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Measuring spatial age segregation through the lens of co-accessibility to urban activities

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ABSTRACT

A growing body of literature underscores the societal and mental health benefits of facilitating interactions between different age groups. While it is acknowledged that age segregation might be experienced in daily activities beyond an individual's home location, the majority of spatial age segregation studies and corresponding measures are almost exclusively based on the concentration and distribution of age groups at the neighborhood level as the major determinants. Disregarding potential encounters with individuals from different age groups in places beyond the residential space could result in fragmented estimates of the level of spatial age segregation. To take such encounters at various activity locations into consideration, it is important to determine both how accessible these places are to individuals of different ages and the likelihood of being exposed to other age groups. This article introduces a methodological approach to assessing spatial age segregation that accounts for the degree of age-adjusted co-accessibility to different activity locations, in addition to the age structure of neighborhoods. We use spatially disaggregated data about activity locations across the cities of Amsterdam, Rotterdam, The Hague, Utrecht, and Eindhoven in the Netherlands to calculate several spatial accessibility metrics, and to estimate age diversity and co-accessibility scores for each activity. Our analysis results demonstrate how the proposed methodology can provide new insight into the potential moderating effect that exposure to other age groups in places outside of the home can bring to the level of spatial age segregation.

1. Introduction

Spatial age segregation occurs when individuals of different ages do not occupy the same space and, thereby, lack mutual interactions (Hagestad & Uhlenberg, 2005). Evidence suggests that bringing different age groups together could have a number of societal benefits that range from the reduction of ageism and the risk of isolation in later life to the promotion of socialization between the young and the old (Coleman, 1982; Douglas & Barrett, 2020; Hagestad & Uhlenberg, 2006; W. H. Organization, 2007).

Common indicators of spatial age segregation that have extensively been used in literature are the concentration and distribution of different population age groups residing within a neighborhood (Athey, Ferguson, Gentzkow, & Schmidt, 2021; Beguin, 1982; Cagney, 2006; Cowgill, 1978; Deng & Mao, 2018; Rogerson & Plane, 1998; Sabater, Graham, & Finney, 2017). Even though this is important to consider when aiming to identify the existence of segregation, in reality people may further experience age segregation in places outside of the residential space. This implies that the location and distribution of different daily activity spaces (e.g. parks, restaurants, supermarkets, workplaces) across the urban fabric may either promote or obstruct encounters with people from different age groups (Oldenburg, 1989; Song, Merlin, & Rodriguez, 2013; Wong & Shaw, 2011; Xu, 2019; Zock et al., 2018). For instance, a park that is accessible to and visited by children, adults, and the elderly promotes mutual exposure and could induce interactions between these age groups. Subsequently, determining spatial age segregation solely on the basis of population distribution in the residential space may lead to partial or biased insights into this phenomenon.

Access to different activity locations is rarely considered in studies of spatial age segregation. Only a limited number of studies of general spatial segregation have accounted for locations beyond the residential space (Reardon & O'Sullivan, 2004; Schnell & Yoav, 2001; Wong, 1993; Wong, 2002; Wong & Shaw, 2011). However, accounting for how accessible various activity locations are to different age groups merits attention as a key component of spatial age segregation, in addition to the commonly considered factor of age structure (i.e., the presence and concentration of different age groups). Three reasons underscore the necessity for considering access to activity locations in a spatial age

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segregation context: (1) social encounters and interactions primarily occur in places outside of home (Kwan, 2013; Wong & Shaw, 2011), (2) easy access to facilities has been shown to encourage their use (Talal & Santelmann, 2021), and (3) differences in access capacity (e.g. between younger and older people) substantially influence the chance for encounters between age groups. To enable the integration of accessibility in spatial age segregation research and policy, there is a need for methods that do not only capture how accessible activity locations are to different people, but can also assess the possibility of different age groups sharing the same space.

Despite the growing body of accessibility studies, existing metrics fall short in capturing both who can access different destinations and how likely it is that people from different groups meet in these places. Generally, accessibility metrics fall into two categories: (a) place-based (or location specific), and (b) people-centered measures (Kwan, 2009; Miller, 2005). The former capture access according to the number, density, and diversity of activity locations in a neighborhood, whereas the latter measure the degree to which individuals or groups have access to a given set of destinations (Horner, 2004; Vale, Saraiva, & Pereira, 2016).

Typical determinants are space (i.e., the distance between a destination and an origin — usually, the home location of an individual), time (e.g. business or office hours), and cost (i.e., travel time and related costs to reach a destination) (Handy & Niemeier, 1997; Páez, Scott, & Morency, 2012). Regardless of the general category, these metrics often fail to distinguish between a facility that is accessible to a large, yet homogeneous, population age group and one that brings people of different ages together. In other words, there is a need for methods that can capture the degree of *co-accessibility* (i.e., how accessible a given destination is to individuals from different population groups) of activity locations.

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

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

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

2. Related work

2.1. Spatial age segregation

Spatial age segregation, as defined by Hagestad and Uhlenberg in (Hagestad & Uhlenberg, 2005), is determined by the extent to which people of different ages occupy the same space. A large body of literature primarily focuses on residential age segregation. That is, areas are considered age segregated if people belonging to different age groups do not reside in the same city, neighborhood, urban block or building unit (Sabater et al., 2017; Winkler & Klaas, 2012). Evidence has demonstrated that the societal effects of spatial age segregation may include ageism, weaker social ties among different ages, and could lead to a society that is less generative (i.e., a society that cares less for future generations) (Coleman, 1982; Douglas & Barrett, 2020; Hagestad & Uhlenberg, 2006). Similar concerns have been raised by the World Health Organization (WHO), leading to the emergence of the "age-friendly city" concept as a response to the converging trends of ageing. WHO has specifically stressed that older people need more activities that can foster integration within the community and with other age groups and cultures, in proximity to the places they live in (W. H. Organization, 2007).

Empirical studies on age segregation suggest that the degree of segregation varies significantly across different counties in the United States (Winkler & Klaas, 2012), whereas (Sabater et al., 2017) show an increase of this phenomenon in the urban areas of England and Wales throughout the years. Other empirical studies focus on measuring the potential effects that residential age segregation could have on the society or on people's health. For instance, (Deng & Mao, 2018) developed new age segregation metrics towards an improved understanding of its effects on older adults' self-rated health. Similarly, (Lehning, Mattocks, Smith, Kim, & Cheon, 2021) examined the relation between a neighborhood's age structure and people's self-rated health. Their findings support that people living in neighborhoods with an increasing percentage of older adults rated their health lower compared to people who live in areas with more mixed age groups.

Despite the growing body of literature on the effects of spatial age segregation on health outcomes, the primary focus has hitherto been on neighborhood age structure. However, WHO has recently emphasized that strategies towards age-friendly cities should rather adapt neighborhood *structures* and *services* so as *"...to be accessible to and inclusive of older people with varying needs and capacities." (*W. H. Organization, *2007;* W. H. Organization, *2015)*. This implies that, besides neighborhood age structure, the consideration of accessibility to services and activity locations could add meaningful insights into the level of spatial age segregation. This is lacking in existing related studies. This article aims to fill this gap by considering the role of accessibility to activity locations beyond the residential space as an important complementary indicator of spatial age segregation.

2.2. Measuring accessibility

A variety of methods have been introduced for measuring accessibility to various destinations in cities. These methods can be categorized into two main categories: *place-based* (or locational) and *people-centered (*Horner, *2004;* Vale et al., *2016).* Place-based approaches to measuring accessibility aim to determine how accessible different destinations are (e.g. retail establishments, greenspaces, hospitals) from a given set of origins (e.g. home locations) (Hamstead et al., 2018). Conversely, people-centered approaches aim to assess how accessible different locations are to a given group of people or individuals, with particular emphasis on equitable access (Logan, Anderson, Williams, & Conrow, 2021; Talen & Anselin, 1998). An example of the latter approach is (Lucas, Van Wee, & Maat, 2016), in which it is suggested that ethical theories, such as egalitarianism and sufficientarianism, should be combined to evaluate how equitably accessible different facilities are to people. Other people-centered approaches revolve around Hägerstrand's time geography concept (Hägerstrand, 1970) and focus on the spatiotemporal settings of individuals. For instance, (Neutens, Schwanen, Witlox, & De Maeyer, 2008) introduce a method to assess how likely it is for a group of people to meet in a given place according to their location and time schedule. Both approaches determine accessibility in relation to the spatial distribution of destinations in a given area (e.g. a neighborhood or other administrative units), their characteristics (e.g. type, price range, quality) or the ease of reaching them (e.g. in terms of distance, time or cost) (Handy & Niemeier, 1997).

However, the demographic characteristics of the people who have access to the same destinations are rarely considered. Kelobonye et al. (Kelobonye, Zhou, McCarney, & Xia, 2020) proposed the addition of a competition component when measuring accessibility to urban services, and further supported that it can be misleading to consider a large number of accessible urban services as an indicator of increased choices, if the competition or demand for these services is not considered. To demonstrate this, three groups of people were considered, namely the labor force, school-age children, and the population as a whole. The main assumption is that people belonging to each group compete each other for accessible job, education, and shop opportunities, respectively. Related studies that account for people's characteristics focus either on where people reside (and not necessarily on what is accessible to them) or on visitation patterns. For instance, (Moro, Calacci, Dong, & Pentland, 2021) explore income segregation in US cities using Global Positioning System (GPS) and Foursquare data to classify places according to the time different income groups spend at each place. Similarly, (Athey et al., 2021) use GPS data to estimate experienced racial segregation, and highlight that policies concerning the spatial distribution of commercial facilities could largely influence the degree of facility occupation by people belonging to different races.

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

3. Methodology

This section outlines the proposed methodology, in which people's residences (origins) together with activity locations (destinations) are received as input, a set of spatial accessibility measures are then calculated, giving as output a set of age-adjusted co-accessibility score for each activity location (Fig. 1).

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

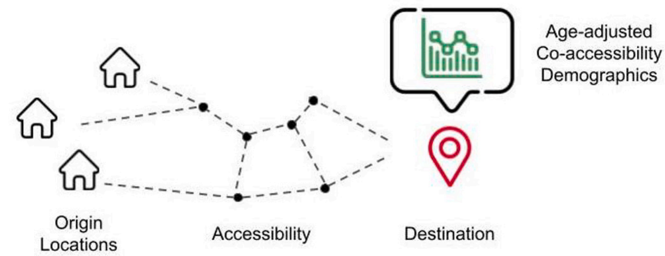

Fig. 1. Simplified graphical overview of the proposed method.

3.1. Spatial accessibility measures

Within the context of this work, we define accessibility according to which activity location is accessible to different people within walking distance. This choice is made for two reasons. First, drawing on related literature, places that lie within walking distance (walkable distances vary between 300 m and 800 m of a person's — usually home — location) may have an effect on people's health and habits. For instance, food stores of either high or low quality in proximity to someone's home have been shown to, respectively, promote or obstruct healthier eating habits and, subsequently, people's health (Escaron, Meinen, Nitzke, & Martinez-Donate, 2013; Larson, Story, & Nelson, 2009). In addition, activity locations within walking distance of individuals belonging to different age groups may encourage encounters and social interaction. Second, by conducting an analysis on the Netherlands Mobility Panel (MPN) data (Hoogendoorn-Lanser, Schaap, & OldeKalter, 2015) we discovered that walking is the third most frequent (i.e., 15%) travel mode in the Netherlands (after car with 29%] and bike with 28%) for shopping and social recreational trips, and the second most frequent (i.e., 25%) travel mode for short trips (i.e., less than 5 km from home, with car and bike representing 23% and 40% of trips, respectively). Besides, walking is the most affordable and accessible travel mode to people of virtually any age and income level, compared to cars and bikes. Given these two reasons, the use of walking distance to an activity location as a determinant of accessibility better fits the context of this article.

To determine which activity locations are reachable within walking distance around each residence we use different pedestrian sheds. Specifically, we use buffers that correspond to 5, 10, and 15-min walksheds. Generally, there is no consensus in literature on which (travel time) distance optimally captures pedestrian trips. Moreover, the distance covered on foot may vary substantially across different population age groups. However, evidence suggests that the three aforementioned walksheds capture the majority of pedestrian trips (Guy & Wrigley, 1987; Handy & Niemeier, 1997; Pushkarev & Zupan, 1975; Zacharias, 2001). The corresponding radii that determine the buffer size can be defined in two ways. According to (Waddell & Ulfarsson, 2003), a 5, 10 or 15-min walk would, respectively, correspond to a 300 m, 500 m or 800 m network radius distance. Another way to determine the radius is by means of average walking speed. Even though this varies across population age groups, (Schimpl et al., 2011) suggest that the lowest average walking speed is found to be 1.2 m/s (for people above 60 years of age), whereas the highest is 1.29 m/s (for people between 40 and 49 years of age). For the longest considered walking trip in our case (i.e., a 15-min walk or 900 s), this would correspond to an $1.29\ m/s \times 900\ s - 1.2\ m/s \times 900\ s = 81\ m$ difference in network radius distance among the different age groups. This difference cannot be reflected in our estimates, given that the resolution of population demographics used in our study is available at $100 \times 100\ m^2$ grid cells. For this reason, we use the average walking speed of 1.26 m/s (i.e., average of all age groups, as defined by (Schimpl et al., 2011)) throughout, to calculate walking trips to different activity locations.

In order to capture the spatial accessibility of each activity location, we represent the case-study environments as a graph. The edges of the graph represent the streets, whereas the nodes represent the street intersections. We then calculate the centroid (i.e., the geometrical center) of each grid cell and identify the closest graph node to this centroid. The resulting node represents the estimated home location of a person, and is used as the origin point in our analyses. We estimate the potential accessibility to different destinations (i.e., activity locations) by calculating walking trips from these origin points, weighed by the length of each street segment and considering the average walking speed defined above[1]. In this way, we calculate the areas accessed on foot within 5, 10, and 15-min trips, and identify the activity locations that lie within these areas. We should emphasize that these denote potentially accessible locations around people's residences and are not based on observed walking trips.

3.2. Age-adjusted co-accessibility

To assess spatial age segregation, we need to look beyond general accessibility to activity locations. For this, we enrich our estimated accessibility measures with a number of age-related variables. First, we calculate the total number of people who have access to each facility within the three considered walksheds. Second, we calculate how many (number and percentage) of these people belong to each age group. As suggested in (Hagestad & Uhlenberg, 2005), instead of accounting for a single age group (e.g. elderly) relative to all others, we consider three main age categories that represent the different walks of life (i.e., children, adolescents and adults, and the elderly). Lastly, within the context of spatial age segregation, it is important to determine not only which age groups have access to each activity location but also to what extent the different age groups have access to the same activity location. To do so, for each activity location we calculate the age diversity of all the people who have access to it by means of Shannon's Equitability Index (EI) (Kent, 2011; Pielou, 1966; Shannon, 1948) using the following formula:

$$EI = \frac{-\sum(P_i \times lnP_i)}{ln(k)} \quad (1)$$

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

4. Data

4.1. Empirical case studies

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

[1] The topography of the studied areas is plain and minor adjustments in the overall walking speed might be required in areas with non-plain topography, though this falls outside of the scope of this article.

4.2. Population demographics

We use the Dutch Central Bureau of Statistics (Centraal Bureau voor de Statistiek, 2020) to collect granular data on population demographics (including household location and age) at a $100 \times 100\, m^2$ grid level. Our population demographics concern the year 2020. In total, the population demographics data include 6949 grid cells for Amsterdam, 5490 grid cells for Rotterdam, 5076 grid cells for The Hague, 3725 grid cells for Eindhoven, and 2988 grid cells for Utrecht. We group residents into three population age categories: *children* (0–15 years old), *adolescents and adults* (16–64 years old), and the *elderly* (equal or above 65 years of age).

4.3. Pedestrian network

We use OpenStreetMap (OSM), an open-source mapping platform containing worldwide geographical data, to collect data on the pedestrian network in the five case-study cities (OpenStreetMap contributors, 2021). The OSM street network has been found to be complete in more than 40% of all countries worldwide (Barrington-Leigh & Millard-Ball, 2017), thereby allowing for replicability of our approach to other cities beyond the ones included in this study. More specifically, we use the *OSMnx* package (Boeing, 2017) to extract walkable streets, by setting the network type to "walk". In this way, we exclude from the analysis streets categorized as motorways, service roads and cycleways, among other categories unrelated to pedestrian movement. OSM data were collected in November 2021. In total, our resulting sample includes 540,896 street segments usable by pedestrians in the five cities. The collected pedestrian street segments lie within the administrative boundaries of the five cities, extended by a buffer of 1 km to avoid potential boundary effects (Hillier, Penn, Hanson, Grajewski and Xu, 1993).

4.4. Activity locations

We use the *Overpass* Application Programming Interface (API) to collect OSM land use data about urban activities. The selection of the activity locations to be included is influenced by Ray Oldenburg's definition of the "third places" (i.e., *"public places that host the regular, voluntary, informal, and happily anticipated gatherings of individuals beyond the realms of home and work"*) (Oldenburg, 1989). We, specifically, extract activity locations where people of different ages perform activities and can socially interact with each other. Subsequently, we exclude land use types that are restricted to a specific population age group (e.g. nightclubs). Similar to the pedestrian network data, we collect activity locations that lie within the administrative city boundaries, extended by a buffer of 1 km. We collected the following activity location types, using the corresponding land use categories: square, park, playground, library, dog_park, beach_resort, swimming_area, cafe, fast_food, food_court, pub, restaurant, marketplace, shop, social_facility, arts_centre, cinema, community_centre, social_centre, theatre, gallery, museum. In total, we collected 30,420 activity locations in September 2021 across the five cities, and more specifically: 10,483 activity locations in Amsterdam, 5226 in Rotterdam, 8118 in The Hague, 4190 in Utrecht, and 2403 in Eindhoven.

5. Results

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

5.1. Co-accessibility of activity locations — Age groups

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

Fig. 2 illustrates the various activity locations across the five case-study cities, classified according to the percentage of a given age group that can access each location relative to all the other groups. In other words, a location yielding a 10% accessibility score in the children's age group would indicate that only 10% of the people who overall have access to it would be children between the ages of 0 and 15. Fig. 2 specifically presents the co-accessibility results pertaining to children (0–15 years of age) and the elderly (65+). The majority of activity locations considered in this article appear to be easily accessible by adolescents and adults (between 16 and 64 years) relative to children and elderly people. For this, we illustrate the percentages of the two latter

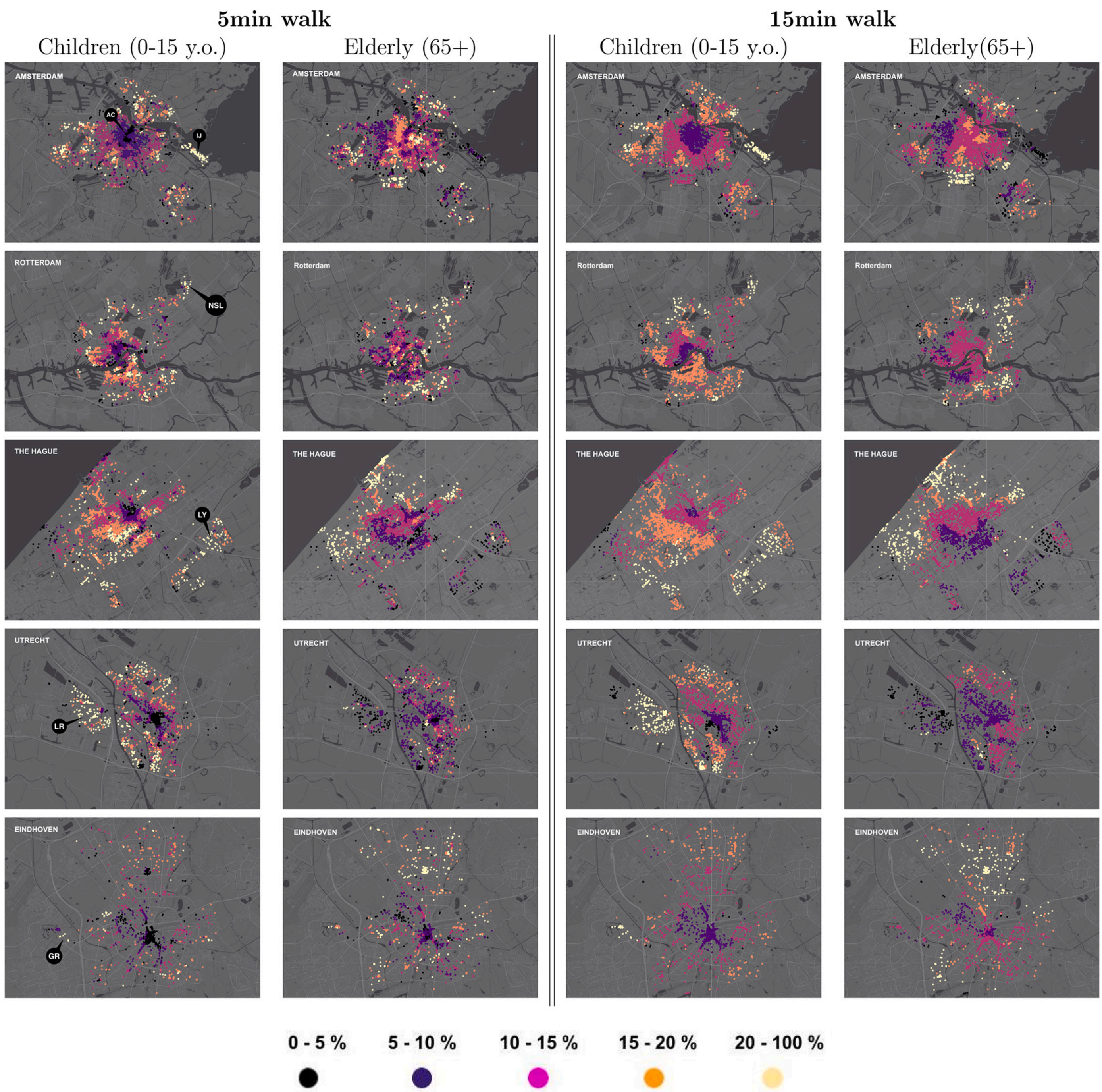

Fig. 2. Activity locations across the five case-study cities, classified according to the percentage of children and the elderly that can access each location relative to all the other groups within two different walking distances (5 and 15-min walksheds).

age groups, as they primarily determine the degree of age diversity at a given destination. Fig. 2 further shows how the different walking radii (five and fifteen-minute walksheds are illustrated in columns) affect the corresponding degree of accessibility across the five case-study cities (rows). We organize the resulting percentages into five classes. The fifth class (i.e., 20%–100%) has a larger increment relative to all others, and corresponds to a relatively small number of locations, where the percentage of either the children or elderly populations — of those accessing the same location — is larger than 20%.

Depending on the city, the largest differences between the percentages of the children and the elderly — of those accessing the same activity location — range between approximately 10% and 50%. An indicative example of this is observed in Amsterdam Center (AC in Fig. 2), where approximately 14% of the total number of people who have access to the activity locations in that area within a 15-min walk from their residence are elderly, and only about 5% are children. Our analysis yields similar results in the Nieuwe Werk (NW) neighborhood of Rotterdam. A notable example of the opposite case is the IJburg (IJ) neighborhood of Amsterdam, where there is a concentration of activities that are predominantly accessible to children relative to elderly populations. Specifically, we estimate that approximately 20–30% of the total number of people who have access to various destinations in IJburg are children and only 2–6% are elderly people. This may further be associated with the age structure of IJburg, where children comprise 23–30% of the total population, whereas only 3–5% are elderly people.

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

5.2. Co-accessibility of activity locations — Age diversity

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

Fig. 3 maps the spatial distribution of activity locations in the five cities with the resulting age diversity scores, considering 5, 10, and 15-min walks from people's residences. The age diversity values are categorized into four classes: low (0–25%), low-to-medium (25–50%), medium-to-high (50–75%), and high (75–100%). Rows represent each of the five cities under study, whereas columns represent the walking trip distances used to determine the accessibility of different destinations.

Across all cities and walking trip distances, the age diversity scores of most areas range from medium-to-high (i.e., 50% < EI < 75%) to high (EI > 75%). An emerging pattern, visible across all the cities under study, is that activity locations with higher age diversity scores tend to be located in the city outskirts. Examples of such areas include Buitenveldert (BU) in Amsterdam, Scheveningen (SC) in The Hague, Overvecht (OV) in Utrecht, Vaartbroek (VA) in Eindhoven and the northern and southern precincts of Rotterdam. In contrast, across all cities, activity locations with low age diversity scores (i.e., EI < 25%) tend to be located in the Inner City (IC) neighborhoods. This, is mostly visible when considering activities accessible within a five-minute walk distance from people's residencies. Overall, activities within a 10 or 15-min walk from people's residencies yield higher age diversity scores.

Fig. 4 provides further insight into the distribution frequency of the various destinations relative to their age diversity scores for the three walking trip distances. The width of each plot is scaled by the number of activity locations with a given age diversity score, whereas the centerline illustrates the value distribution and the median (denoted with a white dot).

The plots illustrated in Fig. 4 highlight two distinctive cases. On the one hand, the majority of activity locations in Amsterdam, Rotterdam, and The Hague appear to have relatively similar and high age diversity scores (i.e., EI > 60%, with most values revolving around the median). On the other hand, the age diversity values of activity locations in both Utrecht and Eindhoven are more evenly distributed. These results suggest that individuals who perform activities within Amsterdam, Rotterdam, and The Hague are, overall, more likely to encounter people of different ages than individuals who perform activities in Utrecht and Eindhoven. However across all the cities under study, while this is not clearly visible in Fig. 4, there are several activity locations with relatively low age diversity scores. For example, there are 314 and 78 activities in Utrecht accessible within a 5 and 15 min walk, respectively, by sets of people of age diversity lower than 20%. People who perform activities in these locations are less likely to be exposed to an age diverse set of people.

Moreover, the diagrams of Fig. 4 further support the previously mentioned observations regarding the effect of walking distance on the resulting age diversity scores. In particular, destinations that lie within a 10 or 15-min walking distance tend to yield higher age diversity scores, relative to those that lie within a 5-min walk. This is particularly evident in the cases of Utrecht and Eindhoven.

6. Discussion

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

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

Our results suggest that the likelihood of an individual to be exposed to people from different age groups when visiting various destinations is influenced by the location of these destinations. For instance, as shown in Fig. 3, individuals who perform activities within the IJburg (IJ) neighborhood of Amsterdam are less likely to encounter elderly people. Specifically, among all the people who have access to activities located in this neighborhood, only 2–6% appear to be elderly (i.e., 65+ years of

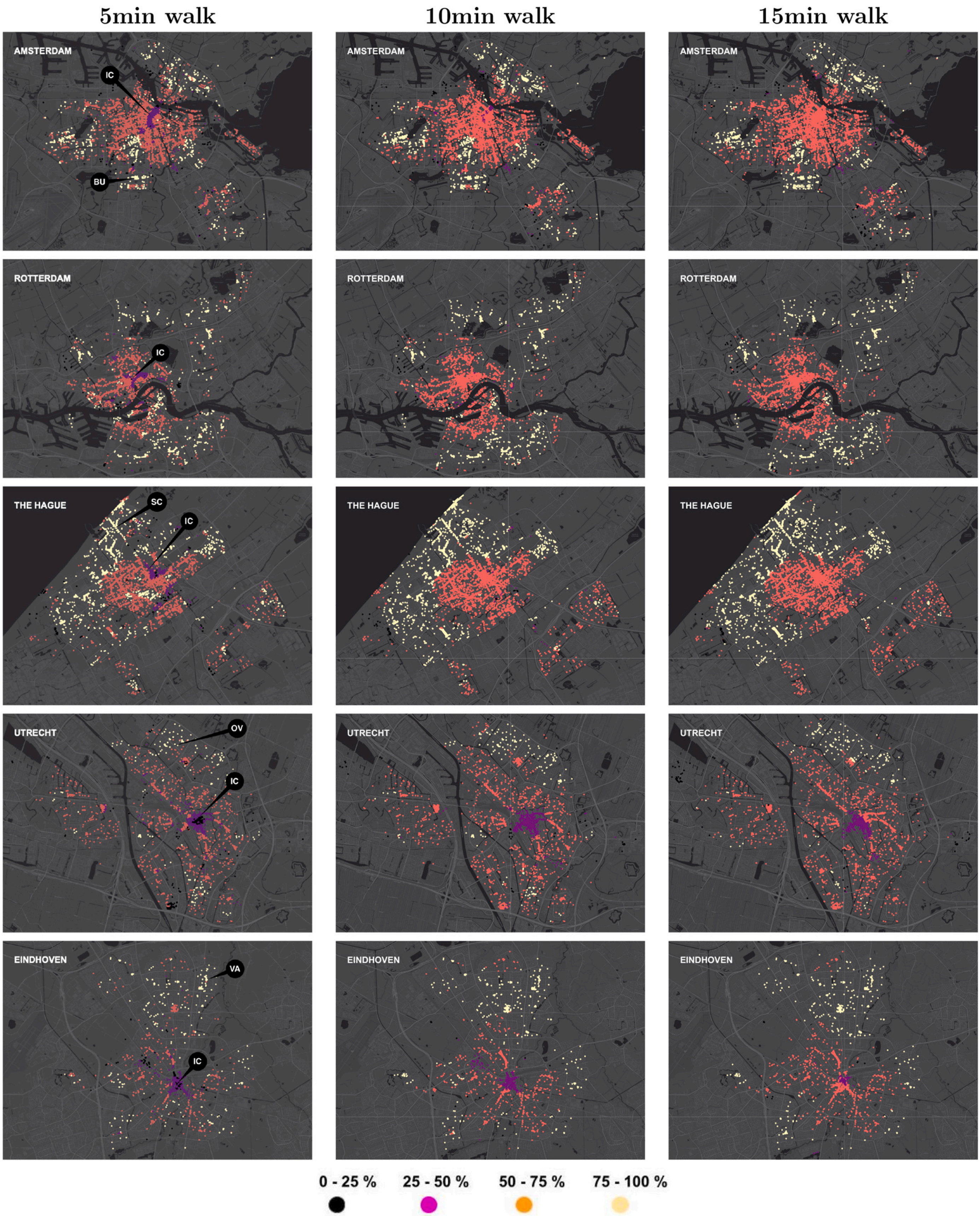

Fig. 3. Activity locations based on the age diversity of the people who have access to them within a 5, 10, or 15-minute walk.

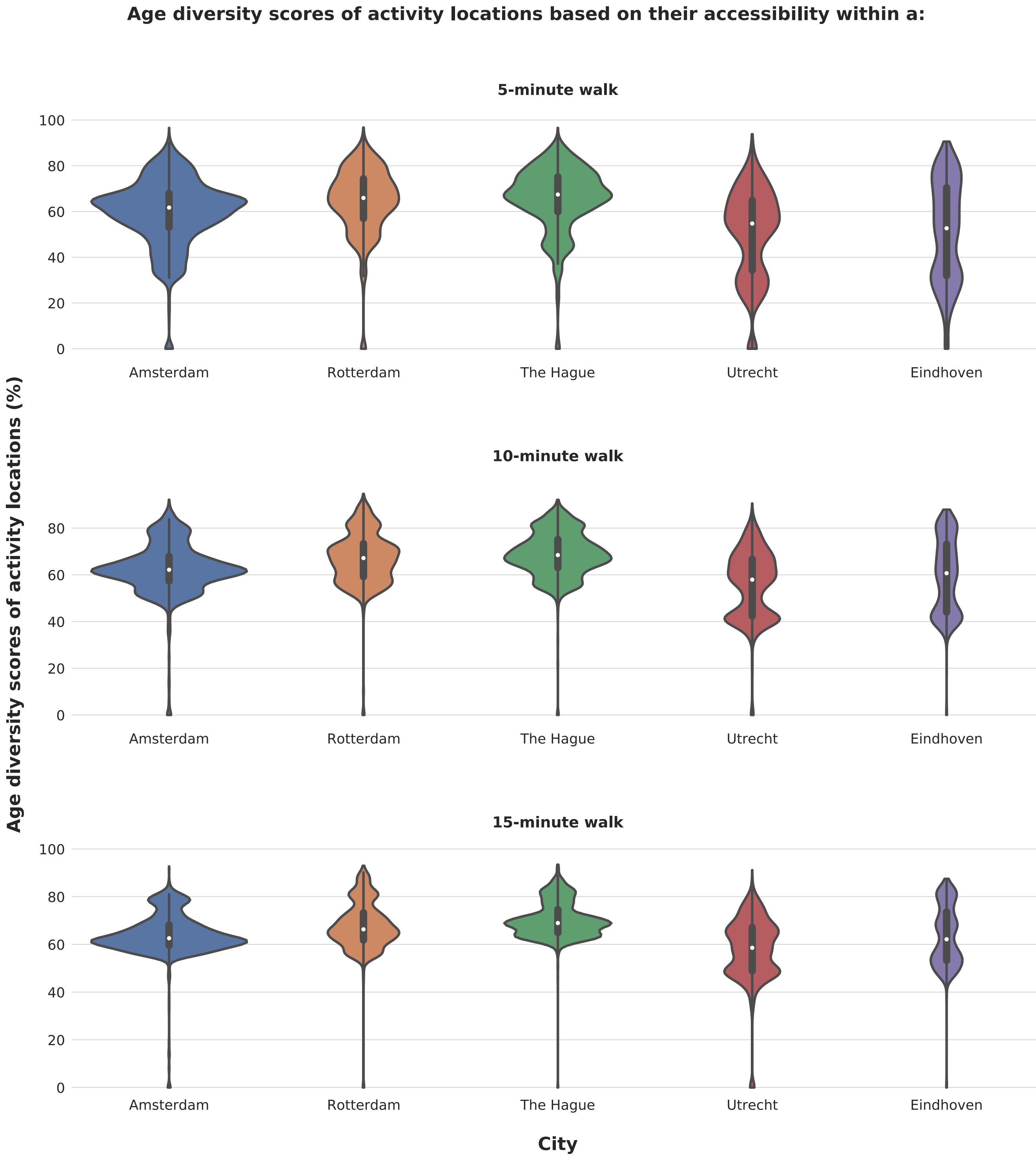

Fig. 4. Frequency distribution of all activity locations by the age diversity of the people who have access to them. The y axis shows the age diversity. The width of each plot reflects the number of activity locations.

age). IJburg is a relatively new neighborhood (first residents moved in there in 2002) and one of the most child-rich neighborhoods of Amsterdam. Our results suggest that, similar to IJburg, other neighborhoods under the so-called "Vinex" policy[2], tend to contain activity locations that are more accessible to children relative to elderly populations. Examples of such neighborhoods include Nesselande (NSL) in Rotterdam, Leidsche Rijn (LR) in Utrecht, Leidschenveen-Ypenburg (LY) in The Hague, and Grasrijk (GR) in Eindhoven.

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

The effect that the spatial distribution of activities has on the co-accessibility and age diversity scores is further supported by the results of the distribution frequency analysis, illustrated in Fig. 4. In particular, our results suggest that the majority of activity locations are accessible to a set of people that is characterized by a medium-to-high age diversity (i.e., 50% < EI < 75%) in Amsterdam, Rotterdam, and The Hague, and by a low-to-medium age diversity (i.e., EI < 50%) in Utrecht and Eindhoven. A potential explanation of this discrepancy could be that in the case of Utrecht and Eindhoven both population density and the density of activity locations are the lowest among the five cities under study. Subsequently, the various destinations appear to be accessible to a lower number of people with a rather unequal representation of the three age categories at hand. Lastly, our results suggest that the time required to reach a destination also influences the co-accessibility and age diversity scores. In particular, destinations that lie within a 10 or 15-min walk yield higher age diversity scores, relative to destinations within a 5-min walk from people's residences (accessible to a lower number of people). This further indicates that promoting people to perform activities only within a 5-min walking radius potentially decreases the likelihood of encountering people from different age groups.

6.1. Comparison of age diversity scores — Activity versus residential space

Existing approaches to measuring spatial age segregation make almost exclusive use of spatially aggregated data (e.g., at the neighborhood or city level) about the distribution of age groups in the residential space to evaluate the level of age segregation. This section discusses how the co-accessibility score at the activity location level proposed by our methodology could further complement and enrich the existing approaches. To do so, we compare two different types of age-diversity estimates of activity locations: one based on the age structure of people who have access to each activity location within a 15-min walk from their residence (similar to what is presented in Section 5.2), and another one based on the age structure of people who reside within the same neighborhood where the various activities are located, assuming equal distribution of age structure over each neighborhood's geographic space. Fig. 5 illustrates the differences between these two approaches.

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

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

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

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

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

[2] Vinex (stands for "Fourth Memorandum on Extra Spatial Planning" in Dutch) neighborhoods were created based on a 1991 policy briefing note from the Dutch Ministry of Housing, Spatial Planning and the Environment. Based on this note, large outer city areas were designated for new housing development. Vinex neighborhoods led to an overall increase of the number of young children who grow up in an urban environment (Centraal Bureau voor de Statistiek, 2013).

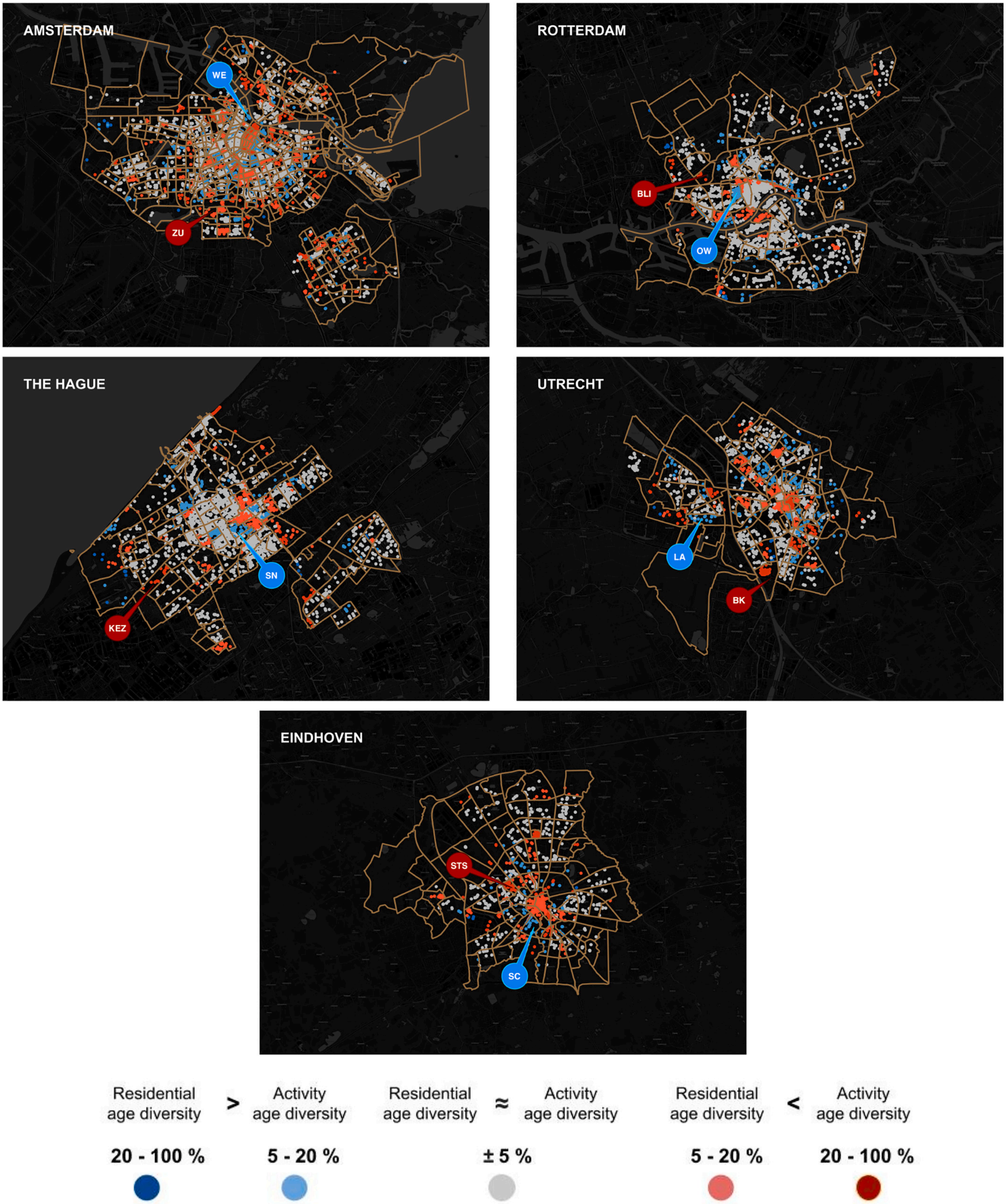

Fig. 5. Points represent the various activity locations within each neighborhood (delineated by its administrative boundary). We compare the age diversity scores of each activity location if calculated according to (1) the set of people who have access to it within a 15-min walk from their residence (i.e., our approach), and (2) the set of people who reside in the same neighborhood where each activity is located, assuming equal distribution of age structure over geographic space (i.e., existing approaches). Differences between the two measurements are indicated by different colors. Specifically, blue indicates that the scores resulting from existing approaches are higher than those estimated with our approach. Red colors indicate the opposite. Gray colors indicate activity locations where both approaches yield similar results. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

experience age segregation in their daily encounters.

6.2. Limitations

There are several limitations in this study that could be addressed in future research. First, we chose to focus our analyses only on one mode of travel, namely walking. Thereby, the results of our analyses reflect pedestrian access measured from people's residencies. Our work can be extended to further account for biking trips and other modes of transport, such as public transportation. Second, our calculations are not based on actual walking trips, but are rather based on the assumption that people tend to perform activities at destinations close to their place of residence. As such, they in fact reflect potential access to different activity locations within different walking distances (i.e., 5, 10, or 15-min walking trips) from home. Data on actual walking trips and visiting patterns (i.e., indicating when and for how long people visit given places), if available, can be easily integrated in our methodology and would provide more accurate estimates of the level of potential encounters. Third, pedestrian mobility behavior may further vary across cities, countries, cultures, or by the type of destination (e.g., people generally tend to visit the closest retail or grocery store to their home, as opposed to more specialized activities for which they might travel longer distances). Fifth, drawing on insights from related work on pedestrian mobility, the characteristics and quality of the routes may substantially influence the routing choices of pedestrians. Examples include scenic environments, differences in the quality of sidewalks, and the mixture of land uses along streets, among others (Miranda, Fan, Duarte, & Ratti, 2021; Sevtsuk & Kalvo, 2020). Our methodology could be extended to further consider these variations in qualitative characteristics and attractiveness scores. Lastly, our analyses use people's residences as origins. In future work, we could consider additional daily activity locations (e.g., schools, workplaces) as origins in our accessibility analyses.

7. Conclusion

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

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

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

Author contribution statement

Vasileios Milias and Achilleas Psyllidis equally contributed to the study conception, research design, and writing of the draft and revised manuscripts. Vasileios Milias further contributed to the data curation, formal analysis, and methodology.

Declaration of Competing Interest

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

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