, Sevtsuk [70] introduces *patronage betweenness* to more accurately capture pedestrian behavior, by incorporating weighted origins and destinations, limited radius distances, detours, and distance decay.

In summary, we identify three main limitations in greenspace accessibility studies. First, accessibility metrics are typically limited to capturing access from home locations [2, 171], even though measuring access from other activity locations such as schools can be implemented with the same metrics. Nieuwenhuijsen *et al.* [2] further stress the need to take routine activity spaces such as *home*, *school* and *commuting routes* into account in greenspace accessibility studies. Second, differences in activity patterns per population age group are not accounted for. Third, on-the-move access is often ignored [2, 17, 171]. Our work draws on these limitations to provide a more refined network-based accessibility measurement method, tailored to different age groups and activity settings.

4.3. Methods

In our proposed age-adjusted greenspace accessibility measure, we consider the main daily activity settings of children and adolescents. Specifically, we measure accessibility from *residential*, *educational*, and *on-the-move* settings by combining walkshed buffer zones and patronage betweenness metrics.

4.3.1. Datasets and software

All data used in this study are open data, available either at the national level or globally. To account for boundary effects, we collect data up to 800 meters beyond the official municipal boundaries of our case-study cities, which further corresponds to the maximum walking distance in our analyses.

As a base map, we use OpenStreetMap (OSM); an open-source mapping platform containing world-wide geographical data collected by a community of users. Specifically, we use OSM to collect data about greenspaces, the road network, and colleges and universities. OSM is increasingly being used as an alternative to commercial or authoritative data [185] (see e.g., Novack, Wang, and Zipf [186], combining OSM street network and land use data for research). The OSM road network is found to be complete in over 40% of countries [138], and covers more informal route segments than official datasets [17]. OSM data were collected in April 2022.

We further collect Dutch official population statistics data of 2021 at the highest available granularity, i.e., a 100 by 100 meter grid, from the Dutch Central Bureau of Statistics [187], providing information on the number of people generally, and children and adolescents specifically, per grid cell. In addition, we collect a dataset containing the locations of primary and secondary schools from the Dutch Education Executive Agency of the Dutch Ministry of Education, Culture and Science [188, 189].

Our method to quantify greenspace accessibility is replicable for any city where the OSM road network is highly complete (see e.g., Barrington-Leigh and Millard-Ball [138]), and where land use data (derived either from OSM or a local data source), granular population data (e.g., at a 100 by 100 meter granularity, differentiating between age categories), and data on locations of educational facilities are available. Data collection and analysis is carried out in Python. We use the *Osmnx* package [159] to extract road network data, as well as the *Overpass* Application Programming Interface (API) to collect OSM data about greenspaces and the OpenStreetMap-based *Nominatim* geocoder to convert school addresses to geo-coordinates. Moreover, we make use of the *Urban Network Analysis* toolbox for Rhino [70, 190] to conduct the betweenness analyses.

4.3.2. Road network and greenspaces

To obtain all roads that are publicly accessible to pedestrians, we use the default Osmnx *walk* network type. We adapt it such that we do *not* exclude all bicycle infrastructure, as OSM tags roads shared by pedestrians and cyclists as both *footway* and *cycleway*. To allow for more efficient analysis, we simplify the network by consolidating neighboring nodes within 10 meters. That is, at complex intersections with multiple network nodes lying within 10 meters from each other, these are collapsed into one while maintaining topological relations.

Drawing on the World Health Organization Regional Office for Europe [1], we define urban greenspaces as "urban spaces covered by vegetation of any kind". We collect land covered by vegetation from OSM (i.e., including parks, nature reserves, forests, woods, scrubs, shrubbery, heath, meadows, grass(lands), village greenery and fells, but excluding typically inaccessible spaces used for crop production, e.g., allotments and farmlands). We then merge adjacent greenspaces into one, and filter out those smaller than 0.5 hectares, in accordance with recommendations by the World Health Organization Regional Office for Europe [191] as well as the European Common Indicator for greenspace accessibility [160]. Moreover, we filter out greenspaces that extend beyond official municipal boundaries or that do not intersect with the pedestrian road network; that is, that are inaccessible to pedestrians. The resulting dataset contains a total of 848 publicly accessible urban greenspaces in Amsterdam, Rotterdam, and The Hague.

For every greenspace, we calculate the walkshed around it, representing the space that can be reached within walking distance. Specifically, we use walksheds that represent 5, 10, and 15-minute walks, as literature suggests that these travel times capture the majority of walking trips [42, 192, 193, 194]. We translate these travel times into distances of 300, 500, and 800 meters, respectively, in accordance with Waddell and Ulfarsson [158]. For each of these distances, we calculate the corresponding walkshed by identifying the area that can be reached on foot from any intersection of roads located within the greenspace.

4.3.3. Quantifying accessibility

We quantify age-adjusted greenspace accessibility in relation to residential, educational, and commuting settings. We calculate (1) the number of children and adolescents living within the greenspace's walkshed (*residence-based*), (2) the number of corresponding educational facilities located within the walkshed (*education-based*), and (3) the number of children or adolescents commuting between home and school through the greenspace (*on-the-move*). That is, we use a network buffer measure to quantify accessibility from residential and educational settings, and a betweenness measure to capture accessibility while on the move, following the work by Wang, Wang, and Liu [43] and Sevtsuk [180].

Residence-based accessibility. To determine how many children live within a greenspace's walkshed, we first map where children live and in what numbers, using the 100 by 100 meter Dutch open dataset on population statistics. This dataset contains the number of children (i.e., age 0 to 14), adolescents (i.e., age 15 to 24), and the overall population (i.e., people of all ages) living in each 100 by 100 meter population grid cell.

We calculate residence-based accessibility A_{res} of a greenspace i by, first, overlaying each walkshed area with the centroids of the population grid cells G to determine the grid cells that lie within a given network distance from each greenspace. We, then, sum the total population of children and adolescents within these grid cells to capture how accessible each greenspace is to these population groups using the following equation:

$$A_{res}[i] = \sum_{j:G_j \in G_{walkshed}} P_j \tag{4.1}$$

where P_j denotes the total population of children or adolescents within a grid cell G_j, and $G_{walkshed}$ denotes the population grid cells with their centroid located within walkshed network distance from greenspace i.

Similarly, we determine the overall number of people (i.e., of any age) that have access to the greenspace from residential settings: this conventional greenspace accessibility measure, capturing accessibility only from home locations and without taking differences between population age groups into account, will serve as a baseline to be compared to the outcomes of our age-adjusted measure.

Education-based accessibility. To calculate the number of educational facilities within the greenspace's walkshed, we use the official Dutch dataset containing school locations, as well as the locations of colleges and universities obtained from OpenStreetMap. We divide them into facilities corresponding to children (i.e., primary schools) and adolescents (i.e., secondary schools, colleges, and universities). Our dataset contains 559 primary schools for children and 362 secondary and higher education facilities for adolescents in the three case-study cities. In contrast to residence-based accessibility, for educational accessibility we do not approximate the number of individual children or adolescents having access. Instead, we quantify the number of facilities per age group. In case facilities are spread over multiple locations, e.g., a school with a main building and an annex, or a university campus consisting of numerous faculties, these locations are considered separately.

We calculate accessibility A_{edu} of each greenspace i from educational settings by overlaying its walkshed area with the children's and adolescents' educational facilities F to determine the number of educational facilities located within each walkshed. We refer to these as $F_{walkshed}$, and define A_{edu} as the total number of facilities within $F_{walkshed}$, such that $A_{edu}[i] = n_{F_{walkshed[i]}}$.

On-the-move accessibility. To quantify greenspaces' accessibility by children and adolescents on the move, we model the flows of children and adolescents commuting between their residential settings (i.e., origins) and educational settings (i.e., destinations). We make use of the patronage betweenness analysis described by Sevtsuk [70]: this analysis results in an aggregate number of children and adolescents modeled to commute via each street segment in our road network. We operationalize this measure using the Urban Network Analysis toolkit [190], which calculates patronage betweenness with the following equation:

$$PB[s]^{r,dr} = \sum_{j,k \in G-\{s\}, d[j,k] \leq r \cdot dr} \frac{n_{j,k[s]}}{n_{j,k}} \cdot W[j,k] \cdot \frac{1}{e^{\beta \cdot d[j,k]}} \tag{4.2}$$

For each street segment s, this equation sums over all potential origin and destination pairs j,k, such that s lies on an admissible path between j and k. Paths are admissible when their distance d is no longer than radius r and at maximum a factor dr (detour ratio) longer than the shortest path connecting j and k. Then the equation takes the share of admissible paths between j and k that lead through s, multiplies it with weight factor W based on the supply and demand of commuters at j and k, and accounts for a distance decay effect β.

In our operationalization, we admit all pairs connected with each other with at most 800 meters radius distance r via the street network, corresponding to a 15-minute walk [158]. As pedestrians take routes up to 20% longer compared to the shortest path [180] and tend to make detours to parks [195], we take all paths into account that are up to 20% longer than the shortest connection between the pair by setting detour ratio dr to 1.2. We apply a distance decay effect (i.e., people are less likely to travel further) β of 0.002, aligning with short walking commutes [42]. We set weight W of the origins to the number of children or adolescents per residential setting (i.e., using input data as in the residence-based measure) and weigh the destinations by facility count (i.e., as in the education-based measure).

In order to aggregate the number of commuters per street segment into an accessibility value per greenspace we follow two different approaches. First, we quantify on-the-move accessibility A_{osmS} of each greenspace i by calculating the total *sum* of children or adolescents that enter and exit the greenspace. To this end, we identify which street segments S cross the greenspace boundaries. We, then, sum the patronage betweenness values PB at these segments and divide the result by two (i.e., one person traversing the greenspace will cross its border twice), as in the following formula:

$$A_{otmS}[i] = \sum_{j:S_j \in S_{crossing}} PB_j \cdot \frac{1}{2} \tag{4.3}$$

where PB_j denotes the patronage betweenness values at street segment S_j, and $S_{crossing}$ denotes the street segments that cross the boundaries of greenspace i.

Second, we quantify on-the-move accessibility A_{osmW} of each greenspace i by calculating the overall commuter-exposure time using a *weighted sum*. Instead of considering all segments crossing the boundaries of the greenspace, we now cut the street segments S at the boundary of the greenspace. Next, we sum the products of patronage betweenness PB and length l of each segment within the greenspace using the following equation:

$$A_{otmW}[i] = \sum_{j:S_j \in S_{within}} (PB_j \cdot l_j) \tag{4.4}$$

where PB_j and l_j denote patronage betweenness and length, respectively, of street segment S_j, and S_{within} denotes all segments located within greenspace i.

Furthermore, for adolescents, we explore the effect of longer radius distances in the patronage betweenness calculation (i.e., up to 1200 meters) on the outputs of our model, considering they might walk further away to their study facilities.

4.3.4. Statistical and spatial analyses

To assess the utility of our accessibility measurement method, we first evaluate the differences and similarities between the conventional baseline measure (i.e., accessibility from home to people of any age; the most-widely used measure in related studies to date) and the various proposed measures by conducting a correlation analysis. We elaborate on patterns behind the correlation analysis, such as linearity of relationships and the distribution of values, in order to better understand what mechanisms drive these differences and similarities. Following this, we explore in further detail the spatial patterns of greenspaces where notable differences between the calculated measures occur.

4.4. Results

This section presents an overview of the results for the three case-study cities: Amsterdam, Rotterdam, and The Hague. Definitions and descriptive statistics of measures for the 848 greenspaces in our dataset (i.e., 398 in Amsterdam, 281 in Rotterdam, and 169 in The Hague) are presented in table 4.1.

4.4.1. Correlation analysis

We first test the distribution of our accessibility results using a Kolmogorov-Smirnov test, which indicates a non-normal distribution. Following this, we assess the linear correlations between all accessibility measures by calculating Spearman's Rho (ρ). All calculated accessibility measures are found to positively correlate with each other ($p<.01$), with strengths ranging from weak to very strong, as presented in table 4.2. In a similar lay-out and coloring, figure 4.1 shows scatter plots of the relationships between the different types of measures for children (left) and adolescents (right).

The conventional baseline measure (see section *A* in table 4.2) generally shows very strong correlations with residence-based accessibility. A clear linear relationship can also be observed in the scatter plot in figure 4.1, row B. With other measurement approaches, however, strengths vary substantially. For children, we find weak to moderate correlations with the education-based measure, and strong to very strong correlations with the on-the-move measure. For adolescents, correlations are less strong, ranging from weak to moderate for the education-based measure and moderate for on-the-move accessibility.

Table 4.1.: Calculated greenspace accessibility measures: definitions, abbreviations, and descriptive statistics of results for greenspaces in Amsterdam, Rotterdam, and The Hague: baseline (*A*), residence-based (*B*), education-based (*C*), and on-the-move (*D*) measures.

	Definition	Unit	Network radius	Age group	Abbreviation	N	Mean	Std.dev.	Min	Max
A	**Baseline** Number of people living within greenspace walkshed	# people	300m	Any age	**base3**	848	1524.5	1878.7	0	16605
			500m	Any age	**base5**	848	3498.3	3872.3	0	31810
			800m	Any age	**base8**	848	7763.3	7635.3	0	58110
B	**Residence-based** Number of children or adolescents living within greenspace walkshed	# people	300m	Children	**res3C**	848	240.2	308.6	0	2240
				Adolescents	**res3A**	848	177.6	251.9	0	2055
			500m	Children	**res5C**	848	546	615.2	0	4630
				Adolescents	**res5A**	848	418.4	520.8	0	3730
			800m	Children	**res8C**	848	1203.6	1185.1	0	9215
				Adolescents	**res8A**	848	937.3	1030.8	0	6715
C	**Education-based** Number of corresponding educational facilities within greenspace walkshed	# facilities	300m	Children	**edu3C**	848	0.4	0.7	0	4
				Adolescents	**edu3A**	848	0.2	0.7	0	7
			500m	Children	**edu5C**	848	0.8	1.3	0	10
				Adolescents	**edu5A**	848	0.5	1.2	0	11
			800m	Children	**edu8C**	848	2	2.3	0	16
				Adolescents	**edu8A**	848	1.1	2.1	0	16
D	**On-the-move** Number of children or adolescents traversing the greenspace while commuting	# people entering	800m	Children	**otms8C**	848	68.7	199.4	0	2322
				Adolescents	**otms8A**	848	34.6	150.8	0	2287
		# people traversing × meters traversed	800m	Children	**otmw8C**	848	11250.6	33024.6	0	387594
				Adolescents	**otmw8A**	848	5772.3	25180.7	0	316204

Table 4.2.: Spearman's Rho correlations between accessibility measures: conventional baseline (*A*), residence-based (*B*), education-based (*C*), and on-the-move (*D*). All measures are significantly positively correlated (p<.01). Notable weak correlations are highlighted in lighter orange color shades.

			base3	base5	base8	res3C	res3A	res5C	res5A	res8C	res8A	edu3C	edu3A	edu5C	edu5A	edu8C	edu8A	otms8C	otms8A	otmw8C	otmw8A
A	**Baseline** Number of people living within greenspace walkshed	**base3**	1																		
		base5	0.962	1																	
		base8	0.900	0.961	1																
B	**Residence-based** Number of children or adolescents living within greenspace walkshed	**res3C**	0.962	0.923	0.858	1															
		res3A	0.958	0.933	0.877	0.942	1														
		res5C	0.935	0.962	0.916	0.957	0.921	1													
		res5A	0.919	0.961	0.930	0.895	0.951	0.936	1												
		res8C	0.880	0.935	0.962	0.886	0.866	0.954	0.913	1											
		res8A	0.854	0.919	0.963	0.821	0.879	0.883	0.949	0.931	1										
C	**Education-based** Number of corresponding educational facilities within greenspace walkshed	**edu3C**	0.547	0.551	0.530	0.541	0.539	0.547	0.534	0.531	0.509	1									
		edu3A	0.308	0.333	0.356	0.285	0.284	0.306	0.312	0.324	0.319	0.295	1								
		edu5C	0.698	0.723	0.707	0.693	0.683	0.721	0.699	0.708	0.678	0.716	0.351	1							
		edu5A	0.358	0.417	0.461	0.309	0.340	0.358	0.402	0.402	0.432	0.293	0.739	0.388	1						
		edu8C	0.791	0.843	0.865	0.777	0.781	0.830	0.822	0.859	0.836	0.536	0.346	0.765	0.423	1					
		edu8A	0.432	0.498	0.543	0.374	0.414	0.429	0.483	0.471	0.525	0.305	0.562	0.440	0.767	0.500	1				
D	**On-the-move** Number of children or adolescents traversing the greenspace while commuting	**otms8C**	0.814	0.791	0.743	0.802	0.789	0.775	0.756	0.730	0.700	0.643	0.295	0.750	0.316	0.727	0.361	1			
		otms8A	0.519	0.545	0.554	0.473	0.504	0.493	0.531	0.504	0.532	0.390	0.595	0.500	0.717	0.523	0.793	0.520	1		
		otmw8C	0.821	0.799	0.753	0.808	0.795	0.783	0.764	0.738	0.709	0.646	0.307	0.756	0.330	0.735	0.373	0.994	0.527	1	
		otmw8A	0.522	0.549	0.557	0.475	0.506	0.496	0.534	0.507	0.535	0.393	0.603	0.502	0.726	0.526	0.796	0.518	0.998	0.528	1

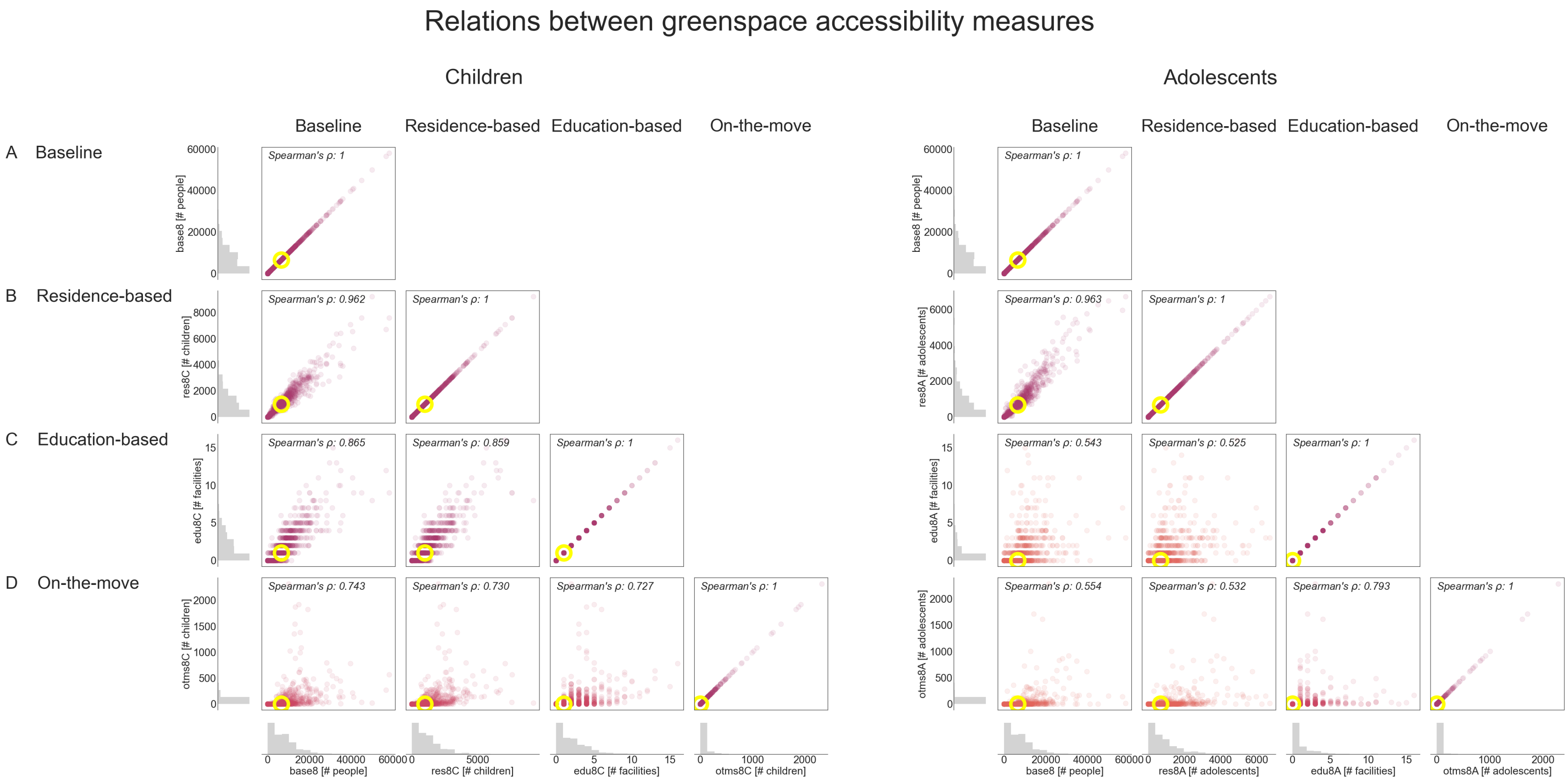


Figure 4.1.: Scatter plots of relationships between accessibility measures for children (left) and for adolescents (right), accompanied by histograms per measure: conventional baseline (*A*), residence-based (*B*), education-based (*C*), and on-the-move (*D*). All measures shown use an 800-meter network radius distance. Scatter plots are colored according to the strength of correlation, in alignment with Table 4.2. Yellow circles in the scatter plots depict the median values.

Specifically, we find very strong correlations between the various residence-based metrics (varying with age group or radius distance) and the baseline (i.e., conventional) metric (see section *B*). Metrics using the same radius distance yield stronger correlations compared to metrics using distances that are further apart. Both residence-based and conventional metrics present similar correlation patterns between them. In addition, we observe correlations between the residence-based metrics are even stronger when within the same age group.

Unlike residence-based metrics, education-based accessibility yields varying results when correlated with conventional metrics (see section *C*). Specifically, as radius distance of the education-based measure increases, children's accessibility to greenspaces presents stronger correlations with residence-based and conventional metrics rising from moderate to very strong. Figure 4.1 (left panel) suggests a linear relationship between baseline and education-based measures for children remains (row C), though less clear than between baseline and residence-based measures (row B). In the case of adolescents, we observe a similar pattern though correlations are weaker. That is, they only rise from weak to moderate. Figure 4.1 (right panel, row C) reflects these lower correlation values for adolescents. The scatter plot suggests no clear linear relationship and both the histogram and scatter plot show education-based values for adolescents remain close to 0 (i.e., 62% score 0) even when residence-based accessibility increases. These patterns also hold when comparing the education-based approach with the residence-based approach.

Regarding children's on-the-move accessibility, we observe strong to very strong correlations with the baseline metric (see section *D*). The histogram plot in figure 4.1 (left panel, row D) shows that on-the-move accessibility values are concentrated around 0. However, for non-zero on-the-move values some tendency of higher values where baseline accessibility values increase can be observed, while generally the spread is wide. That is, the scatter plots also show greenspaces for which the baseline measure yields low values while the on-the-move measure yields high values, and vice versa. Contrary to education-based accessibility, the strength of the correlation decreases when radius distance increases. For adolescents, correlations are moderate and thereby, again, weaker than for the children's age group. Figure 4.1 (right panel, row D) shows that on-the-move values for adolescents generally remain very close to 0 as well (72 % of greenspaces), even more than in the case of children (49%), i.e., many greenspaces are not at all accessible to adolescents commuting. Nevertheless, in case the radius distance increases correlation values do rise. Similar overall patterns are observed when comparing on-the-move accessibility with residence-based accessibility.

Education-based metrics for children present moderate to strong results between them, while results for adolescents range weak to moderate. We find the strongest correlations between pairs of metrics when the age group remains constant (i.e., rising from moderate to strong, relative to the difference in radius distance). Correlations between education-based measures for children and for adolescents are weak, only rising to moderate correlations for further radius distances.

The comparison between education-based and on-the-move accessibility for children yields strong correlations. For adolescents, correlations range from moderate to strong when radius distance increases. Between the two age groups, correlations are weaker, yet here again we observe a pattern of stronger correlations for further radius distances. The effect of increasing the radius distance for adolescents (i.e., to 1000 and 1200 meters) yields only limited differences in on-the-move accessibility outcomes. That is, using radius distances of 1000 or 1200 meters yields significant and strong correlation values of 0.867 and 0.753, respectively. Lastly, both metrics of on-the-move accessibility (i.e., the number of children or adolescents entering a greenspace (*otms* in section D), and its total commuter-exposure time (*otmw*)) present very strong correlations with each other. However, this is not the case when comparing the respective on-the-move metrics between children and adolescents.

4.4.2. Spatial patterns of accessibility metrics

Figure 4.2 and figure 4.3 present an overview of accessibility maps for children and adolescents, respectively. They zoom in on a small area of Amsterdam (top), Rotterdam (middle), and The Hague (bottom) to illustrate differences and similarities between the baseline, residence-based, education-based, and on-the-move greenspace accessibility results of the correlation analysis. All maps are based on measures using an 800m radius distance, corresponding to a 15-minute walk. Examples described in the following paragraphs are indicated in the corresponding maps.

The maps show strong similarities between accessibility results for the baseline and residential approaches, regardless of age group or city, while notable differences emerge for the other measures, in line with the lower correlations found between those measures in the correlation analysis. We focus on what characterizes the greenspaces and their surroundings where these notable differences appear. Specifically, we describe greenspaces that are (1) highly accessible to children or poorly accessible to adolescents from the school setting, as opposed to the home setting, (2) poorly accessible in terms of children's or adolescents' traverse movement, and (3) highly accessible to adolescents from home or traversing, relative to accessibility from educational settings.

High or poor education-based accessibility. Twenty greenspaces score higher in terms of accessibility from children's schools within 800 meters, than in terms of home-based accessibility, although the correlation analysis shows very strong correlations between them. Panel B in figure 4.2 highlights some of these greenspaces in the *City Centre* of Rotterdam. We observe that they are often small-sized: on average, these greenspaces are about three hectares in size — less than half the average size of all greenspaces in our dataset, as well as of those that score relatively low on children's education-based accessibility. Furthermore, these greenspaces are located in an area with a relatively low children's population density, compared to neighboring areas, while children's schools are more equally distributed.

Exemplary cases of greenspaces that score relatively low in terms of adolescents' access from schools, compared to that from their homes, are presented in panel A of figure 4.3. In line with the moderate correlations between adolescents' home-based and education-based access, we observe large differences: greenspaces that score up to high on residence-based accessibility are not at all accessible to adolescents from their educational facilities: although populated, the area hosts only two educational facilities for adolescents.

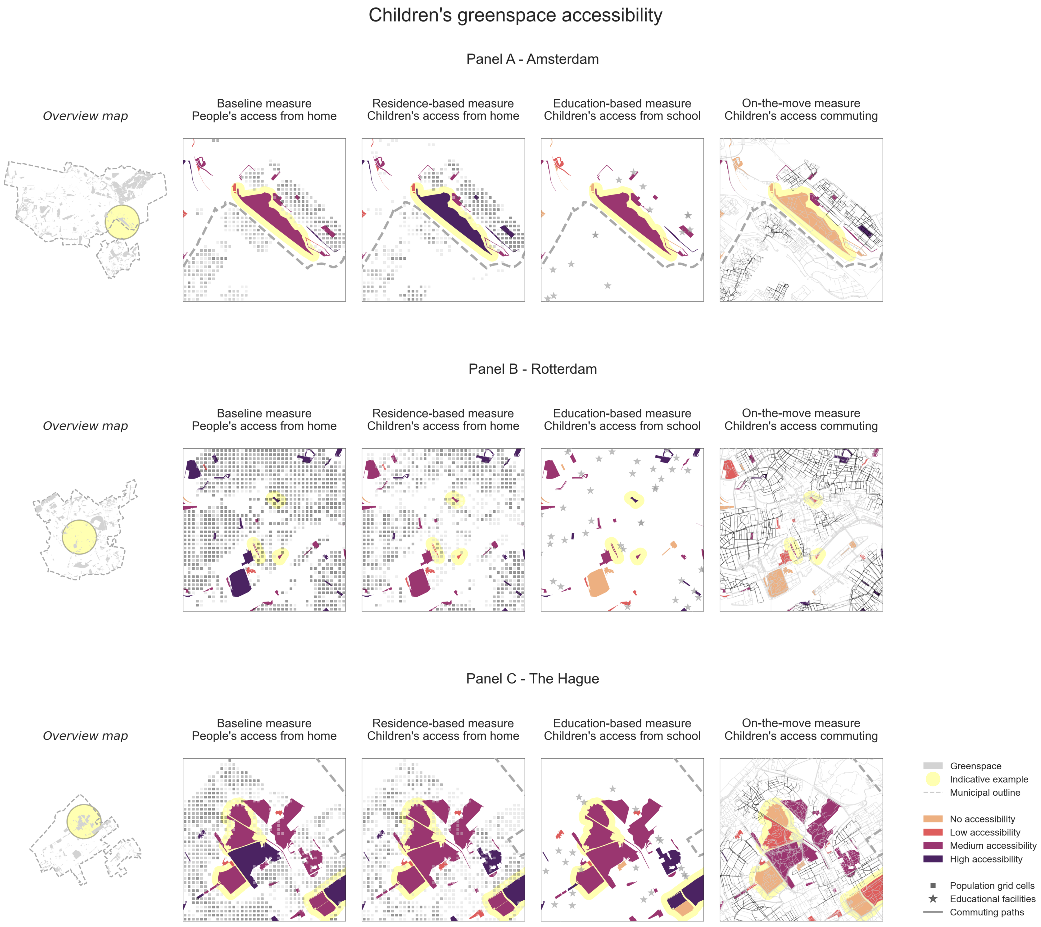


Figure 4.2.: *Children's* greenspace accessibility: (A) baseline, (B) residential, (C) educational and (D) on-the-move accessibility measures for Amsterdam (top), Rotterdam (middle) and The Hague (bottom). Notable examples are highlighted in yellow.

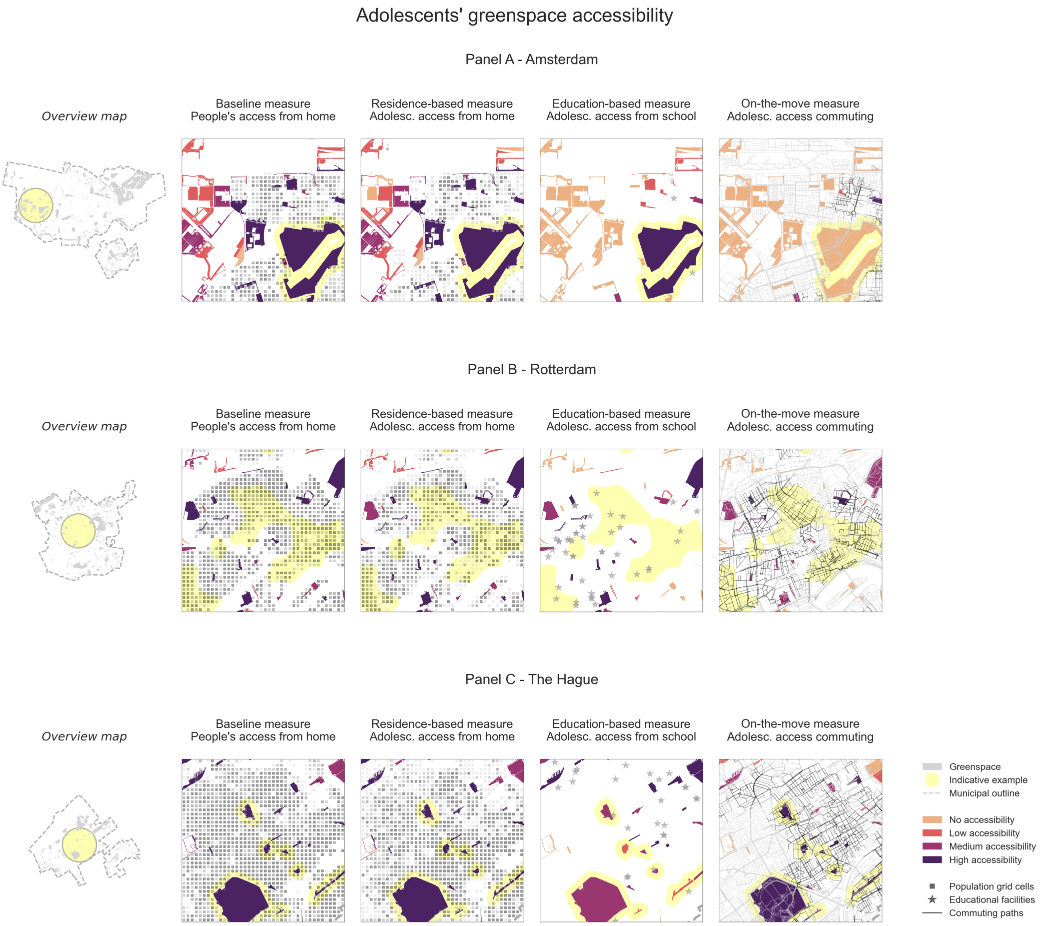


Figure 4.3.: *Adolescents'* greenspace accessibility: (A) baseline, (B) residential, (C) educational and (D) on-the-move accessibility measures for Amsterdam (top), Rotterdam (middle) and The Hague (bottom). Notable examples are highlighted in yellow.

Poor on-the-move accessibility. As shown in the histograms and scatter plots in figure 4.1, many greenspaces are not accessible while on the move, relative to accessibility measurements from home and school settings. The maps illustrate this pattern and show these greenspaces are often large in size or neighboring other open space: for example, eight of the ten largest-size greenspaces in our dataset score relatively poorly in terms of access to children commuting. Notable examples include *Diemerpark* in Amsterdam (figure 4.2 panel A). Diemerpark is large in size and surrounded by water, with few connections to a neighboring residential area with schools only on its Northern side. Another example are the clusters of neighboring greenspaces in the area near *Scheveningse Bosjes*, The Hague (panel C). Here, we observe numerous greenspaces, highlighted in yellow, that score relatively poor on access to children commuting, relative to accessibility from homes and schools.

For adolescents, similar patterns apply, with a notable example being *Sloterpark* in Amsterdam (figure 4.3, panel A). This large-size park is highly accessible from adolescents' homes and schools, but not at all accessible to adolescents commuting. Furthermore, we note that greenspace is lacking in large areas where adolescents commute, for example in the *City Centre* of Rotterdam (panel B).

High residence-based and on-the-move accessibility. Contrary to the large number of greenspaces that are not accessible to adolescents commuting, we also find areas for which on-the-move greenspace accessibility is high. Notable examples can be found in the area North of *Zuiderpark*, The Hague (figure 4.3, panel C). Here, on-the-move accessibility is as high as residence-based accessibility, while access from schools remains lower. These areas are characterised by a high population and road network density, and greenspaces of medium to large size.

4.5. Discussion

4.5.1. Interpretation of results

In the following paragraphs, we discuss the interpretation of the analysis of results in the three case-study cities. Figure 4.4 shows indicative examples of greenspaces that we will further elaborate on in this section.

Our results indicate that measuring greenspace accessibility from children's and adolescents' home locations yields similar results to conventional measures (i.e., measuring accessibility from home locations of people of any age). Even though neighborhood population density may vary per age group, the resulting differences in accessibility appear to be small. We further observe similar outcomes when measuring accessibility from children's educational facilities. This potentially has to do with the fact that social facilities such as schools in the Netherlands are distributed such that the facilities in a neighborhood match the corresponding number of inhabitants or residences, allowing children to reach them without having to travel long distances. That is, similar to school catchment area principles, our case-study cities have policies to ensure that the number of primary schools matches the population of an area [196, 197, 198].

Nevertheless, our analysis indicates that a number of greenspaces score relatively high in terms of accessibility from educational facilities, relative to accessibility calculated

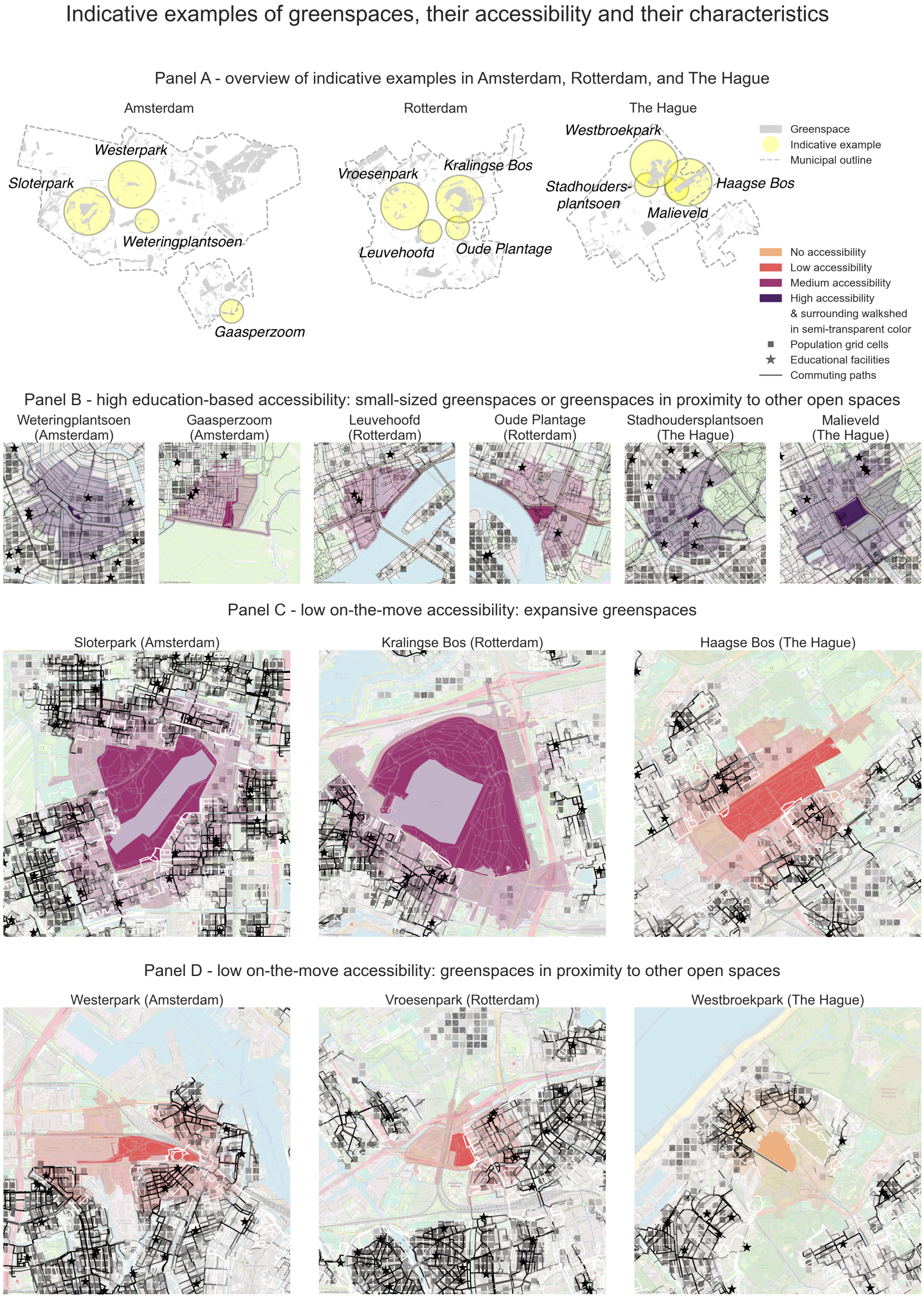


Figure 4.4.: Geometry, accessibility, and surroundings of indicative greenspaces in Amsterdam (left), Rotterdam (middle), and The Hague (right). Greenspaces are colored according to accessibility level, together with their semi-transparently colored 800m radius walkshed (equivalent to a 15-minute walk).

from home locations. A common characteristic of this set of greenspaces is their small size (see figure 4.4, panel B). That is, the largest greenspace in this set is *Malieveld* in The Hague with an area of 11 hectares, while the mean area of this set is approximately three hectares and less than half of the mean area of all greenspaces. Moreover, none of the 100 largest greenspaces in our dataset are included among them. This suggests that the degree of accessibility of small to medium-sized parks may be more dependent on variation in the density of surrounding educational facilities relative to the distribution of homes, for example, due to proximity to other greenspaces or water bodies, as opposed to large greenspaces where differences even out. Moreover, even when using alternative input data about the age structure or the location of facilities (i.e., age demographics at the neighborhood level, or school locations from OSM), the findings regarding highly accessible small-sized greenspaces hold.

Furthermore, when we compare the three age-adjusted measures with the conventional baseline measure, we see that the on-the-move measures yield correlation strengths that are weaker than in the case of residence-based measures, but stronger than the education-based approach. This may relate to the core principle of the on-the-move measure, which is to connect both residential and educational settings. Interestingly, on-the-move accessibility (i.e., while commuting between home and school) in the case of children yields correlations varying from strong to very strong not only with the baseline measure, but also with the residence-based measures, while with the education-based measures, correlation strengths are lower. Looking further into the differences that appear to induce the differentiation between the age-adjusted measures, we identify two key factors: (a) the size of the greenspace, and (b) the configuration of surrounding open space, homes, and facilities — a pattern which, again, also applies when alternative population or educational facility data are used. More specifically, our results suggest that expansive greenspaces make it difficult to fully traverse from one side to the other within a 15-minute walking commute, resulting in low to medium accessibility (figure 4.4, panel C). These greenspaces typically have a width that exceeds 500m, which restricts traverse movement to children entering and exiting on the same park side, while making a slight detour on their way to school. This could indicate that well-connected park edges may motivate traverse movement even in the case of expansive greenspaces. On the contrary, the use of their central areas appears to be limited to purposeful visits only. Conversely, greenspaces with a width between 300 and 450m appear to enable traverse movement from one side to another through their center, resulting in higher accessibility values.

A representative example of the effect that its surroundings can have on greenspace accessibility is *Westbroekpark* in The Hague (figure 4.4, panel D). Even though our results yield medium home- and education-based accessibility scores, its location in between other greenspaces and water bodies and correspondingly limited road connections to this park's surroundings lead to negligible on-the-move accessibility (homes and school facilities are mainly located on the north side of the park and at a distance that hinders small detours). A similar example is the *Vroesenpark* park in Rotterdam with low on-the-move accessibility, owing primarily to its location in immediate vicinity to a railway, canal, and zoo. However, *Westerpark* in Amsterdam is an interesting example of a greenspace that, although neighboring a railway and canal as well, is estimated to allow traverse movement by children at its east side. This appears to be induced by its proximity to educational facilities and populated neighborhoods, and by its limited width and reasonably good connection to the surrounding road network. In other words, its degree of connectivity, medium size, and the density and configuration of surrounding facilities appear to make up for the movement limitations posed by neighboring open spaces.

When adjusting our metrics to adolescents, the resulting correlations between the various accessibility measures (i.e., baseline, residence-based, education-based, and on-the-move accessibility) are largely moderate, rising to strong only for on-the-move measures. This underscores that conventional accessibility metrics, calculated solely from home locations and not adjusted to different population age groups, would not capture many variations in greenspace accessibility scores. The majority of higher education facilities appear to be clustered, opposed to rather equally distributed in the case of children's schools, and so do the corresponding commuting routes. As a result, a large amount of greenspaces are not accessible by adolescents from educational (62%) or on-the-move settings (72%) At the same time, in many areas that are traversed by adolescents on the move, greenspaces are completely lacking. This may suggest that developing new greenspace in these areas could introduce opportunities for longer, routine-based exposure, especially in the case of adolescents.

4.5.2. Implications for urban greenspace research and planning

Given the results discussed in the previous paragraphs, we argue that the three measures (i.e., residence-based, education-based, and on-the-move) introduced in this chapter offer new insights into greenspace accessibility. Specifically, measuring accessibility from educational or on-the-move settings often yields different greenspace accessibility scores relative to the ones calculated with conventional metrics. Even though our analysis is based on estimates of pedestrian mobility (e.g., patronage betweenness models), the results present similarities to related literature in environmental exposures. For instance, Ma *et al.* [199] find that people's exposure to noise would be underestimated when only measured from home locations.

To the best of our knowledge, our work is the first to apply patronage betweenness models in the context of greenspace exposure research. We demonstrate that these models provide new perspectives on greenspace accessibility, compared to conventional accessibility approaches that do not account for exposures on the move. This is in line with the need to consider dynamic settings in environmental exposure research, as underscored by Nieuwenhuijsen *et al.* [2], Helbich [171], and Kestens *et al.* [200].

Our method is largely automated and parameters can be adjusted to account for other settings (e.g., residences of friends and family [36]), other population groups and their corresponding activity places, or to assess the accessibility of other types of public space. Contrary to the conventional approaches, our method offers rich insight into greenspace accessibility for different population age groups, from various settings while also accounting for on-the-move exposure.

This work aspires to provide urban planners and policy-makers with a tool to assess the accessibility of greenspaces, especially in relation to the daily routine activities of different population age groups. Our method could support practitioners in assessing where new greenspaces could be introduced to allow for increased routine exposure. Moreover, our findings could provide guidelines for city planning, in terms of greenspace size, the density and distribution of surrounding facilities, and the configuration of the surrounding road network.

4.5.3. Limitations

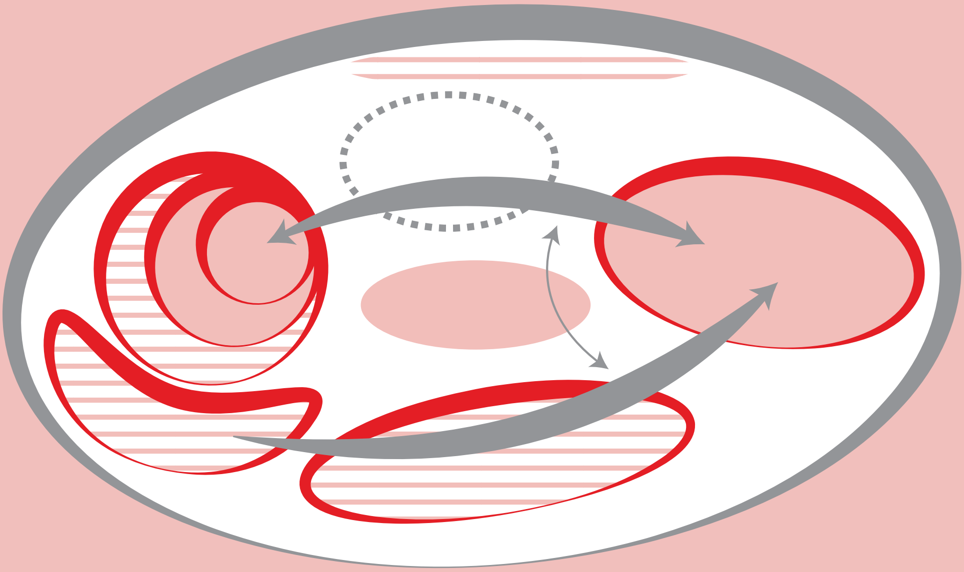
There are several limitations in this study that could be addressed in future research. First, the greenspaces used in our analyses include only those that are categorized as such in the land use data (e.g., OSM) of the three case-study cities. Future work could further incorporate greenspaces that are perceived as such by people, even if categorized differently in the land use data, such as vegetated squares or streets. Second, given the lack of actual accessibility data, our measures of greenspace accessibility are based on model estimates to represent walkshed areas and pedestrian commuting flows at the street level (e.g., by applying the patronage betweenness model with parameters adjusted to the context at hand). Third, in our betweenness analyses we use distance as the main indicator (i.e., shortest paths in combination with detours within a given threshold) for modeling people's routing behavior. Drawing on insights from related work on pedestrian mobility, differences in route quality characteristics might induce inaccuracies. Specifically, this can be the case along car-free roads or in scenic environments [201]. Our method can be extended to consider varying attractiveness scores per street, based on the quality of sidewalks, the degree of land-use mix along streets, or the presence of urban furniture [195]. Fourth, the patronage betweenness analyses conducted in this study are subject to limitations in terms of computational efficiency. In order to mitigate these limitations, we applied simplifications to the road network (e.g., consolidating neighboring nodes in the network), which generally do not affect the derived outcomes, given that the overall road network topology is preserved. Fifth, our study is limited to pedestrian mobility, even though biking is a prevalent alternative active travel mode for children in the Netherlands. Our work can be extended with greenspace accessibility adjusted to biking trips, using the bicycle network in combination with bike-specific mobility parameters. In addition, future work could consider multi-modal trips that would include walking and biking trips in combination with public transportation. Lastly, this work could be extended by accounting for different preferences and needs among people regarding greenspace visits. As we have already pointed out, accessibility may be the most important factor of greenspace use, yet other aspects, such as perceived safety or availability of amenities [22], might also come into play that could further induce exposure to greenspaces.

4.6. Conclusion

In this chapter, we proposed a novel age-adjusted method for measuring greenspace accessibility. Our method is tailored to three important aspects of children's and adolescents' daily activities, namely their homes, their educational facilities, and the commutes between them. Integral to this method are two types of network measures that capture pedestrian movement along streets: (1) walkshed buffer zones that capture the number of children and adolescents having access to each greenspace relative to their homes and schools, and (2) betweenness measures that estimate the flows of children and adolescents traversing each greenspaces on foot while commuting. We demonstrated our method using the most populated cities in the Netherlands to exemplify its implementation and outcomes. Our analyses showed that the three measures (i.e., residential, educational, and on-the-move accessibility) capture different aspects of greenspace accessibility, and highlight the importance of acknowledging variation in activity settings per population age group. Our results showed a consistent variation of greenspace accessibility relative to park size, and to the configuration and density of the facilities surrounding each greenspace. While this is consistent across our three case-study cities, generalizability to other contexts warrants further study.

This work is the first to demonstrate the utility of the betweenness measure for measuring greenspace accessibility, and can be replicated in any city with land use, street network, population statistics, and educational facilities data available. Our methodology has practical value for urban planners and (public health) policy makers, who can use it as a tool to assess potential exposure to greenspaces for different population age groups. We aspire that our method could facilitate identifying greenspaces that promote or hinder routine use by different population groups and, correspondingly, the implementation of customized policies and interventions to increase exposure to greenspaces at the local level. In an era where people face increased risks of mental health problems, among others, due to urbanization [202], and urban densification threatens greenspace availability [203], this advocacy is key.

Future work could extend our methodology by accounting for a larger variety of human activity settings, other population groups, or alternative active travel modalities such as biking. It could further be refined by considering people's experiences, preferences, and needs around greenspaces.



5

Access for unsupervised play

In this chapter, we study how to measure children's access to greenspace *for unsupervised play*. As identified in chapter 2, children's independence or autonomy is a key factor affecting access, but remains only touched upon in accessibility measures to date. Again, we operationalize our method using OpenStreetMap data that were subject of study in chapter 3. Children's access to space for unsupervised play is related to the restrictions that parents impose based on their perceptions of safety, significantly impacting which play space destinations are accessible to children. Such constraints are not taken into account by widely adopted accessibility indicators that use generic radial buffers or travel distances around the home, including the home-based accessibility measure operationalized in chapter 4. Through an iterative co-design process with professionals on the built environment and children's health, we adapt this home-based accessibility measure into our *child's play* measure, that incorporates traffic, natural barriers, and a range of playful (green) destinations to capture the ease with which children can reach greenspace to play without adult supervision. This method serves as a second novel method complementing those existing to date, and can be used by practitioners to enable large-scale assessment of play space accessibility, to identify associated equity issues, and to benchmark progress towards healthier urban environments.

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5.1. Introduction

Outdoor play space is essential for children's physical activity, social interaction, and exposure to vegetation, all of which contribute to their mental and physical health [8, 21, 28]. Unsupervised outdoor play benefits children's self-esteem, motor skills, independence, risk management, physical activity, and social health in particular [204]. According to research, children express the desire to play unsupervised [31] in environments with challenging equipment or natural features that match their physique, and where peers are present to play with [28, 29, 30, 31].

However, rates of unsupervised outdoor play have decreased over generations, and parental perceptions of safety have shifted dramatically [205, 206], resulting in a reduction of risky play and physical activity [204]. Evidence suggests that changing parental perceptions of safety influence how accessible outdoor play is for children. That is, parents limit their children's unsupervised play [38], because they are concerned about traffic safety [39, 40, 41], incidents involving strangers (so-called *stranger danger*, such as abductions) [30, 32, 39, 40], and play-related injuries [29]. For instance, parents in Texas, USA, allow their children to play unsupervised only in a few places close by the house [30], whereas parents in Japan do not allow unsupervised play in green or other natural spaces other than parks, despite knowing the importance of exposure to nature [40]. Such restricting behaviors can have a significant impact on the outdoor play spaces that children can actually access.

5

Widely used indicators for measuring access to outdoor play spaces do not take into account parental restrictions or children's preferences for accessing places for play. Accessibility is typically measured using radial buffers around or travel distances from dwelling units [15, 17, 23, 43, 53, 207]. Children's accessibility studies use generic network-distance buffer zones or ignore the impact of parental restrictions, such as not allowing children to cross any street independently [21, 208].

To address this gap, we propose a *child's play* accessibility metric, which measures the ease with which children can reach public outdoor play space without supervision. We refine an existing network-distance buffer zone metric to account for the aforementioned restrictions and preferences. We focus on children of primary school age (i.e., approximately 6 to 12 years old) and explore the elements that should make up such a refined metric, as well as its potential and limitations. To that end, we organized two co-design sessions: the first with built environment experts on play space in Utrecht, the Netherlands, and the second with a diverse group of professionals on children's health and the built environment from eight European countries. In these sessions, we iteratively investigated what factors limit or promote children's play, and how they relate to spatial data, such as maps and street-level imagery. By actively involving experts in the process of designing our metric, we not only receive immediate feedback on our work, but we also ensure that we translate their input and ideas meaningfully into our final child's play accessibility metric.

Our participants stated that traffic infrastructure, large greenspaces, and waterways prevent children from reaching play spaces on their own, whereas various types of formal and informal spaces, including small greenspaces, can serve as play spaces. Our child's play metric takes these barriers into account, as well as a broader range of play areas such as playgrounds, schoolyards, and small parks. We describe the co-design sessions that led to the development of our metric, implement it using open spatial data, compare it to widely used indicators for measuring access to play space, and discuss its practical value for play-space design and policy-making. The chapter concludes with a call to action and research directions for the future.

5.2. Methods

Through an iterative co-design process [71], we collect factors that promote or limit children's outdoor play, how these relate to the urban environment, and how we can incorporate these in our child's play accessibility metric. Fig. 5.1 visualizes this process: we recruit participants for two co-design sessions and prepare a spatial dataset, reflecting spaces that potentially limit play space accessibility, such as traffic infrastructure. During the co-design process, we iterate on these spatial data and explore their potential and limitations, before composing our final child's play accessibility metric.

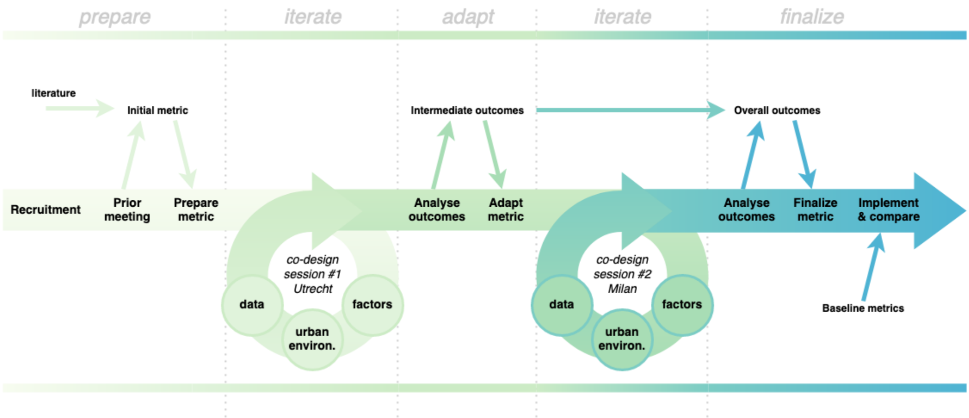

Figure 5.1.: Iterative co-design process: preparation and co-design session 1, adaptation and co-design session 2, and finalisation of our child's play accessibility metric.

5.2.1. Recruiting expert participants

We recruit expert participants via the stakeholder network of the Horizon 2020 *Equal-Life* project[1] [75], combining convenience and snowball sampling [209]. The first session takes place in Utrecht, the Netherlands, with a small sample (n=4) of local professionals on play space in the built environment[2]. The second session takes place in Milan, Italy, with a larger sample (n=16) of experts, both researchers and practitioners, working on children's health and the built environment in eight European countries[3].

[1] https://www.equal-life.eu/en
[2] Working on urban planning, policy-making, and play space assessment for Utrecht.
[3] Four participants from Italy, four from Slovenia, three from the Netherlands, while Slovakia, Ireland, Estonia, Finland, and Belgium each had one participant. Six participants work on the built environment (e.g., urban planning and policy-making, architecture, or geo-information), and ten on children's health (i.e., mental, physical and social health).

We ask participants for their informed consent to participate and in return for participating, we offer them the spatial data shown during the session for own use.

5.2.2. Materials, spatial data, and case-study areas

As materials in the co-design process, we use two types of spatial data: maps from OpenStreetMap[4] and street-level imagery from Google Street View[5]. As case-study cities, we use Utrecht (the Netherlands) for session 1, and Milan (Italy) and Ljubljana (Slovenia) for session 2. These are medium to large cities in Western, Southern, and Central Europe, respectively.

For session 1, we focus on three adjacent districts in Utrecht, that participants are working on at the time of the session, varying in neighborhood typology and socio-economic status. As materials, we use a base map and an initial spatial dataset of features that potentially limit children's access to play space, based on the literature and a prior introductory meeting with the participants: traffic infrastructure (i.e., tram and train railways; main roads ranging from tertiary to motorways; and roads with a maximum speed of 50km/h or higher) [39, 40, 41] and natural environments (i.e., parks, other greenspaces, and water) [40].

For session 2, we focus on central areas in Milan and Ljubljana, characterised by a variety of potential barriers and potential places for play. For these areas, we collect both base maps and street level imagery to serve as materials for the session, and we adapt our spatial data based on preliminary outcomes of session 1.

5.2.3. Co-design process

We run two in-person co-design sessions, both structured in three rounds: (1) What factors promote or limit children's access to play space? (2) How can these be recognised in the urban environment? (3) How do the spatial data we present reflect these factors, and what should be added or omitted? We record audio and collect written and drawn annotations.

For session 1, we started by stating the context and goal of the session, and asking participants to introduce themselves. In round 1, we asked participants to individually note factors that promote or limit play-space access, and to elaborate on these while pasting their notes on a sheet, differentiating between promoting and limiting factors and grouping similar ones. In round 2, we introduced the base map and asked participants to link factors to the map where possible, while indicating locations and exemplifying, based on their local knowledge of the area. In round 3, on top of the base map, we introduced our spatial data highlighting potential limiting urban features (i.e., traffic infrastructure and natural environments) printed on transparent sheets. We asked participants to discuss how these reflect their local knowledge on barriers to play space

[4] OpenStreetMap is an open-source geographical data platform increasingly used in research [185]. We collect land cover, place of interest, and street network data from OpenStreetMap using the *Overpass API* and the *Osmnx* Python package [159]. The OpenStreetMap road network is highly complete in cities world-wide, including many informal road connections [17, 138].

[5] Google Street View is commonly used imagery data in research, including studies on health, greenery, and environmental perception [131].

access, and what should be added or omitted. We concluded the session by discussing the potential of such spatial data for their work.

For session 2, we followed a similar structure but made amendments to accommodate the larger and varied group of participants. To introduce the context and goal, we used a small slide deck and in round 1, we asked the same questions, but used a digital survey tool to collect factors of interest as keywords, followed by a plenary discussion. For round 2, we divided the participants over six tables, to discuss how the base maps and street-level imagery reflected these factors. In round 3, on top of the base maps, we again introduced transparent sheets with our spatial data, now highlighting not only limiting but also promoting urban features (i.e., attractive places for play). We ensured Italian and Slovenian participants commented on the Milan and Ljubljana case, respectively, while mixing them with participants from elsewhere. We invited participants to also introduce examples of other places they are familiar with, for example in their hometown. We concluded the session with a plenary discussion, asking participants recommendations for further development our metric, and discussed what its implications could be.

After each session, we qualitatively analyse the audio transcripts and annotations using thematic analysis [69]. We perform complete coding in an inductive manner and identify themes. Based on the outcomes of the first session, we identify preliminary themes and adapt our spatial data highlighting potential limiting or promoting elements in the urban environment, as input for the second session. After the second session, based on the collective body of outcomes of both sessions, we identify overall themes that feed into our final child's play accessibility metric.

5.2.4. Composing our child's play accessibility metric

To compose our final child's play accessibility metric, we adapt once more the spatial data highlighting potential limiting or promoting urban elements from OpenStreetMap, including barriers, such as roads, that children may not be allowed to cross, and attractive places for play. Then, we collect the pedestrian road network from OpenStreetMap and modify it to account for these barriers, by eliminating street segments that cross them. Finally, based on this modified network, we generate network-distance buffer zones [43] around attractive play spaces using the same principles as in previous work [114] (i.e., see chapter 4).

We implement our metric in the three case-study cities using open data and open-source software (i.e., OpenStreetMap and Python). Repositories containing the implementation of our metric and associated data are publicly available to allow for reproducibility[6]. We evaluate its implications in terms of how many children have access to play space, in comparison with baseline metrics, by overlaying their respective outcomes with high-granularity population data (i.e., per 100 meter grid cell) [187]. As baselines, we use metrics that account only for formal playgrounds and ignore potential barriers to children in the city.

[6]The workflow underlying this chapter is fully reproducible and can be found at https://github.com/rflteeuwen/ChildsPlayAccessibility (https://doi.org/10.4121/2e16ff97-dabb-421f-803d-d05fd3204959). The associated datasets are available at https://doi.org/10.4121/0ec69d2a-d966-4dcd-a415-f05d756636d6.

5.3. Co-design outcomes and their implications

Fig. 5.2 and Fig. 5.3 show impressions of the physical set-up and materials presented during the co-design sessions in Utrecht (October 2022) and Milan (November 2022), respectively.

Figure 5.2.: Impression of co-design session 1 with local experts in Utrecht: physical set-up; and base map materials with spatial data on transparent overlay sheet.

5.3.1. Outcomes of session 1 and implications for session 2

Based on the outcomes of session 1, we identified four themes relevant to our child's play metric: (1) There is limited public space suitable for child's play (e.g., sidewalks, playgrounds, and informal play spaces); (2) The interplay between physical and social factors is important (e.g., neighborhood culture and social cohesion, peers to play with); (3) Greenspaces can promote or limit child's play depending on their type and size; and (4) Traffic is the main barrier to unsupervised play.

For the second co-design session, we collected base maps and street-level imagery of a variety of places, including: playgrounds, small and large parks, squares, streets and crossroads, and bridges. We modified our spatial data to highlight large parks and greenspaces, as well as water bodies, as barriers, while pedestrian bridges were considered permissible crossings. Second, we incorporated playgrounds, schoolyards, and small parks as attractive places for play. Third, in the context of accessibility modeling, we chose to ignore sidewalks as play spaces because we see them as an extension of the home environment rather than a destination for play. We also chose to ignore nuanced play space qualities (e.g., challenging equipment, materials), because participants stated that identifying these requires fieldwork, which we note as an interesting direction for future work.

5.3.2. Overall outcomes: four themes

From the spoken, written and drawn contributions in both co-design sessions by built environment (*BE*) and children's health (*CH*) experts, we identified three themes on how the urban environment limits or promotes access to play space by unsupervised children, and a fourth general theme on unsupervised play.

Figure 5.3.: Impression of co-design session 2 with European experts in Milan: physical set-up at each of the six tables; and base map materials with spatial data on transparent overlay sheet.

The joy and fear of getting there. Having a space to play nearby is key for access, yet the *distance threshold* varies with the attractiveness of the play space, season, and neighborhood (“they can easily navigate through this play neighborhood, then a distance of 400 m is much less of an issue ... then, in a neighborhood where that is not possible at all, then maybe 200 meters is already way too far" (BE, the Netherlands”)). *Traffic* remains the main barrier to children’s independent mobility, for example busy roads with fast-driving vehicles, and bus and tram routes (“this one is the most limiting because it’s the crossing between two really important streets” (CH, Slovenia); “there’s the tramway that passes through, so also this is a, another barrier” (BE, Italy)). Participants in the Netherlands mention bicycle through-routes too. *Nature* may form physical or perceived barriers as well, for example large parks and greenspaces, and waterways (“we often see parks as barriers now” (BE, the Netherlands); “like ‘you stay on this side of the water’” (BE, the Netherlands)). While barriers and associated parental safety concerns may restrict choice of destinations or cause detours, pedestrian bridges and tunnels, or formal crossings may allow children to cross them. Lastly, well-designed routes to play spaces can be playable too (“the play starts then, and I think that’s very important, as opposed to the barriers” (BE, Ireland)).

A perfect place for play. The spectrum of playable spaces ranges widely, including the aforementioned routes, grounds specifically equipped for play (i.e., playgrounds), and open spaces (i.e., informal play spaces), all of which may, however, still be boring for play if not designed well. Attractive *playgrounds* have challenging, varied equipment matching different ages and abilities (“risk-free playgrounds, they don’t exist” (CH, the Netherlands)). Participants prefer natural materials and find both sunlight and shade important. *Informal play spaces* include squares and other open spaces where children can be active (“they use it as a skate park” (BE, Slovenia); “they’re running around” (CH, Belgium)), spaces with interesting statues or landmarks ("improving the playfulness of the area a lot" (BE, Slovenia)), spacious sidewalks ("many children they don't even get to a play area at all" (BE, the Netherlands)), and greenspaces. Greenspaces, specifically, have potential, depending on their character, size, and vegetation type: While large parks form a barrier, visited only under supervision, their *outskirts* may be playable without supervision ("only on those fields where you can see them" (BE, the Netherlands)); And *small parks*, well-integrated in the urban fabric, with an open layout and playful vegetation, are destinations for play ("kids love trees" (BE, Ireland)). Yet, not all small greenspaces may be represented in data ("places where I feel the presence of the nature ... it's difficult to map" (BE, Italy)). Lastly, a special type of informal play spaces are those part of children's routines, such as *schoolyards* ("they often also go to this school" (CH, Slovenia)) or churches "in Italy, because they go to church" (BE, Italy).

Social interactions in physical space. Public space is shared by everybody, and thereby social interactions play a key part. Foremost, children love to play with others ("children go to those places where other children, probably they meet also other children" (BE, the Netherlands)), and parents feel more comfortable letting them. A neighborhood "play culture" (BE, the Netherlands) and visible traces of outdoor play, e.g., chalk on sidewalks or play equipment, reinforce play further. Parental perceptions of safety benefit from the confidence their children are seen by others. Social cohesion and control, natural surveillance, other young families, and knowing your neighbors contribute to this ("then it's probably easier to let their children free a little earlier" (BE, the Netherlands)). Occasionally, however, interactions have adverse effects, either with peers ("because 'it's my place, you're not allowed to come here'" (BE, the Netherlands)), or other groups of people ("also drinking at night or like also hanging out there during the day can be also limiting for kids" (BE, Italy); "this conflict with dogs, dog owners, can be quite serious" (BE Slovenia)).

Un-, semi-, or supervised play? Some notes. Participants stress "it is also very good for children if they play outside with other children and not just under supervision of their parents" (BE, the Netherlands). Yet, possibilities for unsupervised play depend on their age (with thresholds mentioned varying widely from 5-7 and 11-12 years old), experience ("because children don't play outside often, they are 'poor in experience'" (BE, the Netherlands)), and the cultural context ("in Finnish society ... get really independent really early" (CH, Finland)). Participants also mention semi-supervised play: supervisors doing their own activities close-by ("then they can play around while you are watching and grabbing a coffee" (CH, Belgium)). Lastly, participants feel in some places, supervision is simply inevitable, such as near water ("still, when I see a child climbing or doing stuff around these fences [on the river banks] ... for me, it's completely unacceptable" (BE, Slovenia)).

5.4. Child's play accessibility metric

Based on co-design outcomes regarding barriers, attractive play spaces, and distances, we built our final child's play accessibility metric, using OpenStreetMap data and Python code.

Traffic and natural barriers to unsupervised children were "well-represented" by our spatial data layers (BE, Italy), "the basis is there" (BE, the Netherlands), while participants did mention some barriers are missing, and noted pedestrian bridges or tunnels and formal crossings can help children cross them safely. We refined our spatial data set such that it does not include barriers that can be crossed via pedestrian infrastructure on *bridges or tunnels*. Furthermore, we maintained *large parks and greenspaces* (> 5 hectares, in line with participants' examples) as barriers, but not their *outskirts*, i.e., within 40 meters of its boundaries ("40 meters is a very important distance for natural surveillance" (BE, Ireland)).

As *play spaces*, we incorporated three categories: *playgrounds*, *schoolyards* (including playgrounds located on school premises), and *small parks* (≤ 5 hectares), that are *not* explicitly tagged in OpenStreetMap as private. However, we should note that all of these may still be boring for play, schoolyards may be closed outside of school hours, and not all greenspaces perceived by people are tagged as such in our data. Incorporating these qualities, as well as other *informal playable spaces*, such as squares and routes, requires further research.

We incorporated a *distance threshold* by using street-network buffer zones around play spaces. We used a 300 meter distance (i.e., a 5-minute walk [158]), in line with UNICEF guidelines on children's independent mobility [21, 210], and the 200-400 meter range mentioned by a built-environment participant.

Our metric identifies the areas from where children can reach a play space within a 300 meter walk via the street network without crossing barriers. Fig. 5.4 shows our metric applied on a part of Utrecht West (Fig. 5.4A), and the case-study areas in Milan (Fig. 5.4B) and Ljubljana (Fig. 5.4C).

5.5. Implications and recommendations

5.5.1. Interpretation of results and their implications

Factors affecting children's unsupervised play mentioned by our participants are largely consistent with the literature, for example: limiting (perception of) traffic (safety) [31, 32, 39, 40, 211, 212]; need for diverse spaces, both formal and informal, suiting ages, genders, and abilities [21, 29, 30, 31, 32]; enabling social cohesion and neighborhood support, and the fear of strangers or other groups of people [30, 31, 32, 40, 213]; influence of temporalities [29]; need for spaces nearby [21, 29, 32]; playing (and conflicts) with peers [29, 30, 31, 32]; quantity, quality, size and noisiness of play spaces [29, 30]; enabling safe routes via protected sidewalks and bike lanes [30]; safety concerns for play near water [38]; and children's love for nature [28, 31].

Our findings indicate surprising differences in how greenspaces can either limit or promote children's play based on their character, size, and type of vegetation, and thus provide a plausible explanation for why parents are more likely to let their children play

5

Figure 5.4.: Child's play accessibility metric: zones with access to playgrounds, schoolyards, or small parks within a 300-meter walk for unsupervised play without crossing barriers. Implemented in three urban areas: A) Utrecht West; B) Milan between central station and city center; C) Ljubljana city center.

in parks, rather than, say, forests and woodlands [40], and how small parks can also be beneficial to mental health [122].

When we compare our child's play metric to two widely used baseline equivalents, namely, Euclidean and network-distance buffer zones [17, 43], we see differences in outcomes, as shown in Fig. 5.5. When Euclidean distance buffer zones are used, it is estimated that 90% of children have access to playgrounds from their home in the visualized part of Utrecht West (Fig. 5.5A), compared to 79% when network-distance buffer zones are used around playgrounds (Fig. 5.5B), 94% when network-distance buffer zones are used around a range of play spaces (Fig. 5.5C), and 81% when barriers are incorporated as well (i.e., our child's play accessibility metric) (Fig. 5.5D).

5.5.2. Strengths and limitations

Participants see potential in our metric to speed up play-space accessibility assessment ("you can just run such a scan over it at once and these kinds of areas pop out where maybe really attention [is needed]" (BE, the Netherlands)) and our spatial data triggered them to reflect on potential equality and equity issues regarding access to play space ("the concentration of playgrounds is uneven, yeah it depends maybe on the people living there or whatever ... young families are coming too, and they need more" (CH, Slovakia)). As such, the computational results of our metric can be used to inform urban planning interventions that promote children's ubiquitous access to play space.

However, there is more that influences children's play than what is represented in the spatial data we used, and thus we cannot include it in our metric. Examples include the nuanced qualities (e.g., presence of peers, challenging equipment, materials) that make a space playful; family structure and raising practices; social cohesion and control, and natural surveillance; variations between cultures, seasons, and times of day; and the distractions of the digital era.

Furthermore, as brought up by our participants as well, maps or street level imagery, as we used as materials in the sessions, do not always reflect the real-world situation: "the knowledge out of the neighborhood is just necessary to really be able to assess it" (BE, the Netherlands); "as a non-local person you cannot know this just from the map" (CH, Slovenia).

Lastly, we focused on three case-study cities. While these are spread over three European countries, care with generalising our results beyond remains necessary. However, we implemented our metric using world-wide open-source data and software, to allow transferability and adaptation to other geographical contexts.

5.5.3. From here on: a call to action

Based on our findings, we urge global organizations such as UNICEF and WHO, as well as local and regional governments, and urban planning and public health associations:

- to adopt our child's play accessibility metric to determine which children's residential environments or schools in the city have access to play space, to identify associated equity issues, and to investigate how our metric can help us understand the effects of play-space access on children's health;

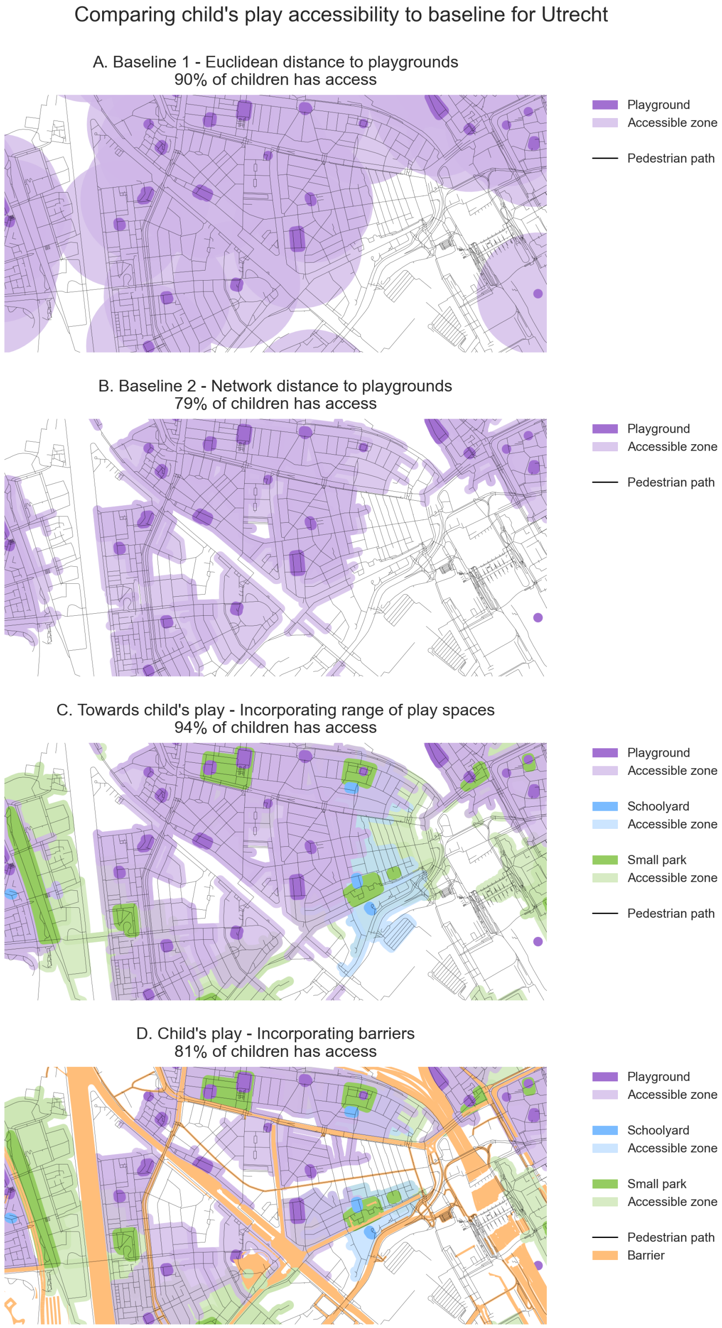

Figure 5.5.: Child's play accessibility metric for the Utrecht area (D) in comparison to: (A) Euclidean distance to playgrounds; (B) network distance to playgrounds; and (C) network distance to a range of play spaces.

- to critically reflect on how to measure accessibility by different population groups in ways that reflect their day-to-day practice, taking into account people's preferences and potential constraints;
- and to conduct field work and collect children's and parents' perspectives on access to play space in cities, so as to complement our scalable metric with local nuances, such as quality of equipment, social interactions, and cultural context.

5.6. Conclusion

In this chapter, we introduced a *child's play* accessibility metric, which measures the ease with which children can reach urban play space without supervision. We developed this metric through an iterative co-design process with 20 European experts on children's health and the built environment and implemented it using open data. Our metric accounts for traffic and natural barriers, that children may not be allowed to cross due to parental safety concerns, and it incorporates a range of play spaces, from equipped playgrounds and schoolyards to small greenspaces. Participants see potential in our metric to support assessments of children's play-space accessibility at scale, and were triggered to consider associated equality and equity issues after seeing our preliminary results. Field work and involving the voices of (young) local citizens remains an essential follow-up to our approach. By understanding all local nuances that limit, enable, or promote access to play, we hope to see cities bustling with healthy, outdoor, unsupervised child's play.

6

Discussion and conclusion

Children's access to urban greenspace is vital for their mental, social, and physical health, and their well-being. Children's access, however, is affected by a multitude of factors, different from the ones that affect the general population. Studies measuring children's access, however, often apply the same methods as they apply to the general population, thereby ignoring key factors that affect children, such as their routine activity-settings, their levels of autonomy, and the barriers they face.

In this dissertation, we designed and evaluated novel methods for measuring children's access to urban greenspace that account for key factors affecting children's access in particular. We conducted four studies to answer our main research question: *How can the factors influencing children's access to urban greenspace be integrated into methods for assessing access across scales and geographical contexts?*

In chapter 2, we synthesized the *factors* affecting children's access to urban greenspace into a conceptual model. We then assessed which factors researchers and practitioners deem important to integrate into measures, which factors accessibility measures implemented in literature account for, and which factors remain unaccounted for. In chapter 3, we delved into measuring greenspace, and studied the *data* sources typically used to represent greenspace in accessibility measures. We collected data on how vegetated people perceive public outdoor spaces to be, compared these perceptions to what is captured in Normalized Difference Vegetation Index and OpenStreetMap data, and studied what spatial characteristics explain notable deviations. In chapter 4, we designed an accessibility measure to account for *en-route* access to greenspace, i.e., by children commuting between home and school. We evaluated how the outcomes of such a measure differ from measuring access from home or school directly, and identified characteristics that make greenspace well-accessible. Lastly, in chapter 5, we co-designed an accessibility measure to account for the parental restrictions, spatial barriers, and greenspace characteristics associated to children's *unsupervised outdoor play*. Again, we evaluated how the outcomes of such a measure differ from a baseline, and explored the value and limitations of our measure.

In this concluding chapter, we answer our research questions, revisit our conceptual model, explore implications of our findings, and discuss what limitations and future work remain.

6.1. Answers to research questions

In this section, we summarize our findings and formulate answers to our four research sub-questions. We conclude by answering our main research question.

RQ1. What factors affect children's access to urban greenspace, and how are these accounted for in accessibility measures?

The factors affecting children's access to urban greenspace are multiple, interrelated, and include not only physical but also social factors [118, 119]. We synthesized these factors, sourced from academic and policy-making literature, and workshops with European researchers and practitioners, into a conceptual model.

Access to greenspace depends on a trade-off between how reachable and how attractive a greenspace is to a child and their companions, and is affected by perceptions of safety. Personal characteristics such as the child's age, gender, level of autonomy, character and condition matter. Children are strongly embedded in a nested social environment [116]. This environment includes the household they live in, and family or guardians that accompany them or set restrictions, and the wider social and support network of people, including peers and friends, and teachers and other caregivers who may set restrictions as well.

Reachability of greenspace concerns the route connecting the child's starting setting to greenspace. Such settings include the home or school, the route between them, the neighborhood, or other routine activity-spaces. Proximity is key and suitable infrastructure is important, depending on the modalities and associated costs. Traffic and other barriers may limit children's access, while the route's surroundings, appeal, and ease of traversal promote access.

Attractiveness depends on how well the characteristics of a greenspace suit the child and their companions, and their motivations to visit the greenspace. Motivations depend on intentions and preferences, concerns, and interests, beliefs and values, while greenspace characteristics may appeal or conflict with these motivations. Both small or informal neighborhood greenspaces and large urban parks are important for children. Attractiveness is affected by vegetation, naturalness, openness, and lay-out. Playfulness is important for the child, as are amenities such as toilets or benches for accompanying adults. Variety of opportunities, a good local climate, and maintenance and management are typically appreciated, while presence of other visitors may result in either pleasant interactions or unwanted conflicts.

A wide range of accessibility measures is implemented in literature, each accounting for a subset of factors, and complementing each other. Our conceptual model serves to assess and illustrate what factors each measure includes, and what remains out of scope. Methods typically focus on measuring reachability from home or school via short routes along suitable infrastructure. They may incorporate greenspaces of a certain scale and size, where, for instance, facilities, amenities, play equipment, vegetation or other natural elements are present. Some measures quantify the trade-off between reachability and attractiveness by assuming short proximity thresholds to small or local greenspaces, opposed to longer routes for large or city-level greenspaces. Several spatial factors may be a *low hanging fruit* to incorporate, including access from third places or while en route, or spatial barriers and traffic. A few measures touch upon a child's (in)dependence and safety, but these factors have not been accounted for directly. Children's characteristics and motivations to visit remain largely unaccounted for as well, while researchers and practitioners deem information on those factors key, emphasizing the need to integrate subjective with objective data [23].

RQ2. How well do greenspace data capture people's perceptions of urban greenspace?

We discovered an overall match between how vegetated people perceive public outdoor spaces in three cities across Europe, presented to them in street-level imagery, and how these places are captured in two large-scale greenspace open data sources: OpenStreetMap, a land use / land cover data set, and Normalized Difference Vegetation Index (NDVI) maps, a satellite-based index.

Places categorized in OpenStreetMap as greenspaces are indeed typically perceived by people as vegetated, while open public spaces such as squares beyond direct vicinity of greenspaces are rarely perceived as vegetated. Pocket-size greenspaces are often perceived vegetated as well [17, 122, 161], as are play spaces, confirming the assumption by Baró *et al.* [47]. While the term *park* is often used interchangeably with greenspace [1, 73], OpenStreetMap areas tagged as park are not always vegetated [165]. OpenStreetMap data serves best to identify perceived greenspaces when selecting OpenStreetMap greenspaces within a short 15-meter radius distance [162].

Between NDVI values and people's perceptions, we observed a moderate significant correlation, contrasting with findings by Kothencz and Blaschke [129] and Leslie *et al.* [128], who focused on parks, or neighborhoods, respectively, but identified no significant correlations. We observed strongest correlations when using NDVI values within a 43-meter radius from the sampled location [162]. We also found that NDVI values can help to identify those OpenStreetMap places that are typically perceived by people as green in many cases [139], while an algorithm based on solely NDVI performs even better.

A variety of spatial characteristics underlie deviations between greenspace data and people's perceptions. Perceived greenspaces do not only have a large amount of vegetation, but also a large variety of vegetation on different height levels, including trees, bushes, grass, and flowers. Places with vegetation on a low level, for instance young trees, or vegetation scattered around in small bits or on private grounds, or located further away, are often not represented as green in data, but are still perceived as such by people. Vegetation may also be located into all directions, and far extending. Other natural features such as water and sand, a good local climate including shade and clean air, and quietness, attractiveness, and safety were also mentioned as reasons explaining why people perceived places as vegetated. Additionally, people mentioned the lack of built-up elements such as buildings, traffic, concrete, parking lots, and associated noise and crowdedness. However, spaces may still be deemed relatively green for their built-up urban context, for example neighborhoods with abundant gardens, natural building materials, or road-side vegetation.

Places *not* perceived vegetated, while captured as such in the data, are characterized by vegetation that is too young, scattered, constrained, dry or barren, or the space being to open and empty. Vegetation may be located far away, or physically inaccessible and therefore disregarded by people, for instance due to elevation difference. The vegetation is then overruled by built-up features such as traffic, infrastructure, buildings, construction work, concrete, and pavements, and an associated bad local climate.

RQ3. How can we assess children's access to greenspace from residential, educational, and commuting settings?

To measure greenspace accessibility from home and school, we used *walkshed* buffer zones [43] identifying areas from where a greenspace can be reached within a 5, 10, and 15-minute walk along the street network, respectively [42, 158, 192, 193, 194]. We used the pedestrian street network, and used greenspaces as captured by OpenStreetMap (i.e., subject of study in RQ2), and home and school locations from local open data sources.

To measure access to commuting children, we adapted the *patronage betweenness* method [70], estimating pedestrian flows within a city, such that it captures patterns of commuting children. We then overlaid these commuting patterns with greenspaces as captured by OpenStreetMap to calculate our *on-the-move* accessibility measure, quantifying how many children traverse each greenspace on a daily basis. Our novel on-the-move accessibility measure opens up possibilities to quantify exposure to greenspace within a city from dynamic settings [2, 171, 200].

We observed several differences in outcomes when measuring access from home, from school, or during commutes, when we implemented our accessibility measures on three case study cities in the Netherlands. Only limited differences in outcomes were observed between measuring access from home and from school, potentially because, in the Netherlands, schools are typically distributed in accordance with populations [196, 197, 198]. We did observe, however, that several small-size greenspaces were relatively well-accessible from schools. Access from commuting settings correlated more strongly with access from home, compared to with access from school. Our results further suggested that expansive greenspaces, with a width exceeding 500 meters, are not often traversed by commuting children. Greenspaces located in between other greenspaces, water bodies, railways, or other land uses were estimated to be traversed by relatively few commuting children, opposed to the number of children having access for purposeful trips from home or from school directly.

RQ4. How to design a greenspace accessibility metric that considers factors associated with children's unsupervised play?

We designed our *child's play* accessibility metric, measuring greenspace accessibility for unsupervised play by working together with experts on children's health and the built environment in an iterative co-design process [71]. This process allowed us to identify key factors, to understand how to recognize them in data, and to explore what the implications of our metric are.

Factors mentioned to affect access for unsupervised play are largely consistent with literature. While many of these factors overlap with the factors affecting children's access to greenspace in general (RQ1), several are stronger or typical to the case of unsupervised play. Close proximity is very important for children without adult supervision [21, 29, 32]. Traffic remains a key barrier [31, 32, 39, 40, 211, 212], but other barriers are mentioned as well. These include public transport infrastructure, and waterways that are perceived as a neighborhood border. Pedestrian bridges and tunnels may allow children to cross these barriers safely. Another type of barrier are large-size greenspaces, where children may get lost and passive surveillance is limited, giving rise to parental safety concerns [40]. Only the outskirts of these greenspace may be accessed without adult supervision. Small-size greenspaces, however, well-integrated in neighborhoods, with an open lay-out, and playful vegetation may serve well for unsupervised play. The child's age and experience affect the level of autonomy they are granted, as well as the presence of other children [29, 30, 31, 32]. Furthermore, the neighborhood culture, social cohesion, and social control may encourage parents to let their children play outdoors without supervision [30, 31, 32, 40, 213]. However, in some places, unsupervised play is simply deemed too dangerous, for example near water [38].

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For recognizing these factors in data, we experienced great advantage in our co-design approach. We used urban environments in three cities across Europe as case studies. We asked our expert participants not only what factors matter, but also to exemplify how they occur in urban environments, to annotate street-level imagery or maps with their local knowledge, and to contest the barriers or play spaces that we identified or missed in our data so far. However, together with our co-design participants, we concluded that geospatial data (e.g., maps, or georeferenced street-level imagery) are not always representative of the real-world situation (i.e., in line with the numerous deviations identified in RQ2).

Our final *child's play* accessibility metric identifies areas from where children can reach (green) play space without adult supervision, specifically within a 300 meter walk [21, 210] along the street network without crossing any barriers. We use walkshed buffer zones as a basis (i.e., as also used to measure access from home and from school in RQ3) [43]. Into the walkshed measure, we incorporated barriers restricting children's independent mobility given parental safety concerns: roads for large amounts or high speed traffic, public transport infrastructure, waterways, and greenspaces larger than 5 hectares (excluding their outskirts where natural surveillance may still be possible [162]). We incorporated small-size greenspaces, playgrounds and schoolyards as places suitable for unsupervised play. We used OpenStreetMap as input data (i.e., subject of study in RQ2) to allow transferability across European cities.

When comparing the outcomes of our metric to a baseline, we observed that incorporating small-size greenspaces as play spaces results in a higher number of children estimated to have access to play space, while incorporating barriers lowers this number. As a result, the number of children estimated to have access to space for unsupervised play remains roughly similar, but the areas where these children reside differ. Participants saw potential in our metric to speed up large-scale assessment of children's urban environments, and to inform spatial equity studies, when complemented with field work and community knowledge to capture local nuances, such as spatial quality, social interactions, and cultural context.

How can the factors influencing children's access to urban greenspace be integrated into methods for assessing access across scales and geographical contexts?

To incorporate factors affecting children's access to urban greenspaces in methods for measuring access, it is key to know what these factors are, which are already incorporated in methods, and what remains to be done. We sourced factors from literature and workshops with researchers and practitioners and synthesized them into a conceptual model, providing a comprehensive visual overview, on which we could map existing methods. Then, we identified the *common denominators*, i.e., factors that hold across multiple geographical and cultural areas within Europe. We then linked these common denominators to spatial indicators that can be recognized in geospatial data that is typically available across cities, regions, and countries. Examples include traffic barriers, greenspace size categories, and distance thresholds.

We found great value in following participatory approaches throughout several stages of this process [71, 214]. Crowdsourced human perceptions informed us which spaces should be regarded as greenspaces in our measures, and to understand the limitations of the input data our measures rely on. Co-design helped us to identify how factors can be recognized in geospatial data, for example traffic and other barriers, and different types of greenspaces. Co-design also allowed us to iterate on our measures several times, testing if the way in which we incorporated these factors indeed better reflected reality, or whether unforeseen issues arose. In addition to participatory approaches, we also found great value in methods already deployed in adjacent domains. Specifically, the betweenness measure typically used to study accessibility of retail locations [70] also proved useful to measure children's access to urban greenspace.

However, not all factors, and not all their aspects, seem fit to be incorporated into methods that can serve across scales and geographical contexts. Examples include interactions, conflicts, and social norms that are typically not captured in geospatial data, personal conditions or interests, beliefs, and values that are challenging to capture at scale, and factors such as playfulness, concerning more aspects than solely the presence of play equipment that is typically captured in geospatial data. Future research may open up new possibilities to account for these factors. Nevertheless, complementing methods for assessing access across scales and geographical contexts with field work and knowledge from local populations and experts remains necessary to capture all the nuances affecting children's access to urban greenspace.

6.2. Revisiting the conceptual model, and reflecting on our findings

While answering our first research question in chapter 2, we contributed a conceptual model of factors affecting children's access to greenspace according to academic and policy-making literature, and researchers and practitioners that participated in workshops that we organized. With presenting this model, an ongoing process of rethinking and revisiting started [67].

Throughout this dissertation, we identified characteristics that make public open space being perceived as *greenspace* (chapter 3), characteristics of greenspaces that are accessible to children *en route* (chapter 4), and characteristics of greenspaces that are accessible for children's *unsupervised outdoor play* (chapter 5). In the following subsections, we revisit our initial conceptual model with the knowledge that we generated, and reflect on our findings by means of the conceptual model. First, we make *additions* to the factors included in our model, and we add novel insights to descriptions of existing factors. Second, we reflect on several *reinforcements* between factors, i.e., factors that strengthen each other, by zooming in on factors of interest and detailing the relationships between them. Third, we reflect on several identified *tensions* between factors, i.e., factors that conflict with each other, or that manifest in different ways depending on the context, by rearranging an excerpt of the conceptual model to illustrate these tensions.

Throughout this section, we report in-text quotes from crowdsourcing participants (chapter 3, together with a *Q-i* reference to appendix B) and from built environment (*BE*) and children's health (*CH*) experts (chapter 5), in line with the corresponding chapters.

6.2.1. Additions

Throughout this dissertation, we identified several factors that were not yet included in the conceptual model as first introduced in chapter 2, and we gained novel insights into the aspects of factors that were already present. In figure 6.1, we incorporate these factors into the model and highlight them, and in appendix C, we incorporate a version of the final revisited conceptual model without these highlights. In the following paragraphs, we explain what these added factors or aspects entail.

Related to the child and its companionship we identified two additional factors, both articulated by built environment experts (BE) from the Netherlands during the workshops described in chapter 5. First, we added *experience* to the child's characteristics, capturing the (lack of) experience that the child gained, for instance, in playing outdoors: "because children don't play outside often, they are 'poor in experience'". Second,

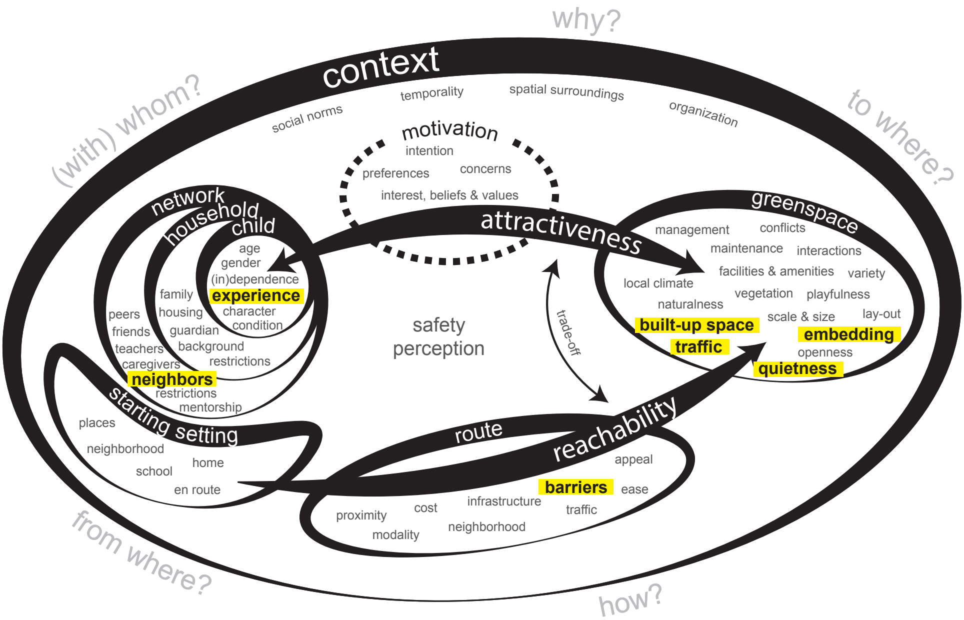

Figure 6.1.: Revisited conceptual model highlighting additional factors *experience* and *neighbors* (in the child's (network) cluster), *built-up space*, *traffic*, *embedding* and *quietness* (greenspace cluster), as well as the *barriers* factor into which new insights were gained (route cluster).

we added *neighbors* as part of the child's social and support network. This factor encompasses other young families living in the neighborhood, and how well neighbors know each other, because "then it's probably easier to let their children free a little earlier". Additionally, an overall play culture, social cohesion, and control in the neighborhood, and associated presence of natural surveillance — all connecting again to perceptions of safety — contributes to children's unsupervised outdoor play.

As to greenspace characteristics we identified four additional factors, voiced by crowdsourcing participants in chapter 3 as a characteristics of places they perceive as green, even if large-scale data does not identify them as such. First, *quietness* was mentioned: "the park looks so calming" (Q-33). Second, and related to quietness, is the presence, or rather absence, of *traffic* in vicinity to the greenspace: "a lot of green and quite far from traffic" (Q-37). Third, limiting perceptions of greenness and relating to traffic, is the presence of *built-up space* in general. That is, a place may have "lots of nice shrubs" but still be "very overpowered by all the buildings" (Q-34), or there may be "a lot of building work and concrete though" (Q-17). Fourth, following from all three empirical chapters, and related to many other factors, is the greenspace's *embedding* in the urban fabric. Embedding encompasses how well-connected the greenspace is to its surroundings, for instance, homes, schools, and other places, along the road network. Embedding relates to close proximity, and thus good accessibility, as well as to so-called *eyes on the street*, i.e., passive surveillance from people in its direct surroundings, contributing to perceptions of safety: "only on those fields where you can see them" (chapter 5, BE, the Netherlands). However, embedding may also relate to the aforementioned — and limiting — factors traffic and built-up space. That is, while close proximity to surrounding buildings may support access and perceptions of safety, it may also reduce the greenness of a place. We will further unpack the, sometimes complex, relationships between embedding and other factors in the upcoming sections 6.2.2 and 6.2.3.

Lastly, we elaborate on barriers along the route — a factor already present in the original conceptual model, but into which we gained new insights. Most strikingly, we identified that *greenspaces* may also be a barrier to children's access to greenspace, in specific conditions, both for access *en route* (chapter 4) and for access for *unsupervised play* (chapter 5). First, when a greenspace is wider than 500 meters, its center is unlikely to be traversed, given that the distance between surrounding houses and schools becomes too large, thereby forming a barrier in itself. Similarly, when a greenspace is located in between other greenspaces, the same issue may occur. Additionally, large-size greenspaces (i.e., 5 hectares and larger) are typically off-limits for unsupervised children, thereby serving as a barrier as well: "we often see parks as barriers now" (chapter 5, BE, the Netherlands). Second, also other natural environments, such as bluespaces (e.g., canals, rivers) may form a barrier. Greenspaces neighboring bluespaces may, again, face the same issue for access en route as greenspaces neighboring each other. Furthermore, water bodies can serve as a perceived barrier denoting the border of the neighborhood perceived as within reach by the parent, "like 'you stay on this side of the water'" (chapter 5, BE, the Netherlands). Third, extensive infrastructure, such as major roads and railways, are an important barrier in the urban infrastructure and fabric, as already elaborated on in the initial conceptual model presented in chapter 2. Infrastructure as a barrier also came forward as limiting access en route in chapter 4, and was stressed by experts in chapter 5: "this one is the most limiting because it's the crossing between two really important streets" (chapter 5, CH, Slovenia).

6.2.2. Reinforcements

In each of our three empirical chapters, i.e., chapters 3 to 5, we put one factor of the conceptual model center stage, specifically perceptions of *vegetation*, access *en route*, and access for *unsupervised play*. In the following paragraphs, we reflect on our findings related to each of these factors, and how they are reinforced by — or limited or otherwise related to — other factors, which we visually summarize in figures 6.2 to 6.4.

Perceptions of vegetation (subject of study in chapter 3) are reinforced by presence of natural elements other than vegetation (e.g., water, sand, wooden materials), a good local climate (e.g., clean air, shade), quietness, large greenspace size, and variety and lay-out of vegetation (i.e., multiple species, in various directions and on multiple height levels). Conversely, proximity to built-up space (e.g., buildings, concrete and pavements, parking space) and traffic may limit perceptions of vegetation, as does too much open space within the greenspace. A key factor indirectly related to perceptions of vegetation is embedding. Greenspaces that are embedded in their (built-up) urban surroundings, often small in size, are perceived as less vegetated than spaces that are more remotely located. In figure 6.2, we present an adaptation of the greenspace cluster of our conceptual model depicting these relationships among greenspace characteristics that define how vegetated it is perceived.

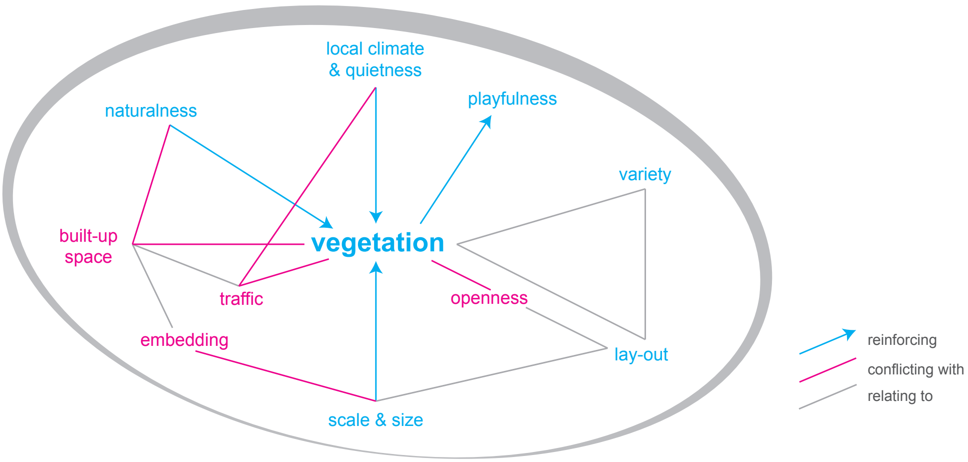

Figure 6.2.: Modified excerpt from the conceptual model of the *greenspace cluster*, illustrating how ***vegetation*** is reinforced by naturalness, large size, local climate and quietness, in turn reinforcing playfulness, while conflicting with openness, traffic, and (embedding in) built-up surroundings.

Access en route (studied in chapter 4) is by definition related to two other starting settings, namely homes and schools, with school locations in turn potentially related to the child's age category. Proximity along the existing infrastructure (i.e., a short route) and embedding (i.e., of the greenspace in its surroundings) contribute to access en route, by improving connectivity. Embedding, in turn, is reinforced by many other factors, including locations of homes, schools, and other routine places (e.g., cafes, shops), the surrounding neighborhood, the scale, size, and lay-out (e.g., shape) of the greenspace, and connecting infrastructure. Infrastructure, however, can also take the shape of a barrier to en-route access (e.g., railway infrastructure, highways), while natural elements (e.g., canals, rivers) may may form a barrier as well, as elaborated on in section 6.2.1. Another factor limiting access en route is the size of the greenspace. Expansive, wide greenspaces are typically not traversed within an 800 meter commute, as opposed to smaller, and thereby more embedded, or more elongated greenspaces that do host traverse movement. Appealing routes may further affect the routes children take and thereby their en-route access, while access en route in turn positively contributes to the ease of reaching greenspace, by allowing children to access greenspace without the burden of undertaking a separate trip. In figure 6.3, we present an excerpt of our conceptual model, depicting relevant factors in the starting-setting, child, route, and greenspace cluster, on top of which we add these relationships.

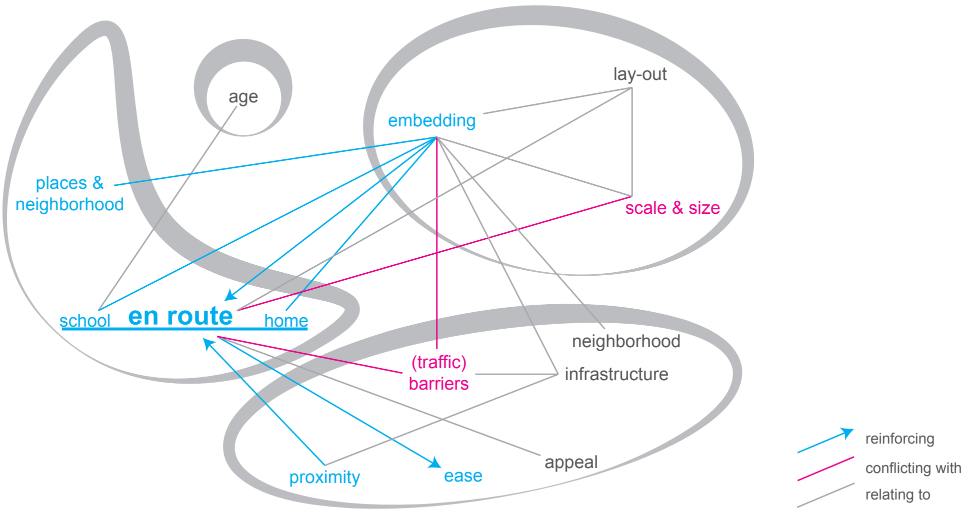

Figure 6.3.: Modified excerpt from the conceptual model of several clusters, illustrating how ***access en route*** is reinforced by proximity and embedding (while embedding is in turn affected by several other factors), while access en route conflicts with large scale greenspaces and (traffic) barriers.

Access for unsupervised play (chapter 5) relates to four core factors: *independence* granted by adults, versus the *restrictions* they impose given *safety perceptions*, and the *playfulness* of the greenspace. In relation to these core factors, many other factors, related to the child and their companions, the starting settings, the route, and the greenspace, play a role. We unpack this complexity of interrelated factors cluster by cluster, and visually summarize it in figure 6.4.

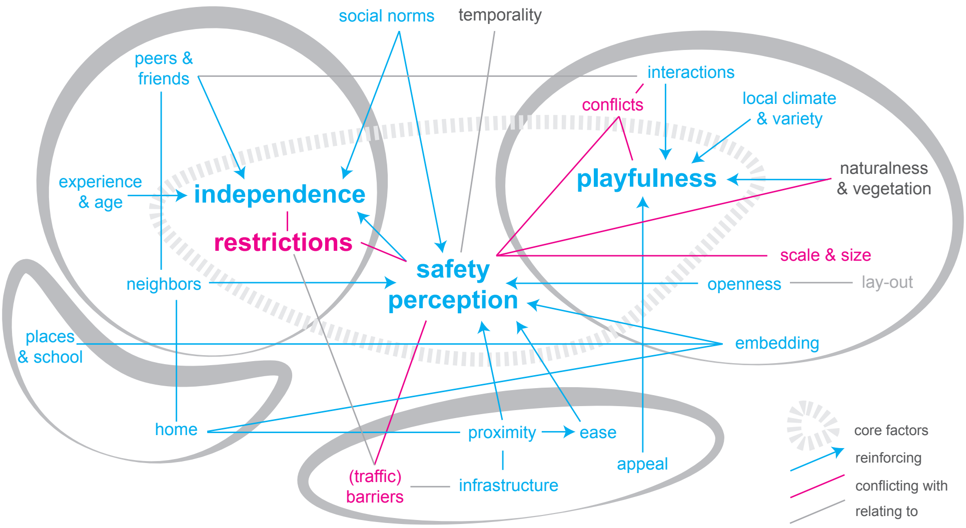

Figure 6.4.: Modified excerpt from the conceptual model of several clusters, illustrating how ***access for unsupervised play*** relates to four core factors — independence, restrictions, safety perception, and playfulness — the factors that reinforce them, and their conflicts with conflicts with (traffic) barriers, large size greenspace, and conflicts with other user groups.

First, the *child's* independence, primarily in terms of autonomy, is reinforced by their experience, coming with age, and by being in proximity to peers and friends to interact with. These peers and friends may be living in neighboring homes, while neighbors of adult age can indirectly promote autonomy through supporting parental perceptions of safety (e.g., through passive surveillance, and neighborhood social safety).

Locations of *starting settings* that people routinely spend time at (e.g., homes, schools, and other places such as shops and cafes) may support embedding, in turn contributing to perceptions of safety. Additionally, concerning the *route*, proximity to the home via good infrastructure contributes to perceptions of safety, both directly and indirectly through the ease of reaching a greenspace. Again, however, infrastructure may also form a barrier when it hosts high volumes of traffic, traffic at high speed, trams, or busses, while canals and large greenspaces may form barriers as well. Adults may set restrictions on crossing these barriers, given limited perceptions of safety.

Regarding the *greenspace*, being well-embedded promotes perceptions of safety, as previously mentioned, while also openness, related to the greenspace lay-out, promotes safety perceptions. Large-size, city-scale greenspaces, however, are typically deemed unsuitable for unsupervised play, as well as natural or densely vegetated greenspaces. Such nature and vegetation, however, can contribute to playfulness, as children value vegetation and water for play. Also a good local climate (e.g., shade, no noise), and variety of vegetation and play equipment contribute to playfulness. Interactions with others, including peers and friends with whom children may undertake the trip, may also contribute to playfulness, while conflicts with other user groups may occur as well, limiting both playfulness and perceptions of safety.

Lastly, social norms can further contribute to independence and perceptions of safety, while temporalities such as the time of day affect safety perception as well.

6.2.3. Tensions

We observe several tensions between factors. That is, factors that manifest in different ways under different circumstances, positively affecting one aspect of children's access to urban greenspace, while negatively affecting another. In figure 6.5, we map these findings on the factor-clusters of the conceptual model, and present the factors and their contradicting effects as a seesaw: Several characteristics of greenspaces (depicted in the seesaw base) positively affect perceptions of greenness (upper right end), while negatively affecting children's access to them (lower left end).

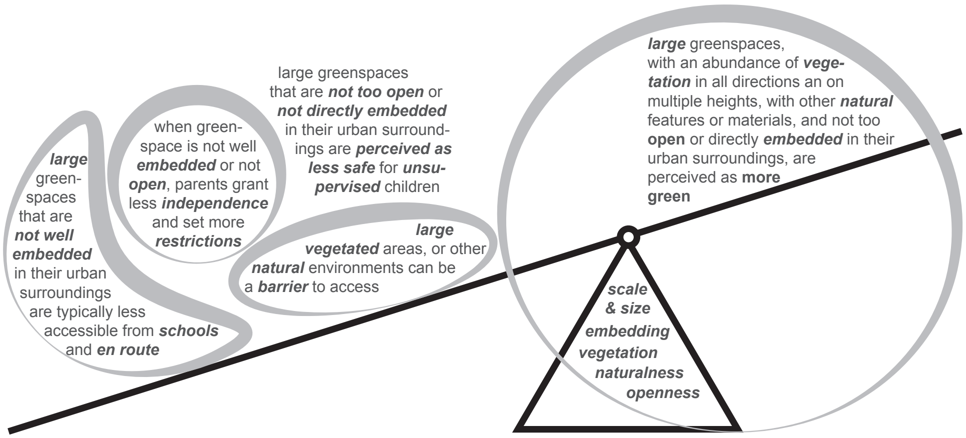

Figure 6.5.: Modified excerpt from the conceptual model depicting how the scale & size, embedding, vegetation, naturalness, and openness within a greenspace (triangular base) can *positively* affect perceptions of greenspace (right end), while also forming barriers to access, *negatively* affecting access for unsupervised play, access from schools and en route, and perceptions of safety (left end).

Large-size, city-scale greenspaces are typically perceived as more green than small and local greenspaces. With their size, they offer retreat from built-up space such as buildings, concrete, and parking space, as well as from traffic, and the noises that traffic causes. Furthermore, they allow for vegetation that is far-extending in all directions. Yet, we found that especially **small-size, local greenspaces that are embedded** in their urban surroundings are well-accessible by children. First, small-size greenspaces scored relatively high on access from schools rather than from homes, potentially due to how these small-size greenspaces are distributed over the city in places that co-occur relatively often with the presence of educational facilities, as opposed to large-size greenspaces. Second, we observed similar patterns for access by children en route between home and school. Expansive greenspaces, with a width exceeding approximately 500 meters, are difficult to traverse within a 15-minute (i.e., 800-meter) commute. Only their well-connected outskirts may be traversed by children who make a slight detour on their way to school, whereas central areas of such large greenspaces are likely to be visited during purposeful trips only. Third, we observed that also for children's unsupervised play, large-size greenspaces are typically a barrier. Only their outskirts, approximately 40 meters from the edges, may be visited by children without adult supervision. Contrary, local, small-size greenspaces — often also open and well-embedded in their urban surroundings — may serve as attractive destinations for unsupervised play.

Vegetation and other natural elements promote how green a space is perceived. This includes vegetation density, variety, lushness, and configuration (i.e., on multiple levels, surrounding the place to all sides), as well as presence of water bodies in the greenspace (e.g., canals, ponds, rivers), and natural materials such as sand and wood. Both vegetation and water bodies, however, **can also form barriers** to children's access. Practically, such barriers can affect how the *infrastructure* allows children to reach the greenspace. For instance, a canal may only be crossed by the infrastructure via a few bridges. Additionally, greenspaces located neighboring water or other greenspaces are typically less accessible to children being *en route*, for similar reasons as large greenspaces are less accessible en route. That is, houses and schools will be located further away, not allowing traversal within an 800 meter commute. Furthermore, both greenspaces (depending on their size) and water bodies (e.g., canals) can serve as a barrier to children's *independent* mobility, and places near water bodies, especially in case of steep banks, are often regarded unsuitable for *unsupervised play* for safety reasons: "for me, it's completely unacceptable" (chapter 5, BE, Slovenia).

The more open a greenspace is the less green it is perceived, because it then has "too few trees and bushes for the size of the open space" (chapter 3, Q-16). Openness, however, **contributes to children's (unsupervised) outdoor play**. First, open space within the greenspace allows active play, for instance "running around" (chapter 5, CH, Belgium). Second, openness implies good visibility, allowing for (passive) surveillance and associated perceptions of safety, either by accompanying adults or by others living or performing activities in the greenspace's surroundings, promoting play "only on those fields where you can see them" (chapter 5, BE, the Netherlands).

With these tensions, our findings suggest that: (1) there may be a balance between how green (i.e., large, vegetated, and natural) a space is and how accessible it is to children (i.e., small, open, and embedded); (2) designing greenspaces may require great care, considering specifically children's access en route and access for unsupervised play, to ensure routine access and avoid adverse effects; and (3) urban environments should provide a variety of greenspaces to suit different use cases and user groups, and to fulfill different roles in the urban or regional green infrastructure.

6.3. Implications

For developing novel accessibility measures. As already stated in chapter 2, no *one-size-fits-all* solution for measuring (children's) access to urban greenspace exists. With this dissertation, we contributed two novel measures for measuring children's access to urban greenspace, each tailored to a specific use case, specifically access en route and access for unsupervised play. These measures should be seen as two complementary additions to the arsenal of measures available in the literature, rather than a single definitive solution. We do, however, demonstrate that tailoring measures to demographic groups (e.g., children) or use cases (e.g., unsupervised play) is possible, and affects the accessibility opportunities these groups are deemed to have.

We accompany our novel measures with their position in relation to a conceptual model of factors. With this conceptual model, we aim to capture the multitude of factors affecting children's access in reality, according to both academia and practice. Throughout this dissertation, we illustrated how such a model can support communication of the limitations that each measure comes with. We argued how accessibility measures should acknowledge the multitude of relevant factors, incorporate them where possible, and be transparent about which remain unaccounted for. We also encourage other researchers to do the same, both when designing novel measures and when implementing existing measures.

Additionally, we let our novel measures be accompanied by open-source Python code, and made not only the scientific publications but also the resulting data openly available. Thereby, we empower those who want to replicate our research, to implement our measures, to adapt them to other groups, use cases, or geographical contexts, or to question our measures with the information necessary to do so.

For (and with) health research. This dissertation was motivated by how access to greenspace is vital for children's health, well-being, and development. The work has been conducted within the context of the Horizon 2020 project named "Equal-Life: Early environmental quality and life-course mental health effects", investigating the effect of a multitude of interrelated environmental factors on children's health and well-being [75]. Working in this context taught us a lot about the complexity of studying health indicators, mediators, moderators, and outcomes, as well as of the challenges of informing policy-making practice through research insights and applying them in practice.

With our research, we also aim to demonstrate the complexity of measuring a single health indicator, such as *access to greenspace*. No all-encompassing solution exists, and choices on what to account for should be made consciously. In chapter 2, we studied 20 existing measures and in chapters 4 and 5 we contributed two novel measures. We hope that our description of and pointers to these measures inspires and assists health researchers to make conscious choices of what (set of) measure(s) suits their subject of study best, or to formulate specific requirements for measures yet to be developed, either to collaborators within their team or to academia in general.

Furthermore, our collaboration with health researchers and practitioners within the Horizon 2020 Equal-Life project taught us how to speak a common language with and ask the right questions to our collaborators from the health domain, allowing us to understand our collaborators' needs as to what measures are promising to develop, and to incorporate their domain knowledge into our measures. We encourage all researchers, especially when working on multi- or interdisciplinary studies, to consider participatory research methods [214] in their future study design processes.

For communicating about children's access to urban greenspace. As a thread throughout this dissertation, we used our conceptual model of factors affecting children's access to urban greenspace. We used this model to present the factors at hand in chapter 2, to position our three empirical studies in chapters 3 to 5, and to synthesize what we learned about children's access to urban greenspace in section 6.2. Doing so, we aimed to *lead by example* as to how our conceptual model can be used for a variety of communication purposes.

While developing it, we presented a prototype of our conceptual model to a wider audience of researchers and practitioners on healthy urban environments at the 2023 WHO European Healthy Cities Annual Business Meeting and Technical Conference in Utrecht, the Netherlands. We experienced that our model sparked a variety of questions on the factors and on their health outcomes, and prompted conversation and exchange of knowledge among the audience. Specifically, attendees commented on how they value exchange of knowledge between academia and practice, as well as with politicians, city officers, and local communities, and the value of de-jargonizing communications and speaking a common language. Furthermore, attendees discussed the importance of ensuring access to greenspace among the most vulnerable groups of children, and the value of exploring accessibility effects on particular behavioral outcomes such as physical activity. Attendees also posed questions and exchanged knowledge on how to measure particular aspects of children's access to urban greenspace, including what distances are appropriate to use for specific cases, and how quality or attractiveness of greenspaces can be measured.

We hope to set an example on the value of an attractive, clean, and intuitive imagery to convey the complexity of accessibility and its measurement to a variety of people in a transparent and effective manner.

For developing green and healthy cities. As is the case for accessibility measures, our findings indicate no *one-size-fits-all* solution for *greenspaces* exists either. Instead, we found personal characteristics, and variety within a greenspace, to be a key factors affecting children's access to urban greenspace in chapter 2, we found that different factors affect access en route and access for unsupervised play in section 6.2.2, and we identified tensions between factors making a space green, and factors making a space accessible to children in section 6.2.3.

Our conceptual model shows the various angles that one could take in improving children's access to urban greenspace. The possibilities are many. For instance, one could focus on improving access by reducing spatial (traffic) barriers, by ensuring short travel distances, by providing open space within greenspace, by encouraging schools to undertake trips to greenspace, by trying to change neighborhood culture and social norms, or — probably most effective — a combination thereof.

Practically, we found that, for children, distances longer than 300 meters can already be too far when navigating urban environments without adult supervision, and that greenspaces wider than 500 meters are typically not traversed on a day to day basis. Upon seeing the outcomes of our measures, urban planning and children's health practitioners who also participated in the workshops described in chapter 2 stated to find them "useful maps ... underscoring once more what we are working on" (P2.2) while they emphasized that "the data needs to be in order" (P2.4). Regarding the on-the-move measure, they stated "we really liked that it's a dynamic map" (P1.16) and that "our people at [the department of] mobility would be happy with this ... so that helps as an analysis tool for sure" (P2.2). They also mentioned to be working on catchment areas around play spaces themselves, while our child's play metric "is one step further where you just can analyse actual barriers and walking distances so that seems very good to me" (P2.2).

Lastly, throughout this dissertation, we emphasized the particular factors affecting access among children. We believe that comparable yet different factors may exist for other groups of people. When developing *public* greenspaces, all demographic groups deserve attention. Taking it even broader, greenspaces contribute to human health, as well as to healthy ecosystems and environments, through other mechanisms than access. Examples include heat, noise, and air pollution mitigation, water management, biodiversity, and carbon dioxide absorption. That is, for developing green and healthy cities, many considerations could and should be made. In some cases, the characteristics of urban environments associated to these mechanisms may reinforce each other, while conflicts may exist as well, and all are important in their own way. In this dissertation, we unpacked only one of the many ways in which greenspaces contribute to healthy cities.

6.4. Limitations

As any research, this dissertation comes with several limitations.

Computational methods. This research focused on contributing computational methods for measuring access, building upon large-scale open data available world-wide. A major strength or such measures is that they allow to study how equal and equitable greenspace accessibility is distributed within and between cities [46, 47], to study epidemiological effects of access to greenspace [48], to identify locations where interventions are needed the most, and to benchmark progress over time. Using open data further promotes replicability and transferability of our methods. In chapter 3, however, we found notable deviations between people's perceptions and large-scale greenspace data, and noted that studying other quantitative data such as the Green View Index [78, 132] or computer-detected vegetation in street-level imagery [140, 141] remain unstudied. Furthermore, in chapter 5, participants exemplified how maps or street level imagery, serving as materials during the workshop sessions, do not always reflect the local situation.

Children's voices and local knowledge. Throughout this dissertation, we highlighted on several occasions how important it is to complement our computational methods with the knowledge of local communities and the children themselves. During this research, however, we did *not* work with children or their parents directly. Instead, we worked with practitioners who work with children, for instance by performing field work and interviews, and studied literature that describes interviews, questionnaires, and observations: one step removed from the child. This choice was motivated by the aim to design methods that hold across geographical contexts. Working with children and parents directly would have allowed us to gain thorough understanding on the perspectives of a limited group of people from a particular geographical context. However, by synthesizing people's perspectives as described in literature and as shared by practitioners from a variety of local contexts allowed us to identify the common denominators *across* contexts. Specifically, in chapter 2, we synthesized literature that described 45 cities spread over five continents, in chapters 2 and 5 we synthesized experiences from researchers and practitioners working in 11 European countries, and in chapter 3 we analyzed perceptions from participants residing in 21 European countries.

In chapter 2, however, we referred to a greenspace planning framework stressing the need to plan greenspaces not only for but also *with* children [72] and discussed how our findings call for integration of subjective and objective data, in line with findings by Zhang, Tan, and Richards [23]. We further concluded that many factors relating the the child, and their household and network, and their motivations to visit greenspace, remain unaccounted for in generalizable accessibility measures in literature to date, while these characteristics and motivations are important for children's health and built environment practitioners (chapter 2). That is, they "need the children for this" (P1.12), and this challenge remains. As we did in chapter 5, we again call for organizations and researchers, either focusing on global, regional, or local scales, to complement computational methods, designed for application across geographical contexts, with field work to collect perspectives from children and their parents on how they perceive access to greenspace in their local context.

6

The European context. We conducted this research within the European geographical context, a choice rooted in the European H2020 Equal-Life project this research was funded by. We focused on European case study cities, based our conceptual model largely on literature stemming from study contexts in the Global North (chapter 2), collected perceptions from crowd-workers residing in Europe (chapter 3), and incorporated knowledge from European children's health and built environment experts into our methods (chapters 2 and 5). Beyond the European context, however, differences may occur in data completeness and accuracy of land use classes [150, 156], ecosystems [168], and climate, culture and associated greenspace-health associations [3]. Furthermore, although we chose our case study cities such that they are spread over European regions [154], and associated variation in vegetation zones and coverage [155, 156], generalizing our findings towards other European cities requires care. For instance, we did identify limited variation between case study cities in how well data sources capture people's perceptions of greenspace (chapter 3), as well as differences between cultures in various European countries in the factors affecting children's access to greenspace (chapter 5). Although we implemented our methods such that they build upon open data, most of which publicly available world-wide, and made the associated Python code publicly available for transferability, generalizing our methods towards other cities within and beyond the European context may require adaptations.

More than access. While accessibility may be a major driver of greenspace usage and associated health outcomes [10, 22, 23, 24, 25], it is not the only one. On the one hand, children and parents who have access to greenspace may still not make use of it in reality. On the other hand, greenspaces can also contribute to healthy urban environments through limiting air pollution [3, 5], noise [3, 6], and heat [3], and by simply being visible in people's direct residential surroundings [23]. Furthermore, some factors affecting children's access to urban greenspace still remain unaccounted for, including management, maintenance and conflicts within greenspaces, costs associated to reaching the greenspace, other places from where children might access greenspace (i.e., so-called third places [215]), and numerous of the characteristics of the child, their household, network, and their motivations to visit greenspace, as elaborated on before.

6.5. Future work

In this section, we highlight three promising directions for future work, that extend beyond the scope of this dissertation.

From access to outcomes. In this dissertation, we studied existing methods and contributed novel methods for measuring children's access to urban greenspace. While access is not the only determinant of usage, or exposure, it is an important one [10, 22, 23, 24, 25]. We aimed to design our methods such that they incorporate the factors affecting children's access that remained unaccounted for in the past, as to better capture children's lived experiences. In analogy with the questions answered in chapter 3, one could imagine to pose questions like: *How well do accessibility measures capture children's reported, or observed, behavior in using greenspace? And what spatial characteristics underlie deviations that remain?* Reported behavior could stem from questionnaires, such as the large-scale cohort and school study data sets used in the H2020 Equal-Life project this research is conducted within [75], including behavioral outcomes on outdoor activities, frequency and locations of visiting greenspace, and autonomy in going outdoors. Observed behavior could stem from field observations, for instance how many children play outdoors where, when, and for how long [22, 83, 91, 92, 216]. Alternatively, one could perform observations on a larger scale using Global Positioning System (GPS) measurements. GPS data are deemed to have great potential in studying health outcomes [17], and various studies already use GPS to study behavior among children [13, 36], propose to do so [217], or use GPS to study behavior among the general population [20, 199, 218].

Towards measuring public open space. Public open space is, by definition, meant to be shared among all people in society. Public open space includes public greenspaces, but also streets, squares and common grounds, as well as indoor spaces such as libraries, governmental buildings, and transportation hubs, albeit under certain restrictions. In this dissertation, we focused on one group of people — children — and one type of outdoor public open space — those characterized by vegetation, i.e., greenspaces. Our methods could be adapted, and findings revisited, with other types of places or demographic groups as a starting point, each with their own preferences and challenges, for instance women [22, 125, 219], older persons [3, 28, 63, 220, 221, 222], and persons with disabilities [219], as emphasized in the goals by the United Nations [25], as well as adolescents [28, 170, 223, 224, 225], and people from disadvantaged social groups [22, 72, 87, 99]. Similarly, we see potential in exploring access by combinations of groups, for instance children and adults together, resulting in intergenerational access. Additionally, one could adapt and replicate our work for other types of (indoor) public spaces, or in other climates and continents.

Furthermore, also within the scope of measuring children's access to urban greenspace, several factors still remain unaccounted for. In chapter 2, we identified that *low hanging fruit* may be to account for spatial factors that remain unaccounted for, for example third places [215] from which children may access greenspace, such as shops or cafes, and the greenspace local climate, including noise, air quality, shade, and heat. Additionally, in chapter 5, participants brought forward how spacious sidewalks are important public open space for children's outdoor activities — raising the question if child-friendly sidewalks can be identified at scale from sidewalk land use or street-level imagery data [61, 130, 184, 226].

(Mapping) children's voices. When discussing the limitations of this study, we reflected on the value of integrating subjective data with objective data [23], and the value of assessing greenspace accessibility and planning greenspaces *with* children [72]. We see potential in studying how to complement objective, computational, or data-driven accessibility methods, that can be applied across scales and geographical contexts, with subjective, human-centered methods to collect contextualized data from children and their parents, in urban planning processes. For instance, one could (1) apply computational methods to identify locations for interventions, and then (2) collect people's local knowledge on these locations to understand the problem and identify potential solutions. Alternatively, one could (1) first identify locations where citizens or city-makers deem intervention necessary, and (2) consecutively harness computational methods to identify locations with similar characteristics, where the need for intervention may be equally necessary but not yet raised. Yet another approach could be to follow an iterative approach, where objective and subjective data collection processes alternate.

To collect the perspectives of *children*, beyond traditional approaches such as conducting questionnaires and interviews, we see several other promising research methods. Examples include conducting *walking interviews* in which children share thoughts on their environment prompted by walking through it [227], using *photovoice* to empower children to share key issues in their lives by taking photos and discussing them with peers or researchers [79, 228], or doing an *internship as a child*, experiencing the everyday life of children through their own eyes, learning from them in a peer to peer setting [229, 230]. Such perspectives could subsequently be translated into a visual representation of space, to ground them in their geographical context. For instance, one could create *deep maps* to link geographical and cultural representations of a place, aiming to capture meanings attributed to space by people, including experiences and emotions, while acknowledging multiple agents and perspectives [231, 232], or one could create an *an image of the city* — a common understanding of the urban environment as held by citizens in their mental maps [233].

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A

Materials, measures and factors

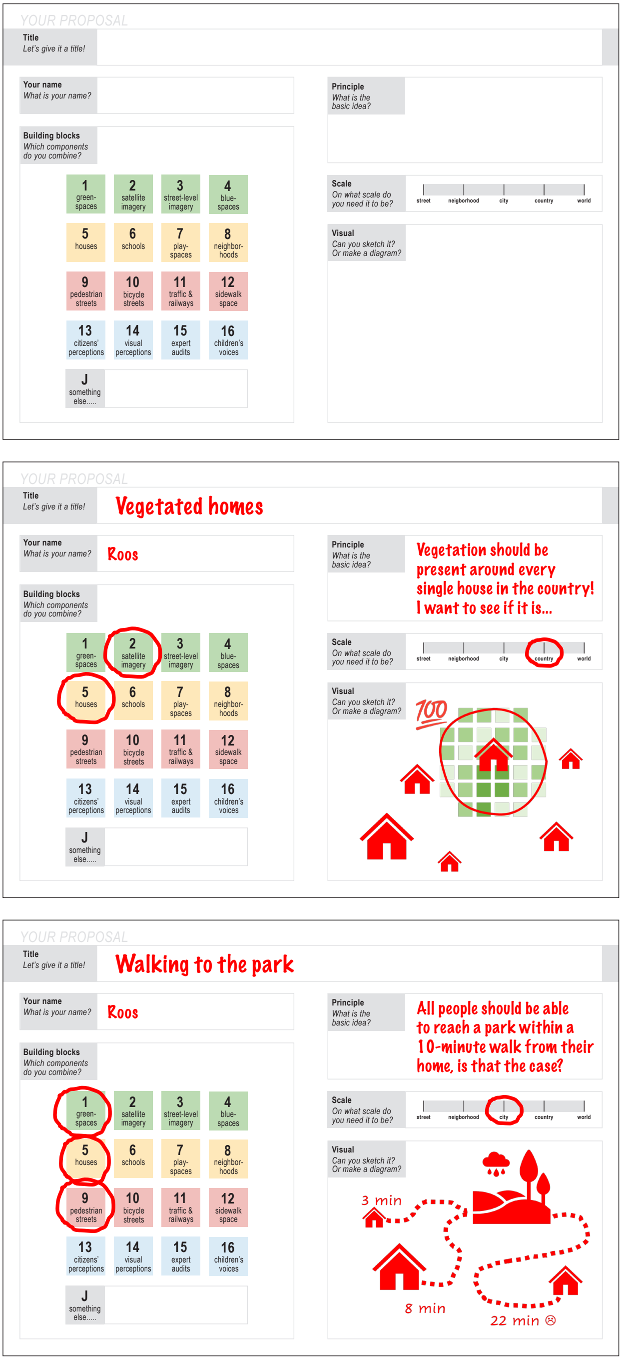


Figure A.1.: Workshop forms with guiding questions for the workshop participants (top): What would they like to measure, why that, on what scale, using what information, and how could the idea look like? Below, two filled examples are presented that were given to the participants to get started.

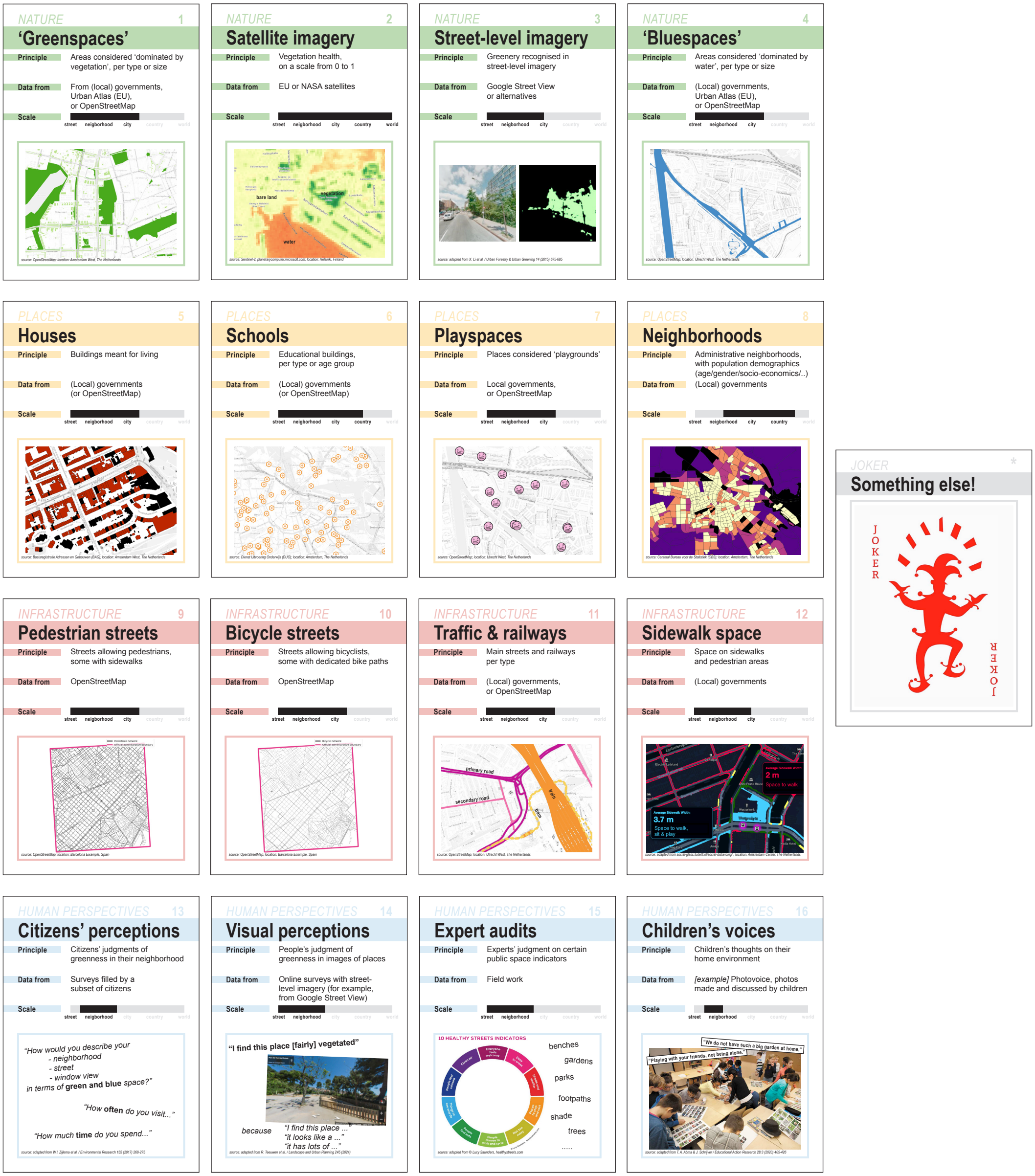


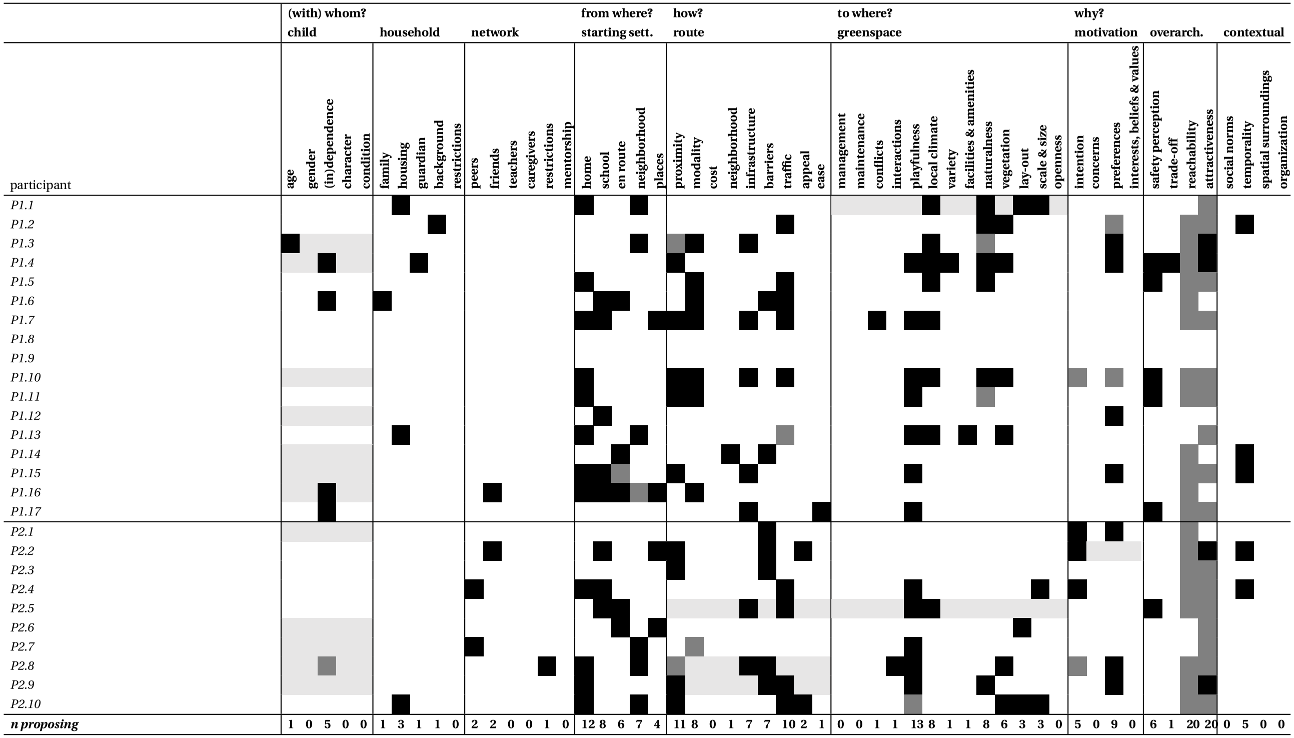
Figure A.2.: Workshop card deck introducing potentially relevant information types. Top to bottom: green- and bluespace data, locations where children perform activities, infrastructure, and people's judgements on greenspace. To the right, a joker card to remind participants to bring up any other information they deem relevant.

Table A.1.: Measures in literature, and the factors they account for, either directly (black cells) or indirectly (grey cells). Measures in literature often account for starting settings, the route (proximity and infrastructure) and several characteristics of the greenspace, while motivations and the child's network remain unaccounted for.

** Two studies with partial overlap in authors [57, 58] seemingly apply the exact same measure and are counted as one.*

	(with) whom?																from where?					how?									to where?													why?											
	child					household					network						starting sett.					route									greenspace													motivation				overarch.				contextual			
reference	age	gender	(in)dependence	character	condition	family	housing	guardian	background	restrictions	peers	friends	teachers	caregivers	restrictions	mentorship	home	school	en route	neighborhood	places	proximity	modality	cost	neighborhood	infrastructure	barriers	traffic	appeal	ease	management	maintenance	conflicts	interactions	playfulness	local climate	variety	facilities & amenities	naturalness	vegetation	lay-out	scale & size	openness	intention	concerns	preferences	interests, beliefs & values	safety perception	trade-off	reachability	attractiveness	social norms	temporality	spatial surroundings	organization
Alderton et al. [112]																	■					■				■									■			■												▒	▒				
Almeida, Barros, and Ribeiro [58]																	■	■				■				■														■		▒								▒	▒		▒		
& Ribeiro et al. [57] *																	■	■				■				■														■		▒								▒	▒		▒		
Baró et al. [47]			▒															■	▒			■				■									■	▒				■										▒	▒		▒		
Christian et al. [37]																	■					■				▒									■		▒					■								▒	■				
Ghale, Gupta, and Roy [111]	▒																					■	▒			■								▒	■				■	■	■	■							■	▒	■		▒		
Gupta et al. [54]																						■				▒		▒							■							■							■	▒	▒				
Hand et al. [35]			▒														■					■																	■											▒	▒				
Iraegui, Augusto, and Cabral [46]	▒																					■				■												■	▒			■							■	▒	▒			▒	
Janssen and Rosu [55]			▒														▒			■		■																		■		■								▒	▒				
La Rosa et al. [60]									▒								▒			■		■				■																■							■	▒	▒			▒	
Mears et al. [53]			▒				■										■			■		■				■								▒	■				■	■		▒								▒	■				
Onder, Polat, and Korucu [115]																						■																■				■							■	▒	▒				
Purwohandoyo et al. [105]																	■	■				■						■		▒					▒			■	■	■			■							▒	▒				
Reyes, Páez, and Morency [107]	■	■							■													■	■		■																									▒					
Robillard, Boisjoly, and Waygood [61]																	■					■	■			■		■																				▒		▒				▒	
Walker, Bormpoudakis, and Tzanopoulos [101]																		■				■				▒																▒								▒					
Weber, Haase, and Albert [113]																	■					■				■									■			■	■	■		■	■							▒	▒				
Wolch, Wilson, and Fehrenbach [110]			▒														▒			■		■																												▒					
Xing et al. [56]																	■					■													■		■	■	■	■		■							■	▒	■				
Ye et al. [59]																	■	■	■			■	▒			■														■										▒	▒		■		
n accounting for	3	1	5	0	0	0	1	0	2	0	0	0	0	0	0	0	16	6	3	6	0	23	4	0	1	14	0	3	1	1	0	0	0	2	10	1	2	7	8	11	1	14	2	0	0	0	0	1	6	23	19	0	5	3	0

Table A.2.: Workshop participants and the factors they propose to measure, either directly (black cells) or indirectly (grey cells). In light grey, clusters of factors are highlighted that participants explicitly stated as critical to measure, without further explanation. In contrast to measures in literature (table A.1), participants emphasize the importance of understanding the child, and to a lesser extent, their household and network, as well as their motives for visiting greenspace.



B

Exemplary quotes and imagery

Table B.1.: *Exemplary quotes to the qualitative analysis of deviations between people's greenness ratings and NDVI values: places that are perceived not-green, but have a high NDVI value. Quotes (Q) selected from the reasons participants (P) provided to motivate their ratings of places in Barcelona (Bar), Rotterdam (Rot), and Gothenburg (Got).*

Nr.	Quote	Place	Participant
Q-1	"there is a large green space out the back of the flats which is very green but the inner area by the flats is quite bleak just road parking no planting trees just some grass"	Got-1.1	P-110
Q-2	"so much concrete it distracts from the trees and limited grass that is there"	Bar-1.1	P-123
Q-3	"looks like a desert"	Got-1.1	P-193
Q-4	"there is greenery, but at a distance, nothing to feel and experience"	Bar-1.1	P-163

Table B.2.: *Exemplary quotes to the qualitative analysis deviations between people's greenness ratings and NDVI values: places that are perceived green, but have a low NDVI value. Quotes (Q) selected from the reasons participants (P) provided to motivate their ratings of places in Barcelona (Bar), Rotterdam (Rot), and Gothenburg (Got).*

Nr.	Quote	Place	Participant
Q-5	"there are many trees around and little public gardens"	Got-2.1	P-67
Q-6	"although there are a lot of buildings, it does have grass and trees, and the water also makes it feel better"	Rot-2.1	P-73
Q-7	"it looks to have good air circulation"	Got-2.1	P-312
Q-8	"for a place where traffic is prohibited, there are quite a few trees around to add to the relaxing feel"	Bar-2.1	P-178
Q-9	"considering it's in the middle of a man made square it seems quite green"	Bar-2.1	P-46
Q-10	"looks quite green for an urban environment"	Rot-2.1	P-240
Q-11	"plaza with trees; seems nice and pleasant"	Bar-2.1	P-55


A. Built-up vs. vegetated side (Gothenburg 1.1)

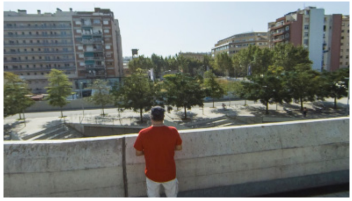
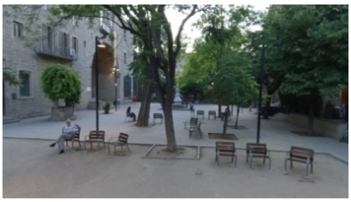

B. Physically inaccessible (Barcelona 1.1)

Figure B.1.: Indicative street-level images of places that are perceived not-green, but have a high NDVI value. Sub-figure titles indicate places in accordance with places referred to in table B.1 with exemplary quotes.


A. Waterfront (Rotterdam 2.1)


B. Green residential neighborhood (Gothenburg 2.1)


C. Quiet, secluded, away from traffic (Barcelona 2.1)


D. Young trees (Gothenburg 2.2)

Figure B.2.: Indicative street-level images of places that are perceived green, but have a low NDVI value. Sub-figure titles indicate places in accordance with places referred to in table B.2 with exemplary quotes.

Table B.3.: *Exemplary quotes to the qualitative analysis deviations between people's greenness ratings and OSM tags: places that are perceived not-green, but are tagged as such in OSM. Quotes (Q) selected from the reasons participants (P) provided to motivate their ratings of places in Barcelona (Bar), Rotterdam (Rot), and Gothenburg (Got).*

Nr.	Quote	Place	Participant
Q-12	"very sparse vegetation and looks dusty and uninviting"	Bar-3.1	P-144
Q-13	"except for few bushes, I don't see any noteworthy green area"	Bar-3.2	P-234
Q-14	"the bushes are quite low and don't stand out much"	Bar-3.2	P-39
Q-15	"some grass but not very lush"	Rot-3.1	P-389
Q-16	"too few trees and bushes for the size of the open space"	Bar-3.3	P-401
Q-17	"the flats seem to have small gardens / grassy areas outside them. There is a lot of building work and concrete though"	Got-3.1	P-103
Q-18	"it is mostly urban with a little green space to one side"	Rot-3.1	P-162
Q-19	"most of the space here is dedicated to roads"	Rot-3.2	P-115
Q-20	"it includes a nice walk surrounded by nice vegetated alleys"	Bar-3.4	P-236
Q-21	"few trees and side shrubs only but on the other end of the street it is a concrete desert"	Bar-3.4	P-280

A. Dusty and uninviting (Barcelona 3.1)

B. Equipped but not green (Barcelona 3.2)

C. Green but not lush (Rotterdam 3.1)

D. Few trees in a large space (Barcelona 3.3)

E. Built-up vs. vegetated side (Gothenburg 3.1)

F. Dominated by roads (Rotterdam 3.2)

G. Conflicting opinions (Barcelona 3.4)

Figure B.3.: Indicative street-level images of places that are perceived not-green, but are tagged as such in OSM. Sub-figure titles indicate places in accordance with places referred to in table B.3 with exemplary quotes.

Table B.4.: *Exemplary quotes to the qualitative analysis deviations between people's greenness ratings and OSM tags: places that are perceived green, but are not tagged as such in OSM. Quotes (Q) selected from the reasons participants (P) provided to motivate their ratings of places in Barcelona (Bar), Rotterdam (Rot), and Gothenburg (Got).*

Nr.	Quote	Place	Participant
Q-22	"lots of different kinds of vegetation"	Bar-4.1	P-89
Q-23	"every location you look at is full of the greenery of the trees, they feel like they are part of the streets and location"	Bar-4.2	P-60
Q-24	"I love this place! Lots of mature trees. Mix of public and private green spaces. Mix of trees, shrubs, plants and grass"	Rot-4.2	P-319
Q-25	"good use of space for planting trees, and as a plus, they we're planted in a way that creates almost a continuous shade"	Bar-4.3	P-155
Q-26	"lots of mature trees hiding the high buildings behind"	Bar-4.4	P-15
Q-27	"the green literally dominates the panoramic view of this place"	Bar-4.5	P-253
Q-28	"for an urban setting, more trees than I would have expected"	Got-4.1	P-5
Q-29	"it has a lot of green trees and shrubs but these are private gardens mostly"	Got-4.2	P-139
Q-30	"open space with grass and trees lining the road"	Rot-4.3	P-240
Q-31	"lots of green space, trees and water life"	Rot-4.4	P-59
Q-32	"the plants and trees are awesome. This whole place is perfect for relaxation. I can smell the nature"	Bar-4.4	P-255
Q-33	"this place looks so clean. The trees are beautiful. The park looks so calming"	Bar-4.7	P-255
Q-34	"lots of nice shrubs, but very overpowered by all the buildings. It still feels very urban but I like the plants"	Bar-4.8	P-15
Q-35	"although there is a concrete pavement, there are many trees planted"	Bar-4.3	P-253
Q-36	"even though a roadway is a large part of the area, it feels like there is a good deal of plants"	Got-4.3	P-6
Q-37	"a lot of green and quite far from traffic"	Rot-4.5	P-314

A. Vegetation variety (Barcelona 4.1)
B. Trees in all directions (Barcelona 4.2)
C. Mature trees (Rotterdam 4.2)
D. Configuration of trees (Barcelona 4.3)
E. Trees hiding buildings (Barcelona 4.4)
F. Dominated by vegetation (Barcelona 4.5)
G. Green for an urban scene (Gothenburg 4.1)
H. Green private gardens (Gothenburg 4.2)
I. Tree-lined road (Rotterdam 4.3)
J. Vegetation along water (Rotterdam 4.4)
K. Calming and clean (Barcelona 4.7)
L. Green but overpowered by buildings (Barcelona 4.8)
M. Green despite concrete (Gothenburg 4.3)
N. Far from traffic (Rotterdam 4.5)

Figure B.4.: Indicative street-level images of places that are perceived green, but are not tagged as such in OSM. Sub-figure titles indicate places in accordance with places referred to in table B.4 with exemplary quotes.

C

Revisited conceptual model

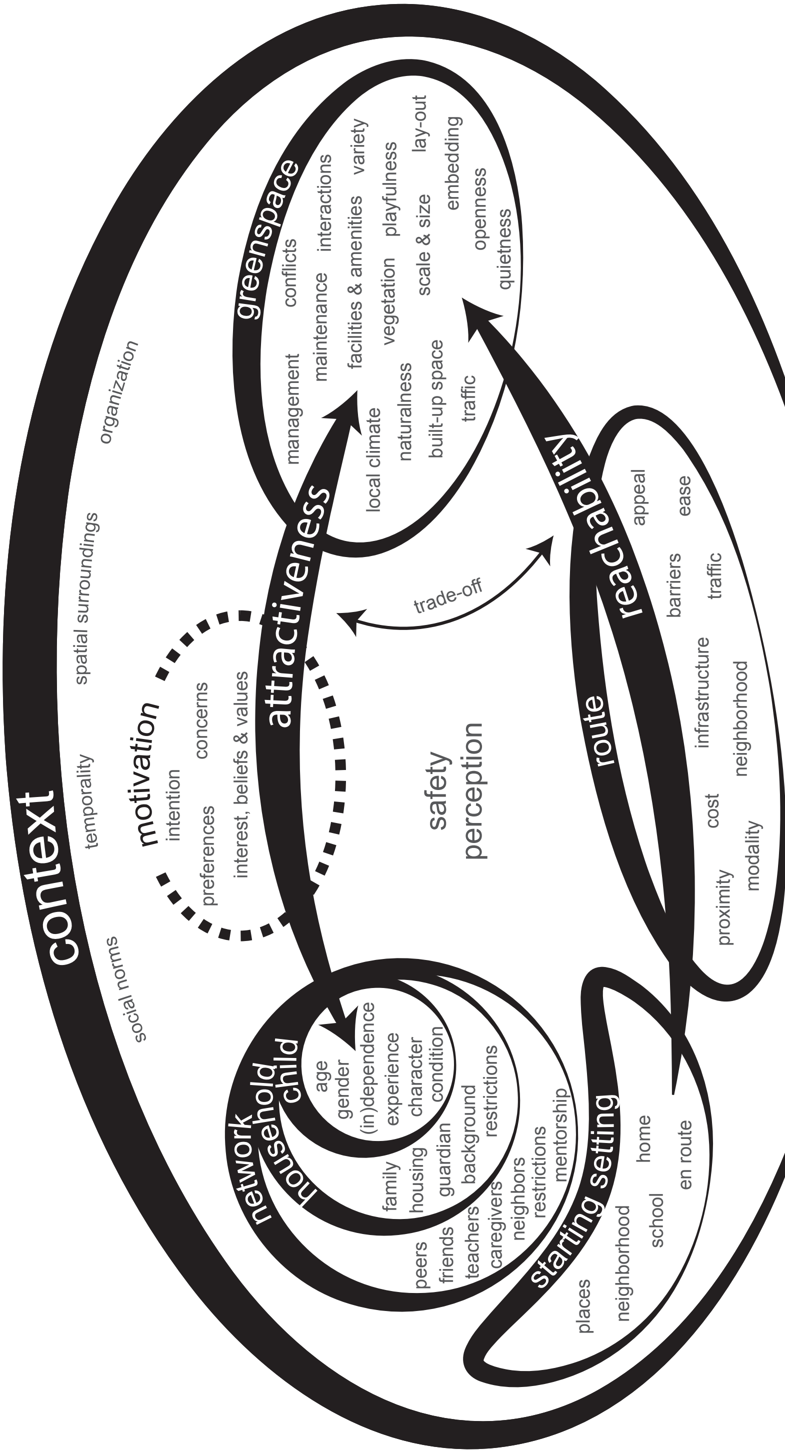


Figure C.1.: Revisited conceptual model of factors affecting children's access to urban greenspace.

List of publications

Peer-reviewed publications

6. **R. Teeuwen**, A. Bozzon, and A. Psyllidis. “Children’s access to urban greenspaces: A survey of factors and measures”. In: Cities & Health (2024). DOI: https://doi.org/10.1080/23748834.2024.2387931

5. 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). DOI: https://doi.org/10.1007/s43762-024-00126-0

4. **R. Teeuwen**, V. Milias, A. Bozzon, and A. Psyllidis (2024). “How well do NDVI and OpenStreetMap data capture people’s visual perceptions of urban greenspace?”. In: Landscape and Urban Planning 245 (2024). DOI: https://doi.org/10.1016/j.landurbplan.2024.105009

3. **R. Teeuwen** and A. Psyllidis. “Easy as child’s play? Co-designing a network-based metric for children’s access to play space”. In: Proceedings of the 18th International Conference on Computational Urban Planning and Urban Management (CUPUM 2023) (2023). DOI: https://doi.org/10.5281/zenodo.10949400

2. **R. Teeuwen**, A. Psyllidis, and A. Bozzon. “Measuring children’s and adolescents’ accessibility to greenspaces from different locations and commuting settings”. In: Computers, Environment and Urban Systems 100 (2023). DOI: https://doi.org/10.1016/j.compenvurbsys.2022.101912

1. A. Psyllidis, F. Duarte, **R. Teeuwen**, A. Salazar Miranda, T. Benson, and A. Bozzon. “Cities and infectious diseases: Assessing the exposure of pedestrians to virus transmission along city streets”. In: Urban Studies 60 (2021). DOI: https://doi.org/10.1177/00420980211042824

Other publications

3. **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.

2. **R. Teeuwen** and A. Psyllidis. “How to map the accessibility of urban greenspaces”. Industrial Design Engineering News, May 2023. URL: https://www.tudelft.nl/en/2023/io/may/how-to-map-the-accessibility-of-urban-green-spaces

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

Presentations and workshops

8. **R. Teeuwen**, V. Milias, and A. Psyllidis. “Assessing universal access to urban greenspaces: what indicators should be used when?”. Presentation at WHO European Healthy Cities Network Annual Conference 2023, Utrecht, the Netherlands, Nov. 2023.

7. **R. Teeuwen** and M. Dohmen. “Greenspaces and noise in the context of the Equal-Life project”. Presentation (online) at EuroCities working group Noise, Oct. 2023.

6. V. Milias, **R. Teeuwen**, and A. Psyllidis. “Modelling accessibility in an exposome: what to use when?”. Workshop at the Equal-Life Stakeholder Forum, Helsinki, Finland, Sept. 2023.

5. **R. Teeuwen**. “Co-designing a network-based accessibility metric for children’s exposure to play space”. Presentation at the EHEN 2023 Conference, Leuven, Belgium, May 2023.

4. 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.

3. **R. Teeuwen** and A. Psyllidis. “Co-designing computational metrics for urban health: The case of children’s access to play space”. Poster presentation at ICT Open 2023, Utrecht, the Netherlands, Apr. 2023.

2. **R. Teeuwen** and A. Psyllidis. “Evaluating children’s access to public outdoor play space”. Workshop at the Equal-Life Stakeholder Forum, Milan, Italy, Nov. 2022.

1. **R. Teeuwen**. “Measuring urban greenspace accessibility from mobile settings”. Presentation at the EHEN 2022 Conference, Barcelona, Spain, May 2022.

About the author

Roos Teeuwen is an urban analytics researcher, born in 1993 in Amsterdam, the Netherlands. From 2011 to 2018, she studied at Delft University of Technology, where she obtained her Bachelor's degree in Architecture, Urbanism and Building Sciences (2014) and her Master's degree in Geomatics for the Built Environment (2018, cum laude). From 2018 to 2020, she worked as Geographic Information System Specialist at Tensing GIS Consultancy. Thereafter, from 2020 to 2024, Roos conducted the research described in this dissertation in the Urban Analytics Lab that is part of the Knowledge and Intelligence Design research group at the faculty of Industrial Design Engineering, Delft University of Technology.

Access to good-quality greenspace is crucial for the health and well-being of children in cities, by providing space for recreation, social interaction, and personal development. Opposed to adults', children's access to greenspace is influenced by factors such as their restricted daily activity-space, limited autonomy, and various physical and perceived barriers. In this dissertation, we propose innovative approaches for assessing urban greenspace accessibility with a specific focus on the factors affecting children's access.