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Measuring children's and adolescents' accessibility to greenspaces from different locations and commuting settings

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ABSTRACT

Recent evidence underscores the importance of greenspace exposure in promoting physical activity, and in having a positive impact on mental health and cognitive development. Accessibility has been identified to be the primary motivating factor when it comes to encouraging greenspace use and, correspondingly, exposure. Existing quantitative approaches to measuring greenspace accessibility predominantly focus on the areas surrounding home locations, often disregarding access from other settings such as schools or workplaces, exposures while on the move, and mobility differences among different population age groups. This article introduces a novel method to measure greenspace accessibility that considers access from different activity settings (i.e., homes, schools, and the commutes between them) for children and adolescents, while accounting for the dependency of human access on the road network. We use Amsterdam, Rotterdam, and The Hague in the Netherlands as case studies to illustrate the utility of our method. Compared to conventional measures of greenspace accessibility, we show that accounting for school and commuting settings, in addition to residences, captures previously untapped accessibility aspects for both children and adolescents. Our approach can be replicated in other cities worldwide, with the aspiration to provide planners and public health policy-makers with a methodological tool that can help in evaluating access and use of greenspaces when designing health-promoting interventions.

1. Introduction

Exposure to outdoor greenness has been associated with a positive impact on physical health, mental health, and cognitive development among children (Dadvand et al., 2015). Parks and other outdoor greenspaces provide important venues that promote physical activity (e.g., walking and biking), thereby contributing to a decreased risk of developing obesity and other related chronic diseases (e.g., high cholesterol or blood pressure) (Coombes, Jones, & Hillsdon, 2010; Sugiyama, Francis, Middleton, Owen, & Giles-Corti, 2010). Moreover, good mental health is positively associated to greenspaces and this relationship holds for a variety of greenspace types and sizes (Wood, Hooper, Foster, & Bull, 2017). 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 (Coombes et al., 2010; Sugiyama et al., 2010; Zhang, Lu, & Holt, 2011; Almanza, Jerrett, Dunton, Seto, & Pentz, 2012; van den Berg et al., 2016; Labib, Lindley, & Huck, 2020). Greenspace use primarily manifests itself in two ways. First, by making *routine purposeful visits* to greenspaces for leisure or physical exercise (van den Berg et al., 2016; Almanza et al., 2012; Rao, Prasad, Adshead, & Tissera, 2007). Second, in the form of *regular traverse movement* through greenspaces, which involves serendipitous walking when commuting to school, work or other activities (Zijlema et al., 2018; Dadvand et al., 2015; Roberts & Helbich, 2021).

Evidence suggests that greenspace use is primarily encouraged by accessibility (Zhang, Tan, & Richards, 2021). Specifically, easy access emerges as the main motivating factor in studies investigating what encourages people to visit a greenspace such as a park (Talal & Santelmann, 2021). Thus, measuring access to greenspaces is critical for evaluating the degree of use and its corresponding impact on health outcomes. It also plays a crucial role in assessing the effectiveness of policies aimed at promoting healthy lifestyles.

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

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others (Zhang et al., 2011). Moreover, greenspace access may vary by age (Kaczynski, Potwarka, Smale, & Havitz, 2009) or socioeconomic status (Cutts, Darby, Boone, & Brewis, 2009). 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 (Colburn, Pratt, Mueller, & Tompsett, 2020; Chambers et al., 2017; Nieuwenhuijsen et al., 2017; Helbich, 2018). 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 (Halden, McGuigan, Nisbet, & McKinnon, 2000; Nieuwenhuijsen et al., 2017). Third, the entrances connecting the greenspace to the road network are frequently overlooked, measuring access on the basis of centroids or park edges instead (Halden et al., 2000; Wang, Wang, & Liu, 2021).

In this article, 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 min. 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 characterizes 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 the article 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.

2. Related work

2.1. Greenspace exposure and health benefits

Recent evidence shows accessibility is a main condition for greenspace use (Zhang et al., 2021; Talal & Santelmann, 2021). 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 (Rao et al., 2007). Children visiting greenspaces are largely engaged in physical recreation and interacting with other children (Talal & Santelmann, 2021), which may in turn affect their health, and visits to greenspaces are positively correlated with mental health and physical activity (van den Berg et al., 2016; Almanza et al., 2012). College students' mental health is positively associated with perceived greenness at university, independent from perceived greenness at home (Loder, Schwerdtfeger, & van Poppel, 2020). Commutes through green environments benefit the cognitive development of children (Dadvand et al., 2015) and the mental health of adults, especially when active (Zijlema et al., 2018), and being on the move through green environments is negatively correlated with depression (Roberts and Helbich, 2021).

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 (Zhang et al., 2011). However, the choice for the most suitable measure for greenspace accessibility depends on the context (Wang et al., 2021). In line with the works of Zhang et al. (2011) and Wang et al. (2021), we first distinguish four types of greenspace accessibility measures: *travel cost*, *statistical index*, *buffer zone*, and *spatial interaction*. In the next sub-section, 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, & Langford, 2012; Shackleton & Blair, 2013). 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 (Labib et al., 2020; Nieuwenhuijsen et al., 2017). 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 (Zhang et al., 2011).

Statistical index measures use predefined areas as units of analysis, such as administrative neighborhoods or census tracts (see e.g., Spotswood et al., 2021; Taubenböck et al., 2021). They quantify the number, total area, or density of greenspaces within the area at hand (Wang et al., 2021). A main shortcoming is that predefined areas are prone to the Modifiable Areal Unit Problem (Openshaw, 1984). 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 (Colburn et al., 2020).

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., Kabisch & Haase, 2014; Wood et al., 2017; Zhang et al., 2021). Network buffer zones are also referred to in literature as *walksheds* (see e.g., Adhikari et al., 2021; Goldenberg, Kalantari, & Destouni, 2018). That is, the areas that can be reached within e.g., a 15-min walk, or an equivalent 800 m network distance. The buffer zone measure is another proximity-based measure that is widely used in public health oriented greenspace accessibility studies (Labib et al., 2020). 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 (Zhang et al., 2011). Wang et al. (2021) 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., Chen, Wang, Lou, Zhang, & Wu, 2019; Park & Guldmann, 2020). 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 (Zhang et al., 2011). However, Wang et al. (2021) state that by adjusting the attractiveness parameter under the assumption that a greenspace can host a maximum number of people may cause biased outcomes.

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 (Sevtsuk, 2020). Betweenness, originally proposed by Freeman (1977), is defined as the fraction of shortest paths between any pair of nodes in a network. Porta et al. (2009), Sevtsuk (2014), Buzzacchi, Leveque, Taramino, and Zotteri (2021) use betweenness to study the accessibility of retail locations, and Psyllidis et al. (2021) demonstrate its utility in the context of infectious diseases. In addition, Sevtsuk (2021) 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 (Nieuwenhuijsen et al., 2017; Helbich, 2018), even though measuring access from other activity locations such as schools can be implemented with the same metrics. Nieuwenhuijsen et al. (2017) 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 (Nieuwenhuijsen et al., 2017; Helbich, 2018; Labib et al., 2020). Our work draws on these limitations to provide a more refined network-based accessibility measurement method, tailored to different age groups and activity settings.

3. Method

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.

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 m 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 (Jokar Arsanjani, Zipf, Mooney, & Helbich, 2015) (see e.g., Novack, Wang, & Zipf, 2018, combining OSM street network and land use data for research). The OSM road network is found to be complete in over 40% of countries (Barrington-Leigh & Millard-Ball, 2017), and covers more informal route segments than official datasets (Labib et al., 2020). 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 m grid, from the Dutch Central Bureau of Statistics (Centraal Bureau voor de Statistiek, 2021), 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 (Dienst Uitvoering Onderwijs, 2022a, 2022b).

Our method to quantify greenspace accessibility is replicable for any city where the OSM road network is highly complete (see e.g., Barrington-Leigh & Millard-Ball, 2017), and where land use data (derived either from OSM or a local data source), granular population data (e.g., at a 100 by 100 m 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 (Boeing, 2017) 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 (Sevtsuk & Kalvo, 2016; Sevtsuk, 2021) to conduct the betweenness analyses.

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 m. That is, at complex intersections with multiple network nodes lying within 10 m from each other, these are collapsed into one while maintaining topological relations.

Drawing on World Health Organization Regional Office for Europe (2017a), 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 ha, in accordance with recommendations by the World Health Organization Regional Office for Europe (2017b) as well as the European Common Indicator for greenspace accessibility [Ambiente Italia, 2003]. 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-min walks, as literature suggests that these travel times capture the majority of walking trips (Pushkarev & Zupan, 1975; Guy & Wrigley, 1987; Handy & Niemeier, 1997; Zacharias, 2001). We translate these travel times into distances of 300, 500, and 800 m, respectively, in accordance with Waddell and Ulfarsson (2003). 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.

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 et al. (2021) and Sevtsuk (2020).

3.3.1. 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 m 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 m 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:

$$A_{res}[i] = \sum_{j:G_j \in G_{walkshed}} P_j \tag{1}$$

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.

3.3.2. 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 $A_{edu}[i] = n_{Fwalkshed[i]}$.

3.3.3. 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 (2021): 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 (Sevtsuk & Kalvo, 2016), which calculates patronage betweenness with the following equation:

$$PB[s]^{r,dr} = \sum_{j,k \in G-\{s\}, d[j,k] \leq r \cdot dr} \frac{n_{j,k[s]}}{n_{j,k}} \cdot W[j,k] \frac{1}{e^{\beta \cdot d[j,k]}} \tag{2}$$

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 m radius distance r via the street network, corresponding to a 15-min walk (Waddell & Ulfarsson, 2003). As pedestrians take routes up to 20% longer compared to the shortest path (Sevtsuk, 2020) and tend to make detours to parks (Salazar Miranda, Fan, Duarte, & Ratti, 2020), 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 (Handy & Niemeier, 1997). 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:

$$A_{otmS}[i] = \sum_{j:S_j \in S_{crossing}} PB_j \cdot \frac{1}{2} \tag{3}$$

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:

$$A_{otmW}[i] = \sum_{j:S_j \in S_{within}} \left(PB_j \cdot l_j\right) \tag{4}$$

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 m) on the outputs of our model, considering they might walk further away to their study facilities.

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. 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 1.

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 2. In a similar lay-out and coloring, Fig. 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 2) generally shows very strong correlations with residence-based accessibility. A clear linear relationship can also be observed in the scatter plot in Fig. 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.

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. Fig. 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. Fig. 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 educationbased 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 Fig. 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

Table 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	16,605
			500m	Any age	base5	848	3498.3	3872.3	0	31,810
			800m	Any age	base8	848	7763.3	7635.3	0	58,110
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	2.0	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	11,250.6	33,024.6	0	387,594
				Adolescents	otmw8A	848	5772.3	25,180.7	0	316,204

Table 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 colour 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

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. Fig. 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 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 m) yields only limited differences in on-the-move accessibility outcomes. That is, using radius distances of 1000 or 1200 m 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.

4.2. Spatial patterns of accessibility metrics

Fig. 2 and Fig. 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 800 m radius distance, corresponding to a 15-min 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.

4.2.1. High or poor education-based accessibility

Twenty greenspaces score higher in terms of accessibility from children's schools within 800 m, than in terms of home-based accessibility, although the correlation analysis shows very strong correlations between them. Panel B in Fig. 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.

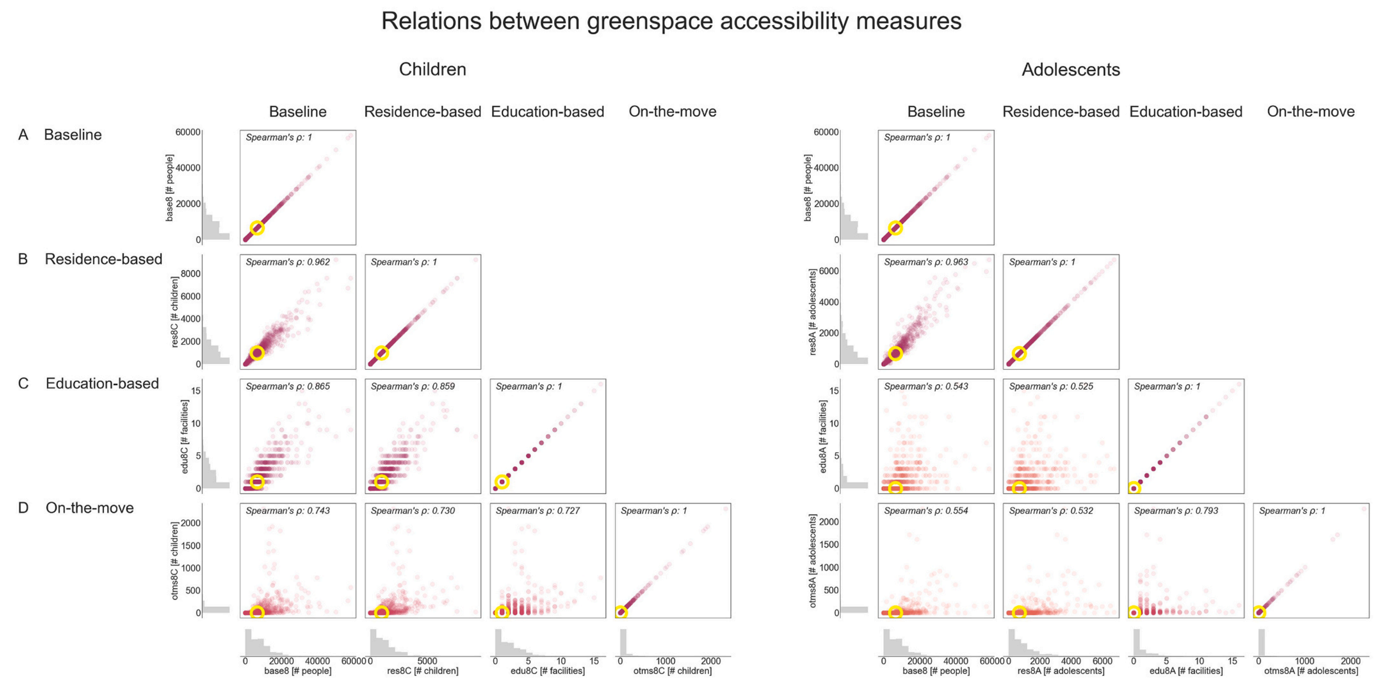

Fig. 1. Scatter plots of relationships between accessibility measures for children (left) and for adolescents (right), accompanied by histograms per measure: conventional baseline (*A*), residence-based (*B*), education-based (*C*), and on-the-move (*D*). All measures shown use an 800-m network radius distance. Scatter plots are colored according to the strength of correlation, in alignment with Table 2. Yellow circles in the scatter plots depict the median values. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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 Fig. 3. In line with the moderate correlations between adolescents' home-based and education-based accessibility, 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.

4.2.2. *Poor on-the-move accessibility*

As shown in the histograms and scatter plots in Fig. 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 (Fig. 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 (Fig. 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).

4.2.3. *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 (Fig. 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.

5. Discussion

5.1. *Interpretation of results*

In the following paragraphs, we discuss the interpretation of the analysis of results in the three case-study cities. Fig. 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 (Municipality of Amsterdam, 2018; Municipality of The Hague, 2021; Municipality of Rotterdam, 2021).

Nevertheless, our analysis indicates that a number of greenspaces score relatively high in terms of accessibility from educational facilities, relative to accessibility calculated from home locations. A common characteristic of this set of greenspaces is their small size (see Fig. 4, panel B). That is, the largest greenspace in this set is *Malieveld* in The Hague with an area of 11 ha, 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

Fig. 2. *Children's* greenspace accessibility: baseline, residential, educational and on-the-move accessibility measures for Amsterdam (A), Rotterdam (B) and The Hague (C). Notable examples are highlighted in yellow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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., 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-min walking commute, resulting in low to medium accessibility (Fig. 4, panel C). These greenspaces typically have a width that exceeds 500 m, 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 450 m appear to enable

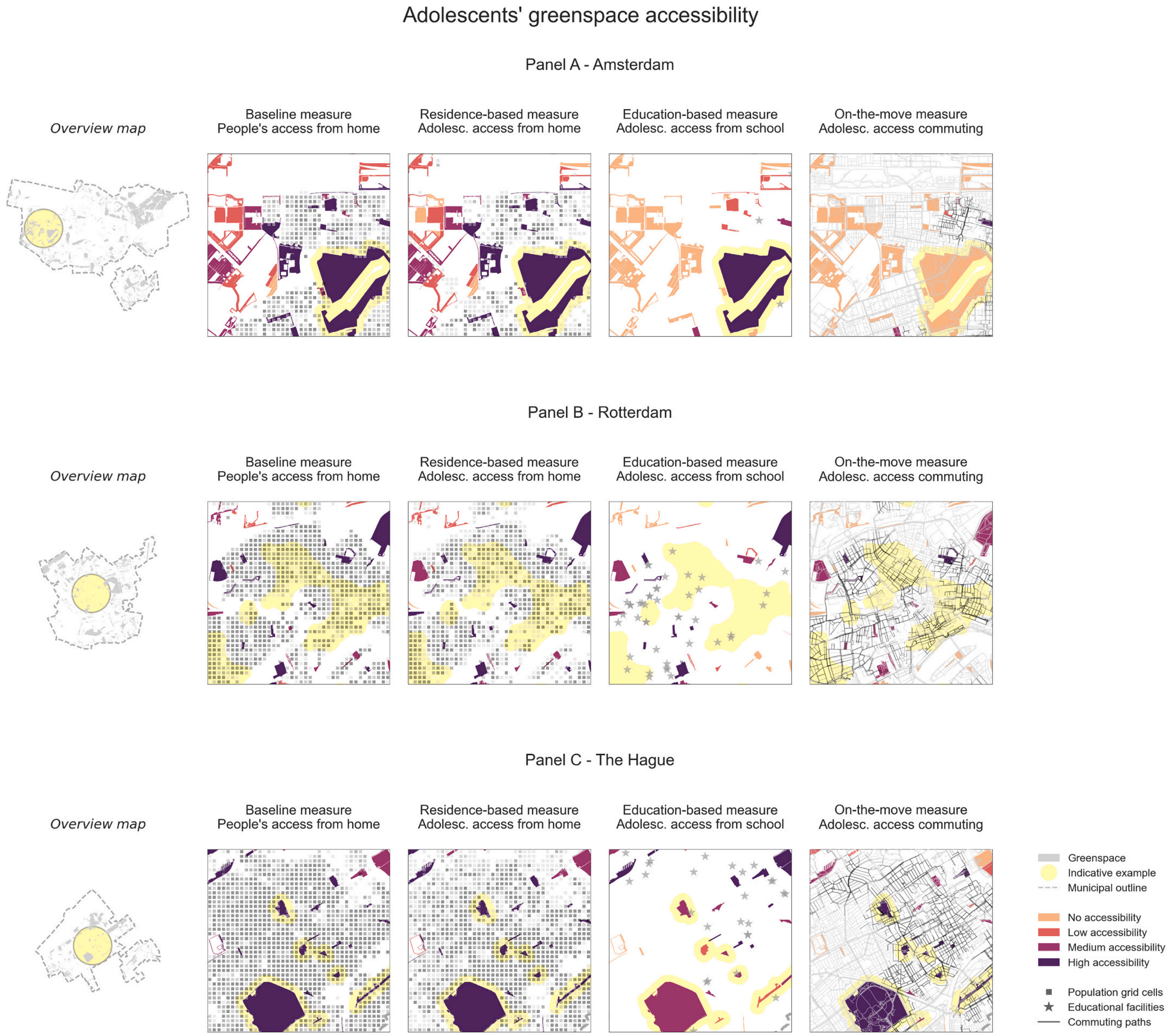

Fig. 3. *Adolescents'* greenspace accessibility: baseline, residential, educational and on-the-move accessibility measures for Amsterdam (A), Rotterdam (B) and The Hague (C). Notable examples are highlighted in yellow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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 (Fig. 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 reasonable 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

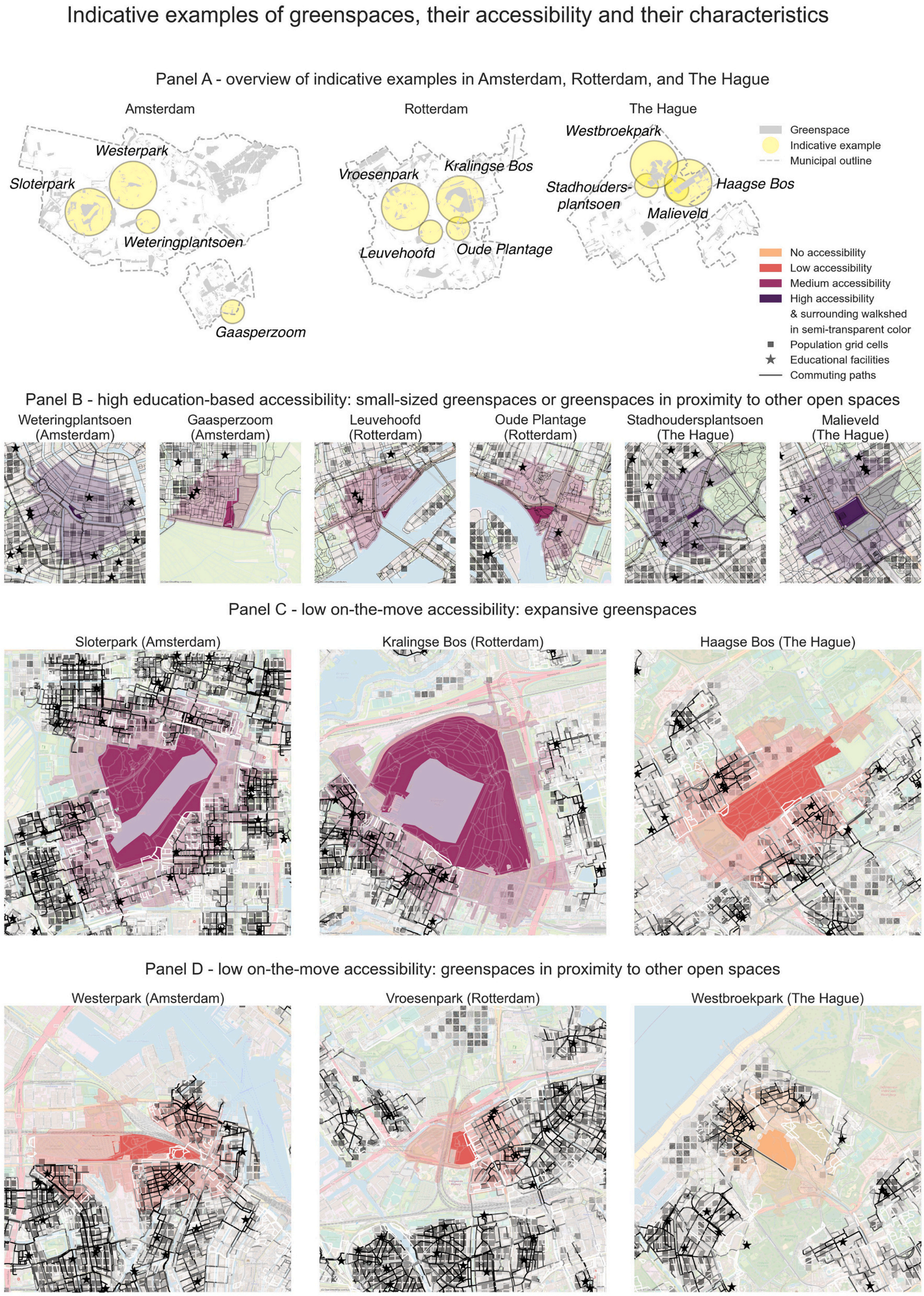

Fig. 4. Geometry, accessibility, and surroundings of indicative greenspaces in Amsterdam (left), Rotterdam (middle), and The Hague (right). Greenspaces are colored according to accessibility level, together with their semi-transparently colored 800 m radius walkshed (equivalent to a 15-min walk).

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.

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 work 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, Li, Kwan, Kou, and Chai (2020) 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 greenspaces 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 Helbich (2018), Kestens, Wasfi, Naud, and Chaix (2017), Nieuwenhuijsen et al. (2017).

Our method is largely automated and parameters can be adjusted to account for other settings (e.g., residences of friends and family (Chambers et al., 2017)), 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.

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 (Sevtsuk & Kalvo, 2021). 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 (Salazar Miranda et al., 2020). 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 (Talal & Santelmann, 2021), might also come into play that could further induce exposure to greenspaces.

6. Conclusion

In this article, 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 measures 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 (Peen, Schoevers, Beekman, & Dekker, 2010), and urban densification threatens greenspace availability (Haaland & van den Bosch, 2015) 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.

Author contribution statement

Roos Teeuwen: Conceptualization, Methodology, Data curation, Formal analysis, Validation, Visualization, Writing – original draft, Writing – review & editing.

Achilleas Psyllidis: Conceptualization, Methodology, Formal analysis, Funding acquisition, Resources, Supervision, Writing – original draft, Writing – review & editing.

Alessandro Bozzon: Funding acquisition, Resources, Supervision, Writing – review & editing.

Declaration of Competing Interest

The author(s) declare no potential conflicts of interest.

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