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How does pedestrian accessibility vary for different people? Development of a Perceived user-specific Accessibility measure for Walking (PAW)

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ABSTRACT

Current accessibility measures assume that all people are the same, whereas in reality there are many different user groups with different needs and perceptions. Furthermore, the concepts of walking accessibility and walkability are often analysed independently from each other. This leads to a mismatch between calculated accessibility and perceived accessibility. This paper seeks to propose a new methodological approach that considers user-specific perceptions and walkability needs when calculating pedestrian accessibility. A Perceived user-specific Accessibility measure for Walking (PAW) is developed for four sample user groups: seniors, children, women, and wheelchair users. This is done by adjusting the Geo Open Accessibility Tool (GOAT) and imputing the perceptions. Per user group, the most important walkability attributes are therefore included in the accessibility formula and weighted according to their relevance based on the literature review using the Analytic Hierarchy Process (AHP) method. Results for a district of Munich, Germany are visualised. When juxtaposed with conventional time-based accessibility measures, our results unveil a more nuanced understanding of pedestrian infrastructure and its variabilities across different user demographics. This approach can help to provide a more realistic portrayal of pedestrian accessibility and to uncover critical gaps in current infrastructure, tailored to the needs of diverse population groups. The method can assist urban and transport planners in designing more inclusive, equitable urban environments. This contributes to a shift towards cities that are not only walkable but also attuned to the diverse needs and perceptions of their residents, ultimately enhancing quality of life and promoting equitable access to urban amenities.

1. Introduction

In order to create “cities for people” (Gehl, 2010) that are walkable for all, it is crucial to consider the needs of the different users. To open up this perspective, we need new planning instruments that take the needs of different user groups into account. For walking, *accessibility* is one of the fundamental needs (see *Fig. 1*), coming right after *feasibility*, which refers to the practicality or viability of a

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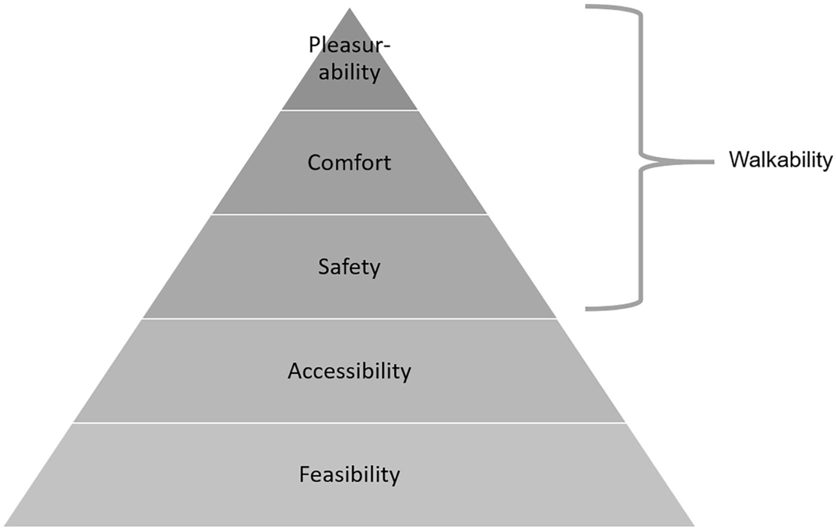


Fig. 1. The concept of the hierarchy of walking needs. Adapted from Alfonzo (2005).

walking trip (Alfonzo, 2005). In this context, *accessibility* refers to the "potential of opportunities for interaction" (Hansen, 1959), which is dependent on the proximity of destinations and the connectivity of the paths (Handy, 1996). Thus, accessibility instruments are suitable tools for evaluating and improving the walking conditions in a city.

However, to fulfil the needs of pedestrians, it is not enough just to provide destinations and connected paths; the paths also need to be safe, comfortable and pleasant – in other words, *walkable*. Being *walkable* means that "residents of all ages and abilities feel that it is safe, comfortable, convenient, efficient, and welcoming to walk, not only for recreation but also for utility and transportation" (American Planning Association, 2006). Depending on the walkability of a place, the pedestrian perceives the walking time differently, i.e., attractive routes feel shorter than unattractive ones (Bahn.Ville 2-Konsortium, 2010; Ralph et al., 2020; Gehl, 1971). *Perception* is subjective and refers to how something is understood or interpreted. Exactly how a path is perceived depends strongly on a person's characteristics, abilities and resulting needs. Thus the perception differs among users.

1.1. Accessibility

After the first definition of accessibility by Hansen (1959), which focused on the proximity of destinations, the definition was expanded to include the *ease* with which the destinations can be reached (Koenig, 1980; Niemeier, 1997). In 2000, the definition was further expanded by Bhat, et al. (2000) to "a measure of the ease of an individual to pursue an activity of a desired type, at a desired location, by a desired mode, and at a desired time", now including the *ease of an individual*. Following this, Geurs and van Wee (2004) defined accessibility as "the extent to which land use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)" and cluster its influential factors into four components: land use, transportation, temporal and individual. Hence, over time, individual(s) have gained a central role in the accessibility concept. However, at the same time, the individual component is often neglected in practice (Amaya et al., 2022) with most of the walking accessibility studies assuming that calculated travel distance and/or travel time are the only factors influencing walking accessibility (Merlin and Jehle, 2023), disregarding other factors such as personal abilities and perception.

Accessibility studies can be divided into two approaches: *calculated* and *perceived* analyses. *Calculated* analyses calculate accessibility using spatial data, while *perceived* analyses are based on surveys or reported data. When comparing the results of both approaches for one specific study area, many studies found a mismatch between calculated accessibility and perceived accessibility (Curl et al., 2015; Damurski et al., 2020; Finger and Jedrychowski, 1989; Gebel et al., 2011; Jehle et al., 2022; Lättman et al., 2018; McCormack et al., 2008; Pot et al., 2021; Ryan and Pereira, 2021; Ryan et al., 2016; van der Vlugt et al., 2019; Wilson et al., 2004). This leads to an overestimation of accessibility levels (Curl et al., 2015; Ryan and Pereira, 2021). The reason for this is the missing perception of different user groups in the calculated accessibility measures. The measures treat all people the same, although "the key is to measure accessibility in terms that matter to people in their assessment of the options available to them (Handy and Niemeier, 1997). [...] For the transportation component of accessibility, this means knowing something about what characteristics of different modes of travel matter to people" (Handy and Clifton, 2000). For walking, it is therefore necessary to work with imputed perceptions (Merlin and Jehle, 2023), i.e., to include the walkability elements and user group specific perceptions in order to achieve more realistic results.

1.2. Walkability

While *walking accessibility* is about the existence of destinations and connected pedestrian routes to get there, *walkability* is mainly about how easy it is to walk the routes and/or how surroundings are perceived by people. Many studies have proven that the walkability has an impact on walking behaviour (Carver et al., 2005; De Vries et al., 2010; Owen et al., 2004; Timperio et al., 2004; Wendel-Vos et al., 2004). Although there are many different definitions of *walkability*, most of them name "safety", "comfort" and "pleasurability" as key elements (American Planning Association, 2006; Litman, 2003; Spoon, 2005). Each of those elements is influenced by a multitude of walkability attributes, such as sidewalk width, land use and presence of vegetation (see e.g. Jehle et al., 2022).

However, some walkability definitions also include the terms "accessibility", "connectivity" and "presence of destinations" (Spoon, 2005; Southworth, 2005), which shows the strong links and sometimes fluid boundaries between the concept of accessibility and walkability. In summary, it can be said that the concepts of walkability and accessibility complement each other. Thus, in order to generate realistic analyses, the components from both concepts should be merged and considered in a more integrated way. Some studies, such as Jonietz and Timpf (2012), Anciaes et al. (2015), D'Orso and Migliore (2018), Erath et al. (2017) and Blečić et al. (2018) have already developed first approaches in which walkability attributes were integrated in walking accessibility measures. However, they assumed that walkability is the same for all pedestrian groups, which is not the case (Chan et al., 2021).

1.3. Integration of user needs

According to the capability approach, the capability of a person is related to two main elements: first to the intrinsic ability of the person (combination of all their physical and mental abilities) and second to the characteristics of the environment that affect that capability (Nussbaum, 2020). In other words: people themselves are not disabled, but they are disabled by the environment; for example, stairs without a ramp disable wheelchair users.

The way a person perceives the walking environment depends on multiple personal, social, cultural and economic factors, such as age, gender, nationality and income, which differ among users; thus, each person has their own perception. This individual component is considered in the theoretical accessibility concept but is only applied in very few studies.

Focusing solely on walkability (without access to destinations), there are some user-specific walkability studies. For example, Moura et al. (2017) measure walkability for four different pedestrian groups: children, adults, seniors and impaired pedestrians. They find that: "differentiating the analysis for different types of pedestrian groups and/or trip motives does have a significant impact on the walkability evaluation. What is a reasonably good walking environment for fit adults can be a lot less convenient for seniors or even bad for impaired mobility pedestrians". Beale et al. (2006) developed customisable routing for wheelchair users, which takes slope, surface and obstacles into account as impedances. Furthermore, the popular walkability survey NEWS (Neighbourhood Environment Walkability Scale) (Saelens et al., 2003) was adjusted to serve the needs of different user groups, such as the NEWS-Y for youth (Rosenberg, 2009) or the NEWS-CC for Chinese children (He et al., 2021).

Likewise, some user-group specific walking accessibility studies were found. For example, García-Palomares et al. (2013) use different walking distance thresholds and decay functions for different age groups. Cheng et al. (2019) investigate walking accessibility to recreational amenities for elderly people by using adaptive thresholds for walking distances. Both focus on the fact that accessibility changes as a consequence of differences in individual willingness to reach destinations (Arranz-López et al., 2019); however, they did not include walkability attributes.

Two recent studies were found that consider all three – accessibility, walkability and differentiation per user group. Amaya et al. (2022) assessed accessibility for three different user groups: older adults in good health, older adults with a chronic disease, and older adults with reduced mobility. To do so, they considered the pedestrian network, facilities and shops, public benches, slopes and gradients. They state that "the present findings provide a framework for accessibility analysis. Policymakers and urban planners should be aware that accessibility is sensitive as it is conditioned not only by the environmental and urban factors of the territory, but also influenced by the physical and health characteristics of the study population." Gaglione et al. (2021) measured accessibility of older people by taking ten walkability attributes into account (slope, sidewalk width, surface, illuminance, traffic volume, presence of escalators, presence of benches, presence of green areas, presence of panoramic points, road type). However, both studies point out the limitation that only selected walkability attributes were considered and see a need for further research that includes additional walkability attributes.

1.4. Research gap and objective of the paper

Summarising the current findings, we follow the hypothesis that one accessibility index alone is not sufficient to represent all individual needs, capabilities and preferences. Rather, a variety of user-specific indices is required. Thus, urban and transport planners currently lack appropriate measures for analysing how different people perceive walking accessibility to different destinations. Consequently, it is crucial to include accessibility as well as walkability attributes because both influence the perceived walking accessibility. The goal of this paper is to develop a methodological approach of an "**P**erceived user-specific **A**ccessibility measure for **W**alking (**PAW**)", following the recommended practice of Merlin and Jehle (2023). This can be achieved by using perceived travel time as impedance and including the users perceptions on path and environmental attractiveness (Gaglione et al., 2021; Boakye-Dankwa et al., 2019).

One key activity thereby is to identify the most relevant attributes for measuring walking accessibility for different user groups based on age, gender and capabilities. As walking needs and perceptions not only differ based on people, but also based on places

(Jehle et al., 2022), a global review on perception studies provides an average across different cities and countries. While Chan, Schwanen and Banister see the application of different weights as appropriate when large enough sample sets are taken into account (Chan et al., 2021), the primary goal of this research is not to conclusively evaluate the impact of each individual attribute, but rather to establish a versatile method that can be adapted according to varying input parameters and applied in diverse contexts.

2. Methodology

Aiming to close this research gap and to take user-specific perceptions and needs into account when analysing walking accessibility, PAW was developed for four sample user groups based on gender, age and capabilities: children, seniors, women and wheelchair users.[1] The methodology has been divided into several stages, which will be explained in detail in the following sections. *Fig. 2* provides an overview.

2.1. Literature review

First, a literature review was conducted, focused on walkability studies to identify the main attributes that influence walkability in general (see *Section 3.1*) and then specified to walkability for each of the four selected user groups (see *Section 3.2*). The main keywords for the selection criteria were among others “walkability”, “walking”, “walkability perception”, “pedestrian”, “pedestrian planning”, “urban design”, “built environment”, “pedestrian comfort”, “walkability score”, “walking accessibility” and “street design”, together with “seniors”, “women”, “children” and “wheelchair users” respectively for the user group. To determine the needs and preferences per user group, only articles or guidelines that provided some kind of analysis or ranking of the walkability attributes were selected. A total of 121 articles were reviewed and 40 were selected as input for the weighting schema, based on the included user group perception and evaluation data.

2.2. PAW development for each user group

After identifying the most important walkability attributes from the literature review, the development of PAW was performed in four stages.

2.2.1. Weighting schema

For each of the identified walkability *attributes* $\boldsymbol{a}$, its perceived impact for each *user group* $\boldsymbol{u}$ was analysed and translated into a numerical *weighting factor* $\mathbf{z}_{\boldsymbol{u},\boldsymbol{a}}$ by first conducting a pre-analysis and then using the Analytic Hierarchy Process Online System (AHP-OS)[2]. This system was developed by Goepel (2018) based on the AHP methodology developed by Saaty (1987); which has also been used by other studies in this field (e.g. by Arranz-López et al., 2017; Gaglione et al., 2021). AHP is a method to support multi-criteria decision making that derives ratio scales from paired comparisons of criteria. Inputs can be actual measurements, but also subjective opinions (Goepel, 2018). As a result, weightings and consistency ratios are calculated. Mathematically the method is based on the solution of an eigen value problem (for further explanation see Goepel, 2018; Taherdoost, 2017).

We chose this method because it allows the comparison and ranking of different perceptual attributes in a rather objective way. It provides a systematic framework for bringing together the results of multiple studies and reaching a consensus based on the combined input. *Fig. 3* summarizes the steps of the weighting schema. These are performed for each user group separately. To ensure consistency in the rating, this whole weighting process was conducted by two of the authors whereby each of them was responsible for one or more user groups. For each user group, 10 research papers were considered that assessed their perception of walkability.

In detail, the following steps are performed, separately for each user group:

a. We searched for studies that address the importance of different walking attributes (see *Fig. 3*-a).
b. The walkability attributes were organised into a hierarchical structure in an Excel spreadsheet, considering the importance given to them in each study (see *Fig. 3*-b). For this purpose, we gave them an initial value according to their importance (1 = most important; 2 = second most important; etc.) in each study. While some papers provided a clear ranking of the attributes, others only roughly described the importance in the text. Thus, sometimes the ranking had to be done subjectively by interpreting the provided text.
c. We ranked the attributes based on the number of these values. For example, the attribute with the highest number of “1 (most important)” values was rated as the most important attribute across all studies. The result was a final list with a ranking of walkability attributes (see *Fig. 3*-c). If two different attributes resulted to have the same importance, they are sharing a ranking position.
d. Based on this result, we selected the 20 most important attributes (as AHP-OS is limited to this number of input variables) and established the priority order (see *Fig. 3*-d).
e. We manually input the data into the web tool AHP-OS to perform the pairwise comparisons between all attributes (190 pairwise comparisons) to determine the relative importance of the attributes (see *Fig. 3*-e). For this, each attribute is compared with the

[1] Although we use these user groups as representative groups to identify with, we acknowledge that each of these groups includes heterogeneities in terms of perception and needs that cannot be generalised as they depend on various personal, social, cultural or economic factors.

[2] Available at: https://github.com/bpmsg/ahp-os

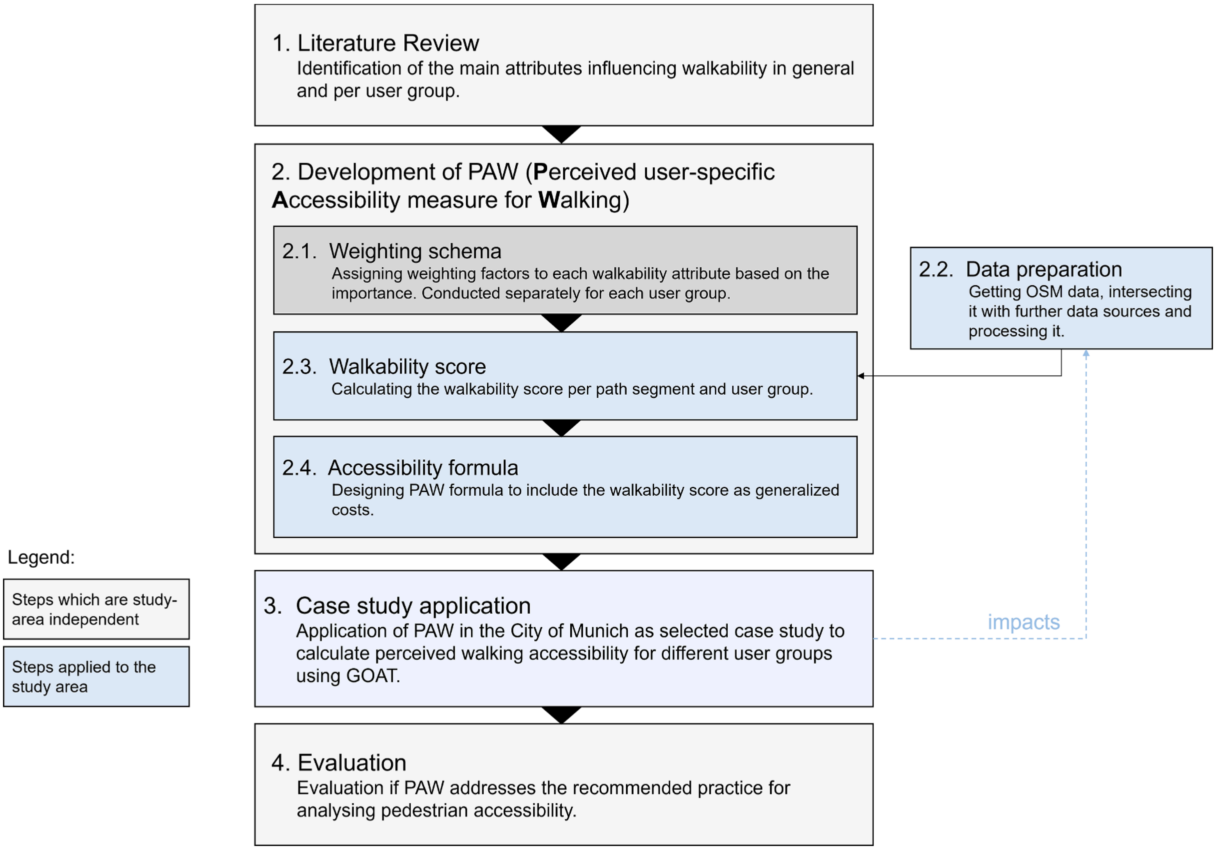


Fig. 2. Methodological overview.

others to determine the relative importance, using a scale of 1–9, where 1 means equal importance, 3 means moderately more important, 5 means strongly more important, and so on. Same as for step b., the relative importance value is given by the authors according to the results of the reviewed articles. In some of the reviewed papers the relative importance was clearly stated, while in others it was rather subjective of how we interpreted the texts written by the researchers. The result is a pairwise comparative matrix. The software normalizes the weights and produces a final weighting list for all attributes.

The results of the weighting schema for all user groups can be found in *Subsection 3.2.5*. An extended version of the table with information on the references used is provided in *Appendix 1*.

To validate the results of the AHP, the APH-OS provides the *consistency ratio* ***CR***, which is calculated through the following formula (Goepel, 2018):

$$\boldsymbol{CR} = \frac{\boldsymbol{\lambda} - \boldsymbol{n}}{2.7699 * \boldsymbol{n} - 4.3513 - \boldsymbol{n}} \tag{1}$$

CR: Consistency ratio
λ: dominant eigen value of the pair wise comparison matrix
n: number of attributes

A CR of ≤10 % is considered as acceptable to work with the results of the AHP analysis (Saaty, 1987). This was fulfilled for all user groups (the achieved CR values per user group can be found in *Subsections 3.2.1* to *3.2.4*).

2.2.2. Data preparation

For the development of the accessibility measure, the Geo Open Accessibility Tool – GOAT[3] developed by Pajares et al. (2021) was used as a basis and adjusted accordingly. The tool uses OpenStreetMap (OSM) data for the pedestrian network, which is found to be the

[3] Available at: https://github.com/goat-community/goat.

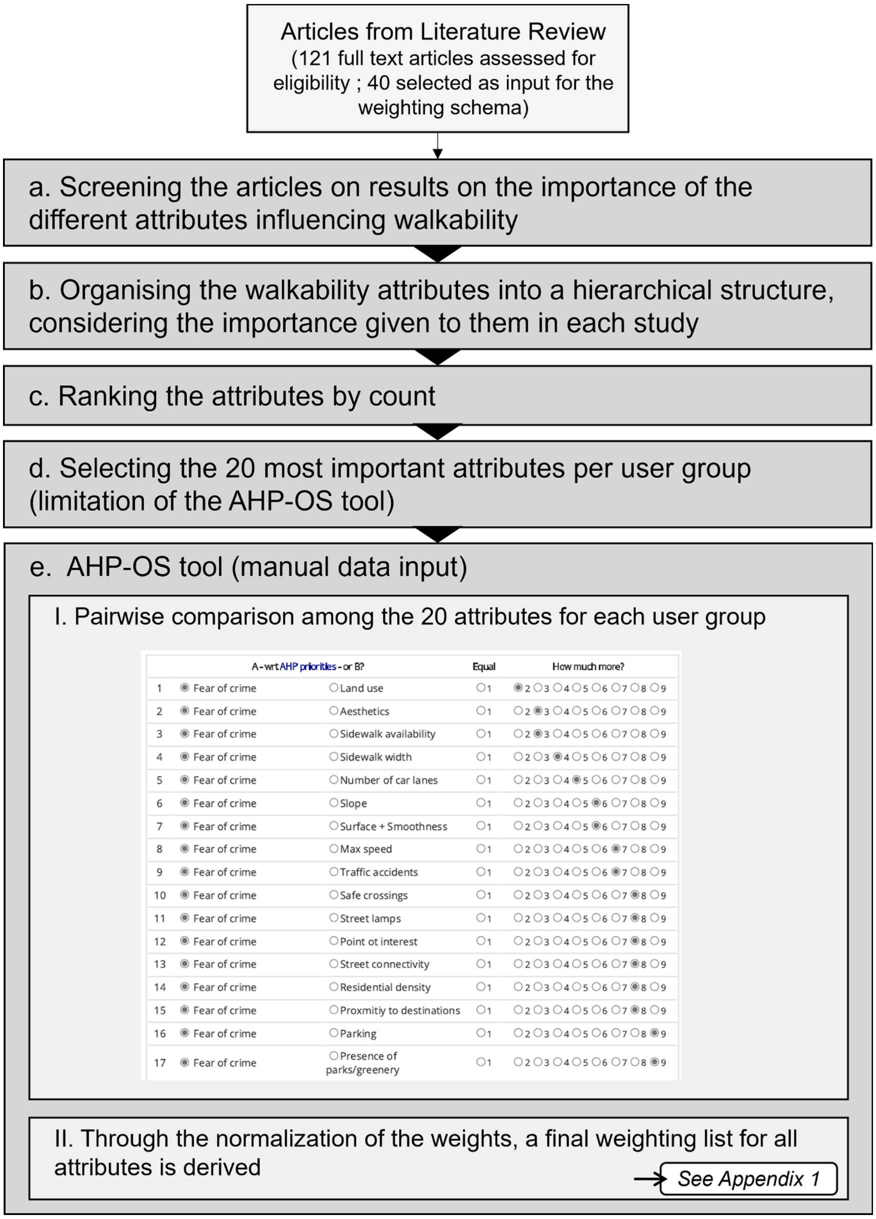


Fig. 3. Method to derive the weighted attributes per user group.

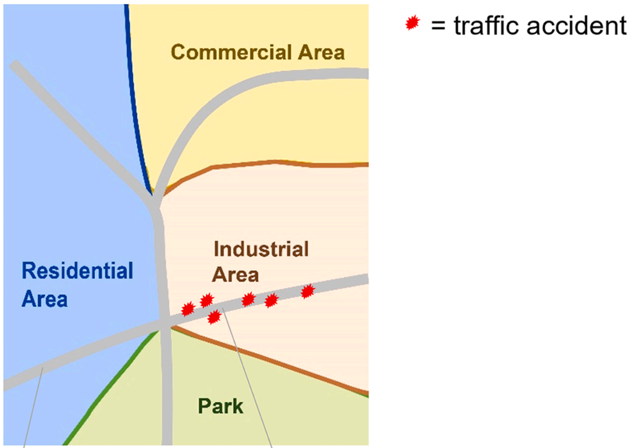
richest data source for the walkability items, and can be fed with unlimited additional data sets.

To prepare the data for the study area, first, the walking network and the surrounding objects were derived from OSM and stored in a PostgreSQL/PostGIS database. From OSM, the path elements are already provided with information on some walkability attributes (e.g. street category, sidewalk availability, surface, smoothness, slope, wheelchair-usability, number of car lanes, maximum speed, parking, illuminance). Other walkability attributes refer to punctual objects (e.g. accidents) or polygon objects (e.g. land use). Using spatial queries, buffers around points were created and the polygons intersected with the paths. In this way, the information for all walkability attributes was derived and assigned to each respective path segment (see Fig. 4).

2.2.3. *Walkability score*

The methodology from the Walkability Index (WALKIE) developed by Jehle and Pajares (2021) is used to obtain one quantitative walkability score per *user group* $\boldsymbol{u}$ and *path segment* $\boldsymbol{p}$.

First, all the *attribute values* are translated into *attribute scores* $\boldsymbol{s_a}$ (see Fig. 5-a). To do so, a score range from 0 to 100 is used, with 0 indicating the lowest and 100 the highest quality. A medium value of 50 represents the ‘average’ walking quality. For example, an excellent smoothness is awarded 100 points, while an intermediate smoothness is awarded 50 points and an impassable smoothness



Attribute a	Attribute value
Way category	Living street
Sidewalk availability	Both
Surface	Paving stones
Number of car lanes	0
Maxspeed	7
Illuminance	Yes
Land use	Residential
Traffic accidents	0
…	…

Attribute a	Attribute value
Way category	Secondary
Sidewalk availability	Right
Surface	Asphalt
Number of car lanes	4
Maxspeed	50
Illuminance	Yes
Land use	Industrial
Traffic accidents	6
…	…

Fig. 4. Schematic illustration of the data preparation procedure.

0 points. A table with all of the attribute scores is provided in the *Appendix 2*. Due to a lack of available studies on how each individual attribute value influences the walkability perception of a specific user group, the same value scores are used for all user groups. In this case, the attribute scores were defined specifically for this study area (based on the values that are found there).

Second, the *attributes* $\boldsymbol{a}$ are matched with the respective *weighting factors* $\boldsymbol{z_{a,u}}$ for each *user group* $\boldsymbol{u}$ (see Fig. 5-b). Third, a *walkability score* $\boldsymbol{w_{p,u}}$ is calculated per *path segment* $\boldsymbol{p}$ and *user group* $\boldsymbol{u}$ (see Fig. 5-c), by the following formula:

$$\boldsymbol{w_{p,u}} = \sum_{a} \boldsymbol{s_a} {}^{*} \boldsymbol{z_{a,u}} \tag{2}$$

$w_{p,u}$: Walkability score of *path segment* p for *user group* u
s_a: Score of *attribute* a
$z_{a,u}$: Weighting factor of *attribute* a for *user group* u

As for the attribute scores, the walkability score ranges from 0 to 100, representing the ease of walking. The results are visualised in *Section 3.3*.

2.2.4. *Accessibility formula*

To incorporate the walkability score of a specific user group in accessibility analyses, a contour-based accessibility measure (isochrone) was used as an approach, with limiting accessibility to walking and extending the generalised cost term by the walkability perceptions. Accessibility can be conceptualised using the following mathematical expression (Geurs and van Wee, 2004):

Fig. 5. Schematic illustration of the walkability score calculation.

$$A_i = \sum_j D_j f(c_{ij}) \tag{3}$$

A_i: Accessibility of place i
D_j: Destination potential found at location j
c_{ij}: Generalised costs of travelling (**walking**) between i and j
$f(c_{ij})$: The impedance function applied to the generalised costs of travel between i and j

Contour-based measures show the number of opportunities that can be reached from one point within a certain distance, time interval or costs. They are valued for their easily interpretable results (Geurs and van Eck, 2001; Albacete, 2016), but have the drawback of not distinguishing between different travel times within the cut-off range c_{max} (Bertolini et al., 2005), as they follow basic impedance functions, such as (El-Geneidy and Levinson, 2006):

$$f(c_{ij}) = \begin{cases} 1 & for\ c_{ij} \leq c_{max} \\ 0 & else \end{cases} \tag{4}$$

So far, the generalised cost term for walking is usually solely comprised of the time and uses an average speed for all users:

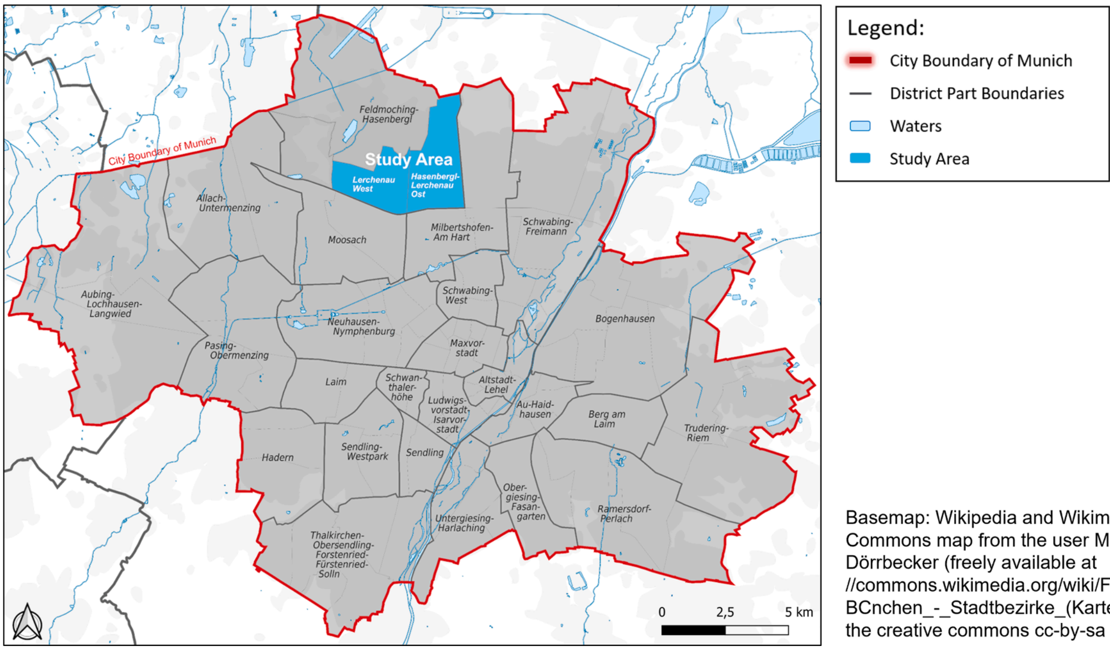
$$c_{ij} = \frac{L}{v_{\varnothing}} \tag{5}$$

L: Length [m]
$v_{\varnothing}$: Average speed [m/s]

For PAW, the formula has been extended by integrating walkability impedances and incorporating different speeds for different user groups:

$$c_{ij} = \sum_p \frac{L_p * \left(\frac{50}{w_{p,u}}\right)}{v_{\varnothing u}} \tag{6}$$

L_p: Length of *path segment p* [m]
$v_{\varnothing u}$: Average speed of *user group u* [m/s]



Basemap: Wikipedia and Wikimedia Commons map from the user Maximilian Dörrbecker (freely available at //commons.wikimedia.org/wiki/File:M%C3%BCnchen_-_Stadtbezirke_(Karte).png under the creative commons cc-by-sa 2.5 license).

Fig. 6. Study area.

This imputes the perceptions and represents that a path sequence is perceived as longer if it is unattractive, and conversely that an attractive path segment feels shorter. Untermann (1984) claims that the acceptable walking distance can be doubled through high walkability levels. To represent this, the concept of "perceived time", which has also been used by other authors in comparable studies (e.g. Erath et al. (2017); Gaglione et al. (2021); Boakye-Dankwa et al. (2019)), was applied. Therefore, for this study, the 'standard' walkability score is defined as 50. For walkability scores > 50, the time is perceived shorter and for walkability scores < 50, the time is perceived longer.

2.3. Case study application

To test the developed PAW, it was applied to a selected study area in the City of Munich.

Table 1
List of walkability attributes from literature review and data availability for the study area.

Walkability Categories	Attributes	References	Data source
Infrastructural quality and comfort	Way category	(Moura et al., 2017)	OSM
	Sidewalk availability	(Handy and Clifton, 2001; McGinn et al., 2007; Lo, 2009)	OSM
	Sidewalk width	(Alfonzo, 2005; Southworth, 2005; Moura et al., 2017; Vural Arslan et al., 2018)	OSM
	Slope	(Handy and Clifton, 2001; Wimbardana et al., 2018; Clifton et al., 2007)	DTM Germany 20 m v1
	Surface + smoothness	(Alfonzo, 2005; Moura et al., 2017; Wimbardana et al., 2018)	OSM
	Segregation from bicycles	(Bundesamt für Strassen (ASTRA) and Fussverkehr Schweiz, 'Schwachstellenanalyse und Massnahmenplanung Fussverkehr', 2019)	OSM
	Signage, orientation	(Ralph et al., 2020; Hillier et al., 2007; Gorrini and Bandini, 2019)	*n.a.*
	Freedom from barriers	(Lo, 2009; Vural Arslan et al., 2018; Zakaria and Ujang, 2015)	OSM
	Shelter, shade	(Alfonzo, 2005; Whyte, 1980; Pilipenko et al., 2018; Erath et al., 2015; Hoogendoorn and Bovy, 2004)	*n.a.*
Traffic safety and road influences	Spatial separation of footpath from road	(Saelens et al., 2003; Hillnhütter, 2016)	OSM
	Number of car lanes	(Southworth, 2005; Ewing, 1999; Speck, 2013)	OSM
	Traffic load	(Moura et al., 2017; McGinn et al., 2007; Hillnhütter, 2016; Ortega et al., 2021)	*n.a.*
	Proportion of heavy goods vehicles	(Saelens et al., 2003; Vural Arslan et al., 2018)	*n.a.*
	Noise	(Erath et al., 2015; Hoogendoorn and Bovy, 2004; Kelly et al., 2011)	*n.a.*
	Emissions/air quality	(Hoogendoorn and Bovy, 2004; Schweiz, 2021)	*n.a.*
	Max speed	(Alfonzo, 2005; Southworth, 2005; Saelens et al., 2003; McGinn et al., 2007)	OSM
	Safe street crossings	(Moura et al., 2017; Handy and Clifton, 2001; Lo, 2009; Wimbardana et al., 2018; Hoogendoorn and Bovy, 2004; Kelly et al., 2011)	OSM
	Traffic accidents	(Moura et al., 2017)	Statistikportal
	Parking	(Saelens et al., 2003; Clifton et al., 2007; Erath et al., 2015)	OSM
Security	Illuminance	(Saelens et al., 2003; Wimbardana et al., 2018; Clifton et al., 2007)	OSM
	"Social hotspots" – fear of crime	(Saelens et al., 2003)	*n.a.*
	Underpasses	(Jehle et al., 2022; Hillnhütter, 2016)	OSM
Environment and liveliness	Population density	(Saelens et al., 2003; Vural Arslan et al., 2018; Crane, 1996; Marquet et al., 2017)	Census
	Cleanliness	(Moura et al., 2017; Saelens et al., 2003; Kelly et al., 2011)	*n.a.*
	Vegetation and Water	(Wimbardana et al., 2018; Clifton et al., 2007; Speck, 2013; Lin et al., 2015; Rafiemanzelat et al., 2017; Hillnhütter, 2021)	OSM
	Microclimate/inner-city aeration	(Pilipenko et al., 2018)	*n.a.*
	Land use	(Southworth, 2005; Wimbardana et al., 2018; Pushkarev and Zupan, 1971; Gao et al., 2022)	OSM, ATKIS
	Number of Points-of-Interest (POIs)	(Saelens et al., 2003; Hillnhütter, 2016; Ortega et al., 2021; Lin et al., 2015)	OSM
	Aesthetics	(Lo, 2009; Speck, 2013; Lin et al., 2015; Hillnhütter, 2021; Cervero and Kockelman, 1997)	*n.a.*
	Pedestrian flow rate	(Lo, 2009; Hillnhütter, 2021; Jacobs, 1961)	*n.a.*
Urban equipment	Benches	(Alfonzo, 2005; Hillnhütter, 2016; Hillnhütter, 2021)	OSM
	Bins	(Alfonzo, 2005; Vural Arslan et al., 2018; Hillnhütter, 2016)	OSM
	Public toilets	(Vural Arslan et al., 2018)	OSM
	Water fountains	(Alfonzo, 2005; Whyte, 1980)	OSM

n.a. = no data available.

2.3.1. Study area

Due to high level of OSM data completeness from a previous study (Jehle, 2020), the Munich districts "Hasenbergl-Lerchenau Ost" and "Lerchenau West" were chosen as the study area (see *Fig. 6*). The area has a diverse structure, including small single-family homes and large social housing blocks, as well as car-oriented commercial zones and pedestrian-oriented recreation areas. The study area covers an area of 869 ha and has 47,052 inhabitants (München, 2022).

2.3.2. Analysis

PAW is calculated for the four selected user groups and compared with each other. Therefore, isochrones from three sample locations (childcare, supermarket, park) were calculated and intersected with population data from Census (Statistische Ämter des Bundes und der Länder, 'Census Data'. May, 2011) as destination potential D_j. The catchment area c_{max} was set to 5 min of perceived time. The results are visualised in maps and are presented in *Section 3.4*. To allow a comparison with 'standard' time-based analyses, each map also contains a reference isochrone.

2.4. Evaluation

The recommended practice for analysing pedestrian accessibility developed by Merlin and Jehle (2023) was used as an overall framework to compare the proposed methodology with accessibility practice recommendations. The results are presented in *Section 3.5*.

3. Results

3.1. Main attributes influencing walkability

The main attributes that influence walkability were identified by the literature review and have been grouped into five categories: 1) Infrastructure quality and comfort; 2) Traffic safety and road influences 3) Security; 4) Environment and liveliness; 5) Urban equipment. As some attributes may have an effect on several categories, they were allocated to the category where the effect is considered to be higher. *Table 1* presents the list of these categories, their main attributes and the references from the literature review. In addition, the column "Data source" lists which data sources were available per attribute for the study area.

3.2. Needs and preferences per user group

Pedestrian perception, preference and behaviour assessment can be complex because of the heterogeneities depending on various personal, social, cultural, economic, and geographical factors (Marquet et al., 2017; Halden et al., 2005; Jaramillo et al., 2012). For instance, a young strong person in a manual wheelchair might not perceive the walkability to be the same as another user with

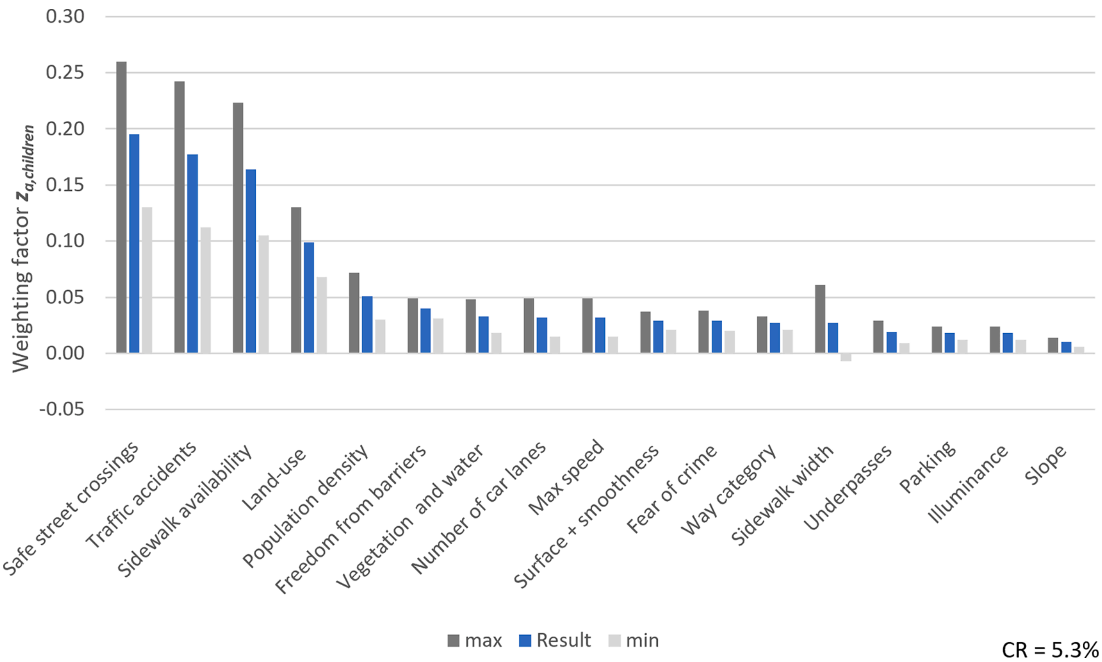


Fig. 7. Key walkability attributes for children and their weights.

different strength or physical functionality, such as an older adult wheelchair user (Tseng, 2020), or it may be that pedestrians in rural areas behave differently to urban pedestrians (Holzer, 2018).

Despite the impossibility of calculating perceived accessibility precisely and accurately for each person, the estimates of a general sample calculation can provide valuable insights (Holzer, 2018). Thus, based on a literature review on walking accessibility perceptions, four sample users as examples of diversity in age, gender, and mobility needs were selected: children, seniors, women, and wheelchair users.

The following *Subsections 3.2.1* to *3.2.4* provide a summary of the physiological and physical characteristics, behaviour and preferences found in the literature review for each of these user groups. In *Subsection 3.2.5*, the quantitative weighting factors are summarised.

3.2.1. Children

Children under 11 years old present specific physical characteristics such as small height, reduced field of vision, as well as motor and cognitive skills that are undergoing a natural developing stage (Grob and Michel, 2011). This can affect their ability of movement and may make it difficult to notice them in street traffic. Their walking speed changes throughout the years from 1.29 m/s at 5 years old (Pinheiro et al., 2014), to almost adult speed at 11 years old (Cavagna et al., 1983). Additionally, they are restless, easily distracted, and curious, they are learning to handle their emotions and have limited awareness of hazards (Grob and Michel, 2011). These physical and mental characteristics lead to unpredictable behaviour. *Fig. 7* shows the key walkability attributes for children that resulted from the AHP method. Safe infrastructure and protection from road traffic is especially important. Specifically, this means the availability of sidewalks (De Vries et al., 2010; Rosenberg, 2009; Davison and Lawson, 2006; Zhao et al., 2021) and safe crossings (De Vries et al., 2010; Davison and Lawson, 2006; Zhao et al., 2021; Hume et al., 2006; Molina-García, 2020). A high number of roads that have to be crossed and high traffic density/speed are negatively associated with children's walking activity (Davison and Lawson, 2006; Zhao et al., 2021). Parks are especially attractive to walk through (De Vries et al., 2010; Timperio et al., 2004; Rosenberg, 2009). Concerning the built environment, quiet neighbourhoods are found to have a positive impact (Hume et al., 2006), while graffiti (Hume et al., 2006) and crime (Davison and Lawson, 2006) are found to have a negative impact on children walking.

3.2.2. Seniors

Ageing leads to a gradual decline in physical, sensory, and mental abilities, such as vision and hearing impairment (Grob and Michel, 2011; World Health Organization, 'World Report on Ageing And Health', Luxemburgo, 2015; Loh and Ogle, 2004). Seniors (here defined as humans > 60 years old) are a heterogeneous group because health is related to different factors such as genetic predisposition, environment, and lifestyle. Nevertheless, the probability of chronic diseases rises with increasing age and the medication provided for, and symptoms of these can affect the independence, mobility, reaction time, and environmental perception of seniors (Grob and Michel, 2011; World Health Organization, 'World Report on Ageing And Health', Luxemburgo, 2015). These physiological changes also affect walking speed. Although the speed of older people depends on their physical and mental health, it can be assumed that an average 70-year-old person walks at approximately 0.97 m/s (Grob and Michel, 2011; Himann et al., 1988; Shkuratova et al., 2004). With the loss of muscle strength and motor limitations (Grob and Michel, 2011), the risk of falling increases. Falls are one of the greatest causes of morbidity among older people and are a determinant of mobility restriction (Gill et al., 2001). To prevent this, safe, comfortable and barrier-free footpaths are especially important. This includes the availability of sidewalks of sufficient width (Grob and Michel, 2011) with smooth surfaces (Moura et al., 2017) and safe street crossings (Leonardi et al., 2020; Distefano et al., 2021; Aronson and Oman, 2004; Lockett, 2005). With increasing age, slope becomes a bigger barrier (Moura et al.,

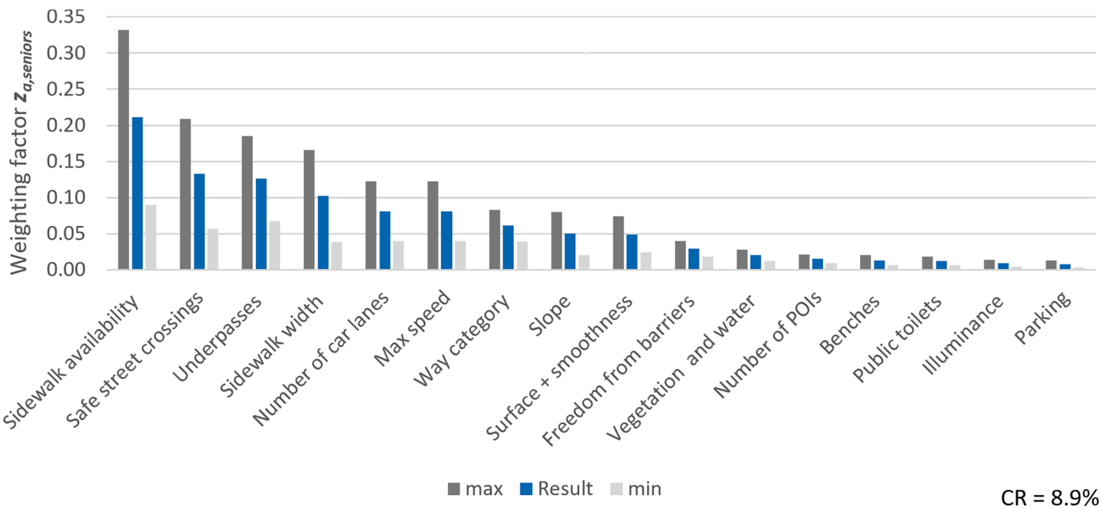


Fig. 8. Key walkability attributes for seniors and their weights.

2017) and walking becomes more and more tedious (Jehle et al., 2022), therefore, the availability of benches is crucial so people can rest. In *Fig. 8* , the key walkability attributes for seniors that resulted from the AHP method are shown.

3.2.3. Women

Several studies have found gender differences in walking behaviour (Adlakha and Parra, 2020; Clifton and Livi, 2005; Golan et al., 2019; Hatamzadeh et al., 2020; Hille, 1999; Nichani et al., 2019; Pelclová et al., 2013; Rišová and Sládeková Madajová, 2020). In general, women walk a bit slower than men (Grob and Michel, 2011; Coffin and Morrall, 1995; Montufar et al., 2007; Toor et al., 2001). The average walking speed of a woman between 30 and 40 years old is about 1.4 m/s (Bohannon, 1997). One main psychological difference between men and women is the perception and experience of fear (Hille, 1999; Rišová and Sládeková Madajová, 2020; Loukaitou-Sideris, 2014). The strong perception of fear leads to high security and safety needs. *Fig. 9* shows the key walkability attributes for women that resulted from the AHP method. The biggest barrier to walking is the fear of crime (Golan et al., 2019), followed by land use (Hatamzadeh and Hosseinzadeh, 2020) and the aesthetics of the environment. Fear experienced by many women leads to behavioural adjustments and precautions, such as not walking alone, avoiding certain locations, not travelling after sunset, not wearing certain types of clothing or jewellery (Hille, 1999; Loukaitou-Sideris, 2014), and may also lead to reduced activity in general (Adlakha and Parra, 2020). Women are more aware of and more strongly influenced by their environment than men (Jehle et al., 2022; Erath et al., 2015; Clifton and Livi, 2005). However, inconsistent results from different studies suggest that gender differences may vary across different geographical and cultural contexts (Pelclová et al., 2013).

3.2.4. Wheelchair users

Disability is a complex and multi-dimensional concept (EUROSTAT, 2021). About 15 % of the world's population is currently affected by disability. People with disabilities are defined as "those who have long-term physical, mental, intellectual or sensory impairments which in interaction with various barriers may hinder their full and effective participation in society on an equal basis with others" (Commission, 2010). In this research, we focus on wheelchair users as a sample user group. Wheelchair users have diverse abilities and moving speeds. For manual wheelchairs, movement speed varies from 0.48 m/s for older people to 0.8 m/s for athletes. The average speed is about 0.65 m/s (Sonenblum et al., 2012). Infrastructural quality and comfort are the most important attributes for wheelchair users. Here the priorities are sidewalks free of barriers (Beale et al., 2006; Mackett et al., 2008; Mrak et al., 2019; Matthews et al., 2003; Berlin Senate Department for Urban Development, 2011), of sufficient width (Moura et al., 2017; Beale et al., 2006; Mackett et al., 2008; Ferreira and da Penha Sanches, 2007) that are well maintained with adequate surface materials and smoothness (Moura et al., 2017; Beale et al., 2006; Tseng, 2020; Ferreira and da Penha Sanches, 2007; Oeda et al., 2003). Furthermore, safety at crossings (Ferreira and da Penha Sanches, 2007; Lawson et al., 2022) is among the most important factors for these users (see *Fig. 10*). Interestingly, the availability of benches is also regarded as important – not for the wheelchair users themselves but for people accompanying them.

3.2.5. Summary of the weighting factors

Although the minimum and maximum values in *Fig. 7*-*Fig. 10* show large deviations in some cases, the overall trend of the attribute importance is clearly recognisable. When comparing the resulting weighting factors between the different user groups, it is evident that there is a difference in the reported perception of the walkability attributes. The weighting factors resulting from the AHP method are summarised in *Table 2*. As no spatial data was available for some of these attributes (highlighted in grey), the attribute list was reduced accordingly and the weighting factors were adjusted. In order to prevent the (un)availability of data from distorting the results, the

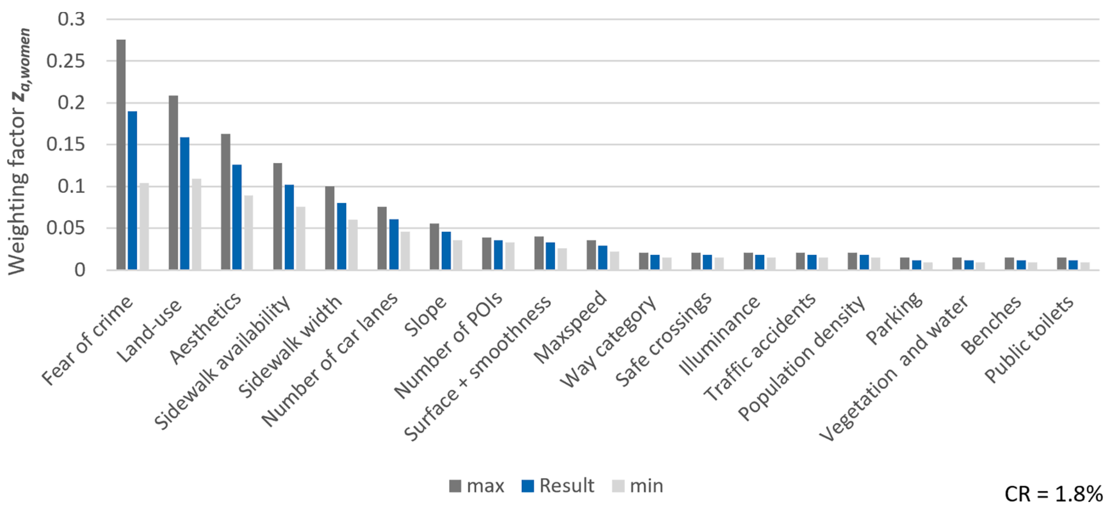


Fig. 9. Key walkability attributes for women and their weights.

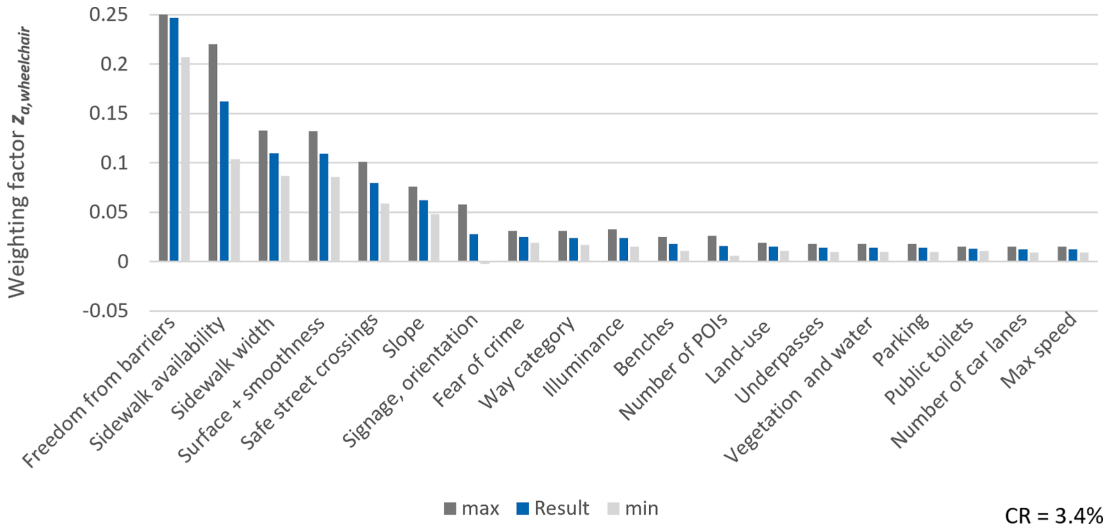


Fig. 10. Key walkability attributes for wheelchair users and their weights.

previously determined weighting factors of the categories were retained and only the weighting factors of the attributes were changed. The factors of the unavailable attributes were assigned to the closest proxies (highlighted in blue). For example, no specific data set was available for vegetation and water, but the land use data set contained some information on parks and green spaces. Therefore, these two attributes were addressed together. Only the attributes with available data are taken into account in the remaining steps of this study.

3.3. *Walkability scores for the case study*

For the calculation of walkability scores, first, all *attribute values* that occur in the study area are translated into *attribute scores* s_a. The results are presented in *Appendix 2*. The walkability scores per user group are derived by multiplying the *attribute scores* s_a by the respective *weighting factors* $z_{a,u}$. The results are shown in *Fig. 11*. Street level images were reviewed to verify the results.

3.4. *PAW calculation*

By using the walkability scores as impedance factors, representing the perceived walking time, the PAW is calculated for typical locations of interest. The results are visualised in *Fig. 12*. The numbers indicate the accessible population within each isochrone. It is apparent that the perceived walking accessibility differs considerably for different user groups and does not match the 'standard' time-based accessibility that is usually used in studies, which confirms our hypothesis (cf. *Section 1.4*). The speed of wheelchair users is the slowest, which leads to comparably small isochrones and the result that not a single person with this user profile can reach the sample location of the supermarket within 5 min. However, even for women walking at the same speed as the 'standard', the isochrones are reduced in size – in areas where walkability according to their perception is low. On the other hand, in some areas where walkability is high, the isochrone size increases. This represents the fact that people are willing to walk longer distances if the environment is attractive and the conditions are good, and shows that accessibility levels are not just overestimated (see Curl et al. (2015); Ryan and Pereira (2021)), but in some locations with a very attractive environment also underestimated. The isochrone size does thereby not directly reflect the accessible population, as in some areas (e.g. industrial areas and green spaces) no residents can be found.

3.5. *Evaluation*

Table 3 shows which of the recommendations for analysing pedestrian accessibility by Merlin and Jehle (2023) were implemented in PAW.

4. Discussion

The main shortcoming of previous calculated accessibility analyses was that they did not match with the perceived accessibility (Curl et al., 2015; Damurski et al., 2020; Gebel et al., 2011; Jehle et al., 2022; Lättman et al., 2018; McCormack et al., 2008; Pot et al., 2021; Ryan and Pereira, 2021; Ryan et al., 2016; van der Vlugt et al., 2019). To reduce this mismatch, we developed PAW, which includes user-specific walking needs and preferences in accessibility analyses. We worked with imputed perceptions, which we consider as the bridge between calculated and perceived accessibility (see *Fig. 13*).

Table 2
Summary of the weighting factors per attribute and user group.

Walkability Categories	Attributes a	Weighting factors $z_{a,u}$ per user group u							
		Children		Seniors		Women		Wheelchair users	
Infrastructural quality and comfort	Way category	0.297	0.027	0.502	0.061	0.279	0.018	0.742	0.024
	Sidewalk availability		0.164		0.211		0.102		0.162
	Sidewalk width		0.027		0.102		0.080		0.110
	Slope		0.010		0.050		0.046		0.062
	Surface + smoothness		0.029		0.049		0.033		0.109
	Signage, orientation		0.000		0.000		0.000		0.028
	Freedom from barriers		0.040		0.029		0.000		0.247 (+ 0.028)
Traffic safety and road influences	Number of car lanes	0.454	0.032	0.303	0.081	0.138	0.061	0.119	0.0125
	Max speed		0.032		0.081		0.029		0.0125
	Safe street crossings		0.195		0.133		0.018		0.080
	Traffic accidents		0.177		0.000		0.018		0.000
	Parking		0.018		0.008		0.012		0.014
Security	Illuminance	0.066	0.018 (+ 0.0145)	0.135	0.009	0.208	0.018 (+ 0.095)	0.063	0.024 (+ 0.0125)
	Fear of crime		0.029		0.000		0.190		0.025
	Underpasses		0.019 (+ 0.0145)		0.126		- (+ 0.095)		0.014 (+ 0.0125)
Environment and liveliness	Population density	0.183	0.051	0.035	0.000	0.351	0.018	0.045	0.000
	Aesthetics		0.000		0.000		0.126		0.000
	Land use		0.099 (+ 0.033)		0.000 (+ 0.020)		0.159 (+ 0.126 + 0.012)		0.015 (+ 0.014)
	Vegetation and water		0.033		0.020		0.012		0.014
	Number of POIs		0.000		0.015		0.036		0.016
Urban equipment	Benches	0	0.000	0.025	0.013	0.024	0.012	0.031	0.018
	Public toilets		0.000		0.012		0.012		0.013

No data available (see Table 1)
Serves as proxy for another attribute (indicated through arrow)

Imputed perceptions combine the advantages of both approaches: they use the insights from perceived accessibility studies and apply them to the spatial data. This allows more realistic accessibility analyses to be conducted for larger study areas that cannot normally be covered by surveys. In this way, the individual component of accessibility, which has been neglected for a long time (Merlin and Jehle, 2023), is taken into account. To do this, we conceptualised the capability approach, which is tightly intertwined with the individual component of accessibility (Vecchio and Martens, 2021), by examining whether intrinsic capabilities match external conditions. In the field of walkability, similar approaches have been used (Blečić et al., 2015; Fancello et al., 2020; Reyer et al., 2014), however, we went one step further and linked this to the perceived walking accessibility of different user groups. This follows a similar logic to the approach of Gaglione et al. (2021) but considers a higher number of walkability attributes and includes additional user groups.

While PAW is not proven to be more advanced than current practice, it at least addresses most of the shortcomings identified. Although PAW as a methodological approach sounds promising and appears to be more realistic than 'standard' time-based accessibility analyses, there are three main points that need to be discussed.

4.1. Not all persons are the same

We used a technical approach by making perceptions quantifiable. We were pigeonholing people and assigning them very granular

Fig. 11. Walkability scores.

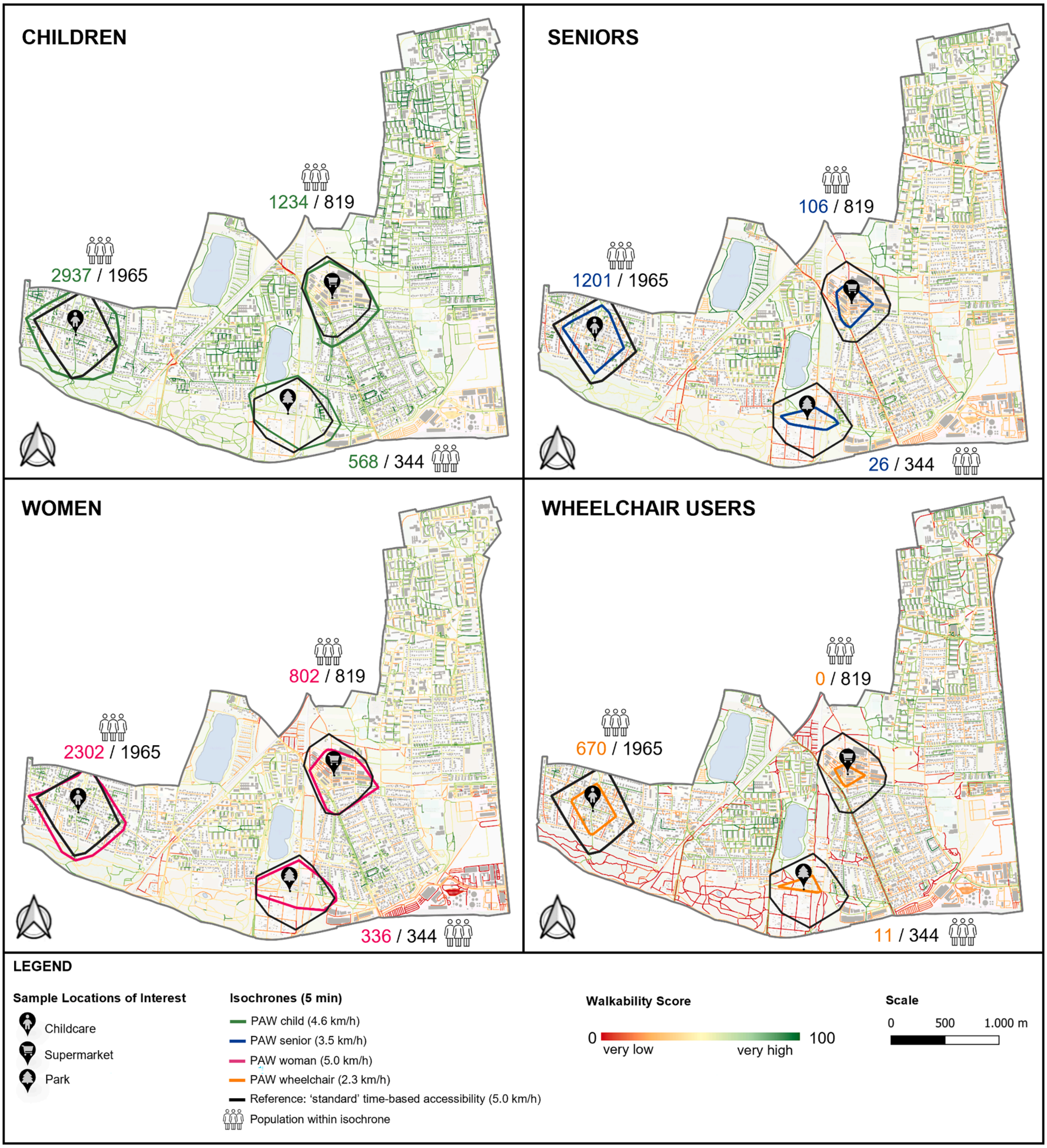


Fig. 12. PAW for typical locations of interest.

Table 3
Juxtaposition of recommended practice and PAW.

Component	Current practice	Recommended practice	Implemented in PAW
Transport	Roadway network	Pedestrian network, including micro elements	Yes
Land use	Administrative zones as origins/specific destination types	Buildings or grid-type zones as origins/specific destination types + land use influences on attractiveness	Partly via land use influences on attractiveness
Individual	All persons the same	Distinct population segments	Yes
Temporal	Not considered	Consider the effect of weather and nighttime	Partly via "security" aspects (illuminance)
Impedance	Distance	(Perceived) Time	Yes
Objective vs. perceived	Objective	Imputed Perception	Yes

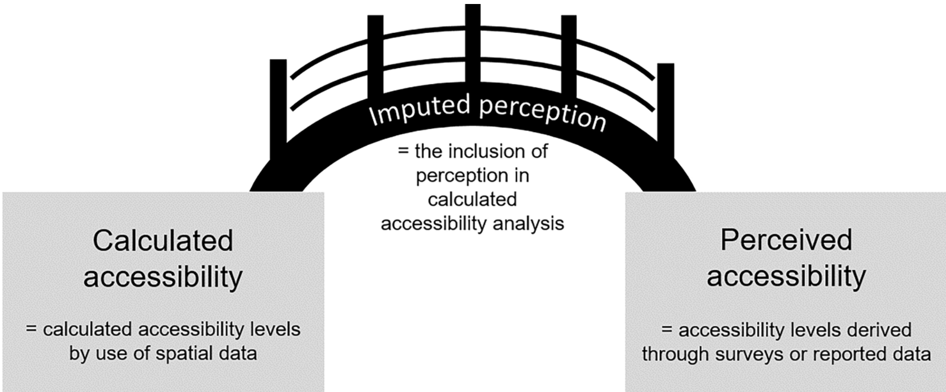


Fig. 13. Bridging the gap between calculated and perceived accessibility.

numbers (for the weighting of the walkability attributes as well as for walking speed). This might be straightforward and easy to communicate but neglects the characteristics, needs and capabilities of individual persons in a categorised group. In reality, people (even within one 'user group') have a wide range of walking speeds and every single person has their own preferences. Also, some users are associated with more than one user group. However, in trying to quantify those needs and translate them into easily understandable measures, we somehow need to find a balance between detail and ease of implementation (Papa et al., 2015). Hence we picked four sample profiles, which we considered as relatable for everyone and provided insights into how their perceived walking accessibility differs from the 'standard' time-based accessibility. The results revealed that especially for wheelchair users and for seniors, accessibility levels are overestimated in 'standard' time-based accessibility analyses. When their needs are not met, their perceived accessibility decreases significantly. In future, the here developed methodological approach can be further refined and transferred to further user groups. Since walkability needs differ not only on the basis of personal characteristics, but also depending on the purpose of the trip (De Vries et al., 2010; Erath et al., 2015; Grob and Michel, 2011; Habibian and Hosseinzadeh, 2018; Sabzali Yameqani and Alesheikh, 2019) and the time of day (Jehle et al., 2022), categorisation based on these factors could also be useful.

4.2. Negotiable factors vs. non-negotiable factors

We used an additive method that calculates the total walkability score by building the sum of the weighted attribute score. While this approach is rather simple and thus easy to understand, in some regards it might be too simplified. For example, if the freedom of barriers is not given on a certain path, it is actually unusable for a wheelchair user. So, in fact, the result should be "0", but if other walkability attributes score high, the overall walkability score will still receive some points. Chan et al. (2021) therefore suggested that some attributes are negotiable and lower scores can be compensated by, and traded against, higher scores on others. But some attributes may be so important to certain people that they act as hard and non-negotiable constraints. The here developed measure approach is currently not able to represent such non-negotiable constraints.

Furthermore, we used the same walkability scale 0–100 for all user groups. But while a low score for wheelchair users could mean that they cannot move on this path because of physical barriers, a low score for women (e.g. as shown in *Fig. 11*) "only" means that it's inconvenient, so they are physically still able to move but may have perceptual barriers, which, in effect, might also prevent them from walking. Overall, the needs are of different natures and the results of the different user groups are not per se comparable. However, they can help to create awareness of the needs and perceptions of different groups.

4.3. Location matters

Interestingly, from the maps in *Fig. 11* and *Fig. 12*, women seem to be more vulnerable than children in this study area. However, this result may not be per se transferable to other locations as the spatial characteristics have a high impact on the results. Thus, this effect may be caused by the chosen study area as for children, traffic safety is the biggest issue, and the chosen study area is largely traffic calmed. For women, environment and liveliness is the most important walkability category, which in this area has rather low scores. The chosen study area is also completely flat, which makes the attribute slope irrelevant. Thus, for other study areas, the results may differ – depending both on the place but also on the people. Especially in other countries, the walking conditions, but also the culture, behaviour and perception of people may be very different, which could lead to different results.

As there is no comprehensive study on the walkability perceptions of different user groups in Munich, we used literature from all over the world as input data for the AHP method. But the results of the same walkability survey could be very different for different places in the world, thus, the application of the results in the Munich context may not be accurate (cf. *Simpson's paradox:* when we aggregate data, we also lose specificity). When transferring this method to another study area, we recommend adapting it to the local context and using walkability studies from near-by or comparable locations as input data for the weighting schema.

4.4. The model is only as good as the input data

The PAW calculation requires a large amount of data – data on the importance of each walkability attribute per user group in order to calculate the weighting schema as well as spatial data for the study area. Although we picked a study area with high data availability, for some attributes, such as crime rates, no data was available. In addition, the presence of green and blue infrastructure was only included to a limited extent. For example, no information on shade and microclimate was available. The lack of certain data sets can have a crucial impact on the results because the model can only be as good as the input data. Therefore, it only makes sense to transfer the PAW to study areas for which at least a moderate amount of spatial data is available.

Moreover, the weighting schema is biased by existing studies by different authors in different contexts, which are naturally based on different setups, methods, assumptions and sample sizes. Thus, for example, the weighting factors for some attributes may be zero because these attributes were excluded from the outset in existing studies and therefore no evidence on their importance is available. Also, if one of the input studies contains a faulty value, the fault is propagated here.

5. Conclusion

This work aimed to contribute to the ongoing attempt of bridging the gap between calculated and perceived accessibility. Therefore, a new methodological approach (PAW) was developed, which considers user-specific walkability needs and people's perceptions in walking accessibility analyses. The juxtaposition of the method with the recommended practice of Merlin and Jehle (2023) shows that for the transport component, the individual component, the impedance calculation and the measure type, the recommended practice was fulfilled. For the land use and temporal component, further adjustments need to be made.

The method was applied for four sample user groups: children, seniors, women, and wheelchair users. Part of this study was also to gain insights into the walkability differences between the various user groups. Interestingly, the importance per walkability attribute differs significantly between each of the user groups. For seniors and wheelchair users, who can both be regarded as, to some extent, mobility-impaired, the infrastructural conditions were the most important. For women, environmental and security factors were found to be the most relevant, which have more of a psychological impact. For children, traffic safety is the most important factor.

The result is not a universal weighting schema for the user-specific walkability attributes, but an example of how these can potentially be integrated in accessibility analyses via imputed perceptions. With the assumption that a pedestrian network that is suitable for the most vulnerable users will be suitable for everyone else, PAW for vulnerable user groups can help planners to design cities that are walkable for all. With increasing global data availability, PAW can be transferred to study areas worldwide and applied to other user groups.

The developed PAW was applied to one study area within Munich for testing the methodology. As a logical outcome of the differences in the importance of the walkability attributes, the perceived walking accessibility also shows marked differences between the user groups. The comparison with 'standard' time-based isochrones and the accessible population within the isochrones reveals that the perceived accessibilities of these user groups do not match the results of solely time-based calculations focused on an average user, confirming our hypothesis (cf. *Section 1.4*). The results show differences in both directions: in areas where walkability is low, the PAW isochrone is smaller, but in some areas where walkability is high, the PAW isochrone is larger. In addition to walkability levels, the walking speed also has a high influence on the accessibility of different user groups. At the same time, the size of the isochrone does not directly reflect the accessible population, as it also depends on population density.

5.1. Limitations and further research

This study adds to the attempts of Amaya et al. (2022) and Gaglione et al. (2021) to provide more realistic walking accessibility analyses by combining the three components – accessibility, walkability and integration of user needs. Although the number of walkability attributes included in the study could be increased, information on some important attributes, such as crime rate, was still missing. When applying the method to other study areas, the weighting schema can be refined while adjusting it to the local context. In addition, we recommend that the developed PAW method be subjected to further testing and comparison with 'standard' time-based accessibility measures in order to ascertain whether the results are indeed more realistic.

Furthermore, it needs to be highlighted that every person is different and the sample user groups we picked here are just an approximation of the 'average' needs of persons with certain characteristics in terms of age, gender and capabilities. For the intended aim of PAW, to serve as methodological approach for a decision support system in planning processes, this categorisation may be beneficial for highlighting shortcomings in overall pedestrian accessibility. However, for specific planning questions, it is inevitable that the method will have to be expanded to further user groups, such as teenagers or visually impaired persons. In addition, further user groups in terms of trip purpose, and time of day, week and year might be useful. As peoples' needs, preferences and perceptions also depend on the local conditions and culture, the developed weighting schema should be adapted to the local context of the study by ideally only using AHP input values that are derived from in situ surveys in this specific location. Through such surveys, real reported statements on the perceptions for specific locations in the study area could also be gathered and included in the resulting accessibility maps to enhance empathy and understanding of the needs of the vulnerable user groups.

The PAW methodology, which was developed here for isochrones, can also be transferred to heatmaps. This would even allow for the implementation of different walking distance thresholds and decay functions for different user groups, as was done by García-Palomares et al. (2013) and Arranz-López et al. (2019). To fully represent the land use component, further focus on the destination potential is needed (e.g. by analysing how many children live within reach). On the temporal component, the consideration of weather and nighttime should be further assessed. To also represent hard constraints, the method should be further enhanced to differentiate between negotiable factors and non-negotiable factors.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work we used ChatGPT and DeepL in order to improve the written texts. After using these tools, we reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Ulrike Jehle: Writing – review & editing, Writing – original draft, Visualization, Methodology, Conceptualization. **María Teresa Baquero Larriva:** Writing – review & editing, Writing – original draft, Methodology. **Mahtab BaghaiePoor:** Writing – review & editing, Writing – original draft, Visualization, Methodology. **Benjamin Büttner:** Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Appendix 1. References and AHP results per user group.

	Attributes	Children			Seniors			Women			Wheelchair Users		
		References	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**
Infrastructural quality and comfort	Sidewalk availability	(De Vries et al., 2010; Moura et al., 2017; Rosenberg, 2009; He et al., 2021; Zhao et al., 2021; Lee et al., 2020)	2	0.164	(Distefano et al., 2021; Pulvirenti et al., 2020; Patterson and Chapman, 2004; Kealey, et al., 2005; Strath et al., 2007; World Health Organization, 'Global age-friendly cities: a guide', 2007)	1	0.211	(Adlakha and Parra, 2020; Clifton and Livi, 2005; Nichani et al., 2019; Pelclová et al., 2013; Gorrini et al., 2021; Yildirim et al., 2012)	4	0.102	(Moura et al., 2017; Beale et al., 2006; Tseng, 2020; Mrak et al., 2019; Matthews et al., 2003; Berlin Senate Department for Urban Development, 2011; Ferreira and da Penha Sanches, 2007; Lawson et al., 2022; Rosenberg et al., 2013)	2	0.162
	Way category	(De Vries et al., 2010; Rosenberg, 2009; He et al., 2021; Timperio, 2006)	6	0.027	(Pulvirenti et al., 2020; World Health Organization, 'Global age-friendly cities: a guide', 2007)	5	0.061	(Adlakha and Parra, 2020; Pelclová et al., 2013; Yildirim et al., 2012)	11	0.018	(Beale et al., 2006; Tseng, 2020; Berlin Senate Department for Urban Development, 2011; Lawson et al., 2022)	8	0.024
	Sidewalk width	(Zhao et al., 2021)	6	0.027	(Distefano et al., 2021; Pulvirenti et al., 2020; World Health Organization, 'Global age-friendly cities: a guide', 2007)	3	0.102	(Nichani et al., 2019; Pelclová et al., 2013; Gorrini et al., 2021; Yildirim et al., 2012; Sethi and Velez-Duque, 2021)	5	0.080	(Moura et al., 2017; Beale et al., 2006; Tseng, 2020; Mackett et al., 2008; Matthews et al., 2003; Berlin Senate Department for Urban Development, 2011; Ferreira and da Penha Sanches, 2007; Rosenberg et al., 2013)	3	0.110
	Slope	(Timperio, 2006)	7	0.010	(Distefano et al., 2021; Pulvirenti et al., 2020; World Health Organization, 'Global age-friendly cities: a guide', 2007)	6	0.050	(Adlakha and Parra, 2020; Golan et al., 2019; Nichani et al., 2019; Pelclová et al., 2013; Yildirim et al., 2012)	7	0.046	(Beale et al., 2006; Tseng, 2020; Mackett et al., 2008; Matthews et al., 2003; Berlin Senate Department for Urban Development, 2011; Rosenberg et al., 2013)	5	0.062
	Surface + smoothness	(He et al., 2021; Zhao et al., 2021; Lee et al., 2020)	5	0.029	(Distefano et al., 2021; Pulvirenti et al., 2020; World Health Organization, 'Global age-friendly cities: a guide', 2007)	6	0.049	(Adlakha and Parra, 2020; Golan et al., 2019; Nichani et al., 2019; Pelclová et al., 2013; Yildirim et al., 2012)	9	0.033	(Moura et al., 2017; Beale et al., 2006; Tseng, 2020; Matthews et al., 2003; Berlin Senate Department for Urban Development, 2011; Ferreira and da Penha Sanches, 2007; Rosenberg et al., 2013)	3	0.109
	Segregation from bicycles	–	–	–	–	–	–	–	–	–	–	–	–
	Signage, orientation	–	–	–	–	–	–	–	–	–	(Moura et al., 2017; Matthews et al., 2003; Berlin Senate Department for Urban Development, 2011)	6	0.028
	Freedom from barriers	(Moura et al., 2017; He et al., 2021; Zhao et al.,	5	0.040	(Pulvirenti et al., 2020; World Health Organization, 'Global	7	0.029	(Golan et al., 2019; Gorrini et al., 2021)	11*	–	(Moura et al., 2017; Beale et al., 2006; Tseng, 2020; Mackett et al., 2008; Mrak	1	0.247

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		Children			Seniors			Women			Wheelchair Users		
	Attributes	**References**	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**
		2021; Lee et al., 2020)			age-friendly cities: a guide', 2007)						et al., 2019; Matthews et al., 2003; Berlin Senate Department for Urban Development, 2011; Rosenberg et al., 2013)		
	Shelter, shade	–	–	–	–	–	–	–	–	–	–	–	–
Traffic safety and road influences	Spatial separation of footpath from road	–	–	–	–	–	–	–	–	–	–	–	–
	Number of car lanes	(Zhao et al., 2021; Molina-García, 2020; Timperio, 2006; Webb Jamme et al., 2018)	5	0.032	(Saelens et al., 2003; Distefano et al., 2021; Aronson and Oman, 2004; Lockett, 2005; Pulvirenti et al., 2020; Patterson and Chapman, 2004; Kealey, et al., 2005; Strath et al., 2007; Lees et al., 2007)	4	0.081	(Adlakha and Parra, 2020; Clifton and Livi, 2005; Golan et al., 2019; Nichani et al., 2019; Pelclová et al., 2013; Gorrini et al., 2021; Yildirim et al., 2012)	6	0.061	(Tseng, 2020; Berlin Senate Department for Urban Development, 2011; Lawson et al., 2022; Rosenberg et al., 2013)	10	0.0125
	Traffic load	–	–	–	–	–	–	–	–	–	–	–	–
	Proportion of heavy goods vehicles	–	–	–	–	–	–	–	–	–	–	–	–
	Noise	–	–	–	–	–	–	–	–	–	–	–	–
	Emissions/air quality	–	–	–	–	–	–	(Adlakha and Parra, 2020)	12*	–	–	–	–
	Max speed	(Zhao et al., 2021; Molina-García, 2020; Timperio, 2006; Webb Jamme et al., 2018)	5	0.032	(Saelens et al., 2003; Distefano et al., 2021; Aronson and Oman, 2004; Lockett, 2005; Pulvirenti et al., 2020; Patterson and Chapman, 2004; Kealey, et al., 2005; Strath et al., 2007; Lees et al., 2007)	4	0.081	(Adlakha and Parra, 2020; Clifton and Livi, 2005; Nichani et al., 2019; Pelclová et al., 2013; Gorrini et al., 2021; Yildirim et al., 2012)	10	0.029	(Tseng, 2020; Berlin Senate Department for Urban Development, 2011; Lawson et al., 2022; Rosenberg et al., 2013)	10	0.0125
	Safe street crossings	(De Vries et al., 2010; Moura et al., 2017; He et al., 2021; Zhao et al., 2021; Molina-García, 2020; Timperio, 2006; Webb Jamme et al., 2018)	1	0.195	(Distefano et al., 2021; Aronson and Oman, 2004; Lockett, 2005; Kealey, et al., 2005; World Health Organization, 'Global age-friendly cities: a guide', 2007; Michael et al., 2006; Kerr et al., 2012)	2	0.133	(Nichani et al., 2019; Pelclová et al., 2013; Gorrini et al., 2021; Yildirim et al., 2012)	11	0.018	(Moura et al., 2017; Beale et al., 2006; Tseng, 2020; Mackett et al., 2008; Mrak et al., 2019; Matthews et al., 2003; Berlin Senate Department for Urban Development, 2011; Ferreira and da Penha Sanches, 2007; Lawson et al., 2022; Rosenberg et al., 2013)	4	0.080

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		Children			Seniors			Women			Wheelchair Users		
	Attributes	**References**	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**	**References**	**Average priority order**	**AHP weight**
	Traffic accidents	(De Vries et al., 2010; Moura et al., 2017; He et al., 2021; Zhao et al., 2021; Molina-García, 2020; Timperio, 2006; Webb Jamme et al., 2018)	2	0.177	–	–	–	(Clifton and Livi, 2005; Gorrini et al., 2021)	11	0.018	–	–	–
	Parking	(De Vries et al., 2010; Zhao et al., 2021; Molina-García, 2020)	6	0.018	(Distefano et al., 2021; Pulvirenti et al., 2020; World Health Organization, 'Global age-friendly cities: a guide', 2007)	13	0.008	(Golan et al., 2019)	12	0.012	(Tseng, 2020)	10	0.014
Security	Illuminance	(De Vries et al., 2010; Timperio, 2006; Webb Jamme et al., 2018)	6	0.018	(Distefano et al., 2021; Pulvirenti et al., 2020; World Health Organization, 'Global age-friendly cities: a guide', 2007)	12	0.009	(Clifton and Livi, 2005; Yildirim et al., 2012; Sethi and Velez-Duque, 2021)	11	0.018	(Tseng, 2020; Mackett et al., 2008; Berlin Senate Department for Urban Development, 2011; Rosenberg et al., 2013)	8	0.024
	Fear of crime	(Rosenberg, 2009; He et al., 2021; Lee et al., 2020; Webb Jamme et al., 2018)	5	0.029	–	–	–	(Adlakha and Parra, 2020; Clifton and Livi, 2005; Golan et al., 2019; Hille, 1999; Nichani et al., 2019; Pelclová et al., 2013; Loukaitou-Sideris, 2014; Yildirim et al., 2012)	1	0.19	(Moura et al., 2017; Mackett et al., 2008; Berlin Senate Department for Urban Development, 2011; Rosenberg et al., 2013)	7	0.025
	Underpasses	(He et al., 2021; Webb Jamme et al., 2018)	6	0.019	(Distefano et al., 2021; World Health Organization, 'Global age-friendly cities: a guide', 2007; Michael et al., 2006; Kerr et al., 2012)	2	0.126	–	–	–	(Moura et al., 2017)	10	0.014
Environment and liveliness	Population density	(Rosenberg, 2009; He et al., 2021; Molina-García, 2020; Ikeda, 2018)	4	0.051	–	–	–	(Adlakha and Parra, 2020; Pelclová et al., 2013)	11	0.018	–	–	–
	Cleanliness	–	–	–	–	–	–	–	–	–	–	–	–
	Vegetation and water	(De Vries et al., 2010; He et al., 2021; Molina-	5	0.033	(Saelens et al., 2003; Kealey, et al., 2005; Strath et al., 2007;	8	0.020	(Golan et al., 2019; Gorrini et al., 2021;	12	0.012	(Berlin Senate Department for Urban Development, 2011)	10	0.014

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		Children			Seniors			Women			Wheelchair Users		
	Attributes	References	Average priority order	AHP weight	References	Average priority order	AHP weight	References	Average priority order	AHP weight	References	Average priority order	AHP weight
		García, 2020; Lee et al., 2020; Webb Jamme et al., 2018)			World Health Organization, 'Global age-friendly cities: a guide', 2007; Lees et al., 2007; Michael et al., 2006)			Sethi and Velez-Duque, 2021)					
	Microclimate/ inner-city aeration	–	–	–	–	–	–	–	–	–	–	–	–
	Land use	(Moura et al., 2017; Rosenberg, 2009; He et al., 2021; Molina-García, 2020; Lee et al., 2020; Webb Jamme et al., 2018)	3	0.099	–	–	–	(Adlakha and Parra, 2020; Clifton and Livi, 2005; Golan et al., 2019; Nichani et al., 2019; Pelclová et al., 2013; Gorrini et al., 2021; Yildirim et al., 2012)	2	0.159	(Moura et al., 2017; Tseng, 2020)	10	0.015
	Number of POIs	(Moura et al., 2017; Rosenberg, 2009; He et al., 2021; Webb Jamme et al., 2018)	7*		(Aronson and Oman, 2004; Lockett, 2005; Strath et al., 2007; Michael et al., 2006)	9	0.015	(Pelclová et al., 2013; Gorrini et al., 2021; Yildirim et al., 2012; Sethi and Velez-Duque, 2021)	8	0.036	(Moura et al., 2017)	10	0.016
	Aesthetics	–	–	–	–	–	–	(Adlakha and Parra, 2020; Clifton and Livi, 2005; Golan et al., 2019; Pelclová et al., 2013; Yildirim et al., 2012)	3	0.126	–	–	–
	Pedestrian flow rate	–	–	–	–	–	–	–	–	–	–	–	–
Urban equipm.	Benches	–	–	–	(World Health Organization, 'Global age-friendly cities: a guide', 2007; Michael et al., 2006)	10	0.013	(Sethi and Velez-Duque, 2021)	12	0.012	(Moura et al., 2017)	9	0.018
	Bins	–	–	–	–	–	–	(Sethi and Velez-Duque, 2021)	11*	–	(Tseng, 2020)	10*	–
	Public toilets	–	–	–	(World Health Organization, 'Global age-friendly cities: a guide', 2007)	11	0.012	(Sethi and Velez-Duque, 2021)	12	0.012	(Moura et al., 2017; Matthews et al., 2003)	10	0.013
	Water fountains	–	–	–	–	–	–	(Sethi and Velez-Duque, 2021)	11*	–	–	–	–

*Not considered for AHP evaluation.

Appendix 2. Attribute values and scores.

Walkability Categories	**Attributes**	**Attribute values**[1]	**Attribute scores s_a**
Infrastructural quality and comfort	Way category	living_street; pedestrian; footway	100
		residential	90
		cycleway	70
		path; road	50
		tertiary; tertiary_link; unclassified; service	30
		track; secondary; secondary_link; bridleway	20
		steps; construction; motorway; motorway_link; primary; primary_link; trunk; trunk_link; proposed	0
	Sidewalk availability	yes; both	100
		right; left	80
		no	0
	Sidewalk width	$> 3\ m$	100
		$1.5 – 3\ m$	50
		$\leq 1.5\ m$	20
	Slope	≤1%	100
		1–2 %	90
		2–3 %	80
		3–4 %	70
		4–5 %	60
		5–6 %	50
		6–7 %	40
		7–8 %	30
		8–9 %	10
		> 9	0
	Surface	paved; asphalt; concrete; concrete:lanes; paving_stones; cobblestone:flattened	100
		stone; sandstone; sett; metal; unhewn_cobblestone; cobblestone	80
		unpaved; compacted	50
		fine_gravel; metal_grid; gravel; pebblestone; rock; wood; ground; dirt; earth	30
		grass; grass_paver; mud; sand	20
		grass_paver	20
		no_data	50
	Smoothness	excellent; very_good	100
		good	90
		intermediate	50
		bad; very_bad	20
		horrible; very_horrible	10
		impassable	0
	Freedom from barriers	yes	100
		limited	50
		no	0
		unclassified	50
Traffic safety and road influences	Number of car lanes	≤1	100
		>1–2	70
		>2–4	30
		>4	0
	Max speed	≤15	100
		>15–30	75
		>30–50	50
		>50–70	25
		>70	0
	Number of street crossings	-1[2]	100
		>2	100
		2	90
		1	50
		0	0
	Traffic accidents [3]	0	100
		1	60
		2	40
		>2	0
	Parking	off_street	0
		on_street	50
		no	100
Security	Illuminance	yes	100
		no	0

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Walkability Categories	Attributes	Attribute values[1]	Attribute scores s_a
	Underpasses	no; colonnade; building_passage; arcade	100
		yes	0
Environment and liveliness	Population density[4]	high	100
		medium	70
		low	30
		no	0
	Land use	community; nature; residential; leisure; water	100
		commercial	50
		agriculture	40
		transportation	20
		industrial	0
	Number of POIs [5]	no	0
		very_low	25
		low	50
		medium	75
		high	100
Urban equipment	Benches[6]	0	0
		1	50
		2	75
		>2	100
	Public toilets[7]	0	0
		≥1	100

If no data on a certain attribute was available, an average value of 50 was assumed.
[1]Further information and explanation on the values from the OSM data sets can be found in the OSM Wiki (https://wiki.openstreetmap.org/wiki/Key:highway).
[2]This value was assigned by us if the max speed is ≤ 30 km/h or the way category is 'residential' or 'service' as we assume that in these cases it is also possible to cross the street without having dedicated crossings.
[3]To project the accident data onto the paths, buffers of 30 m were created around the accident locations and intersected with the paths.
[4]Percentiles are used for the classification.
[5]To assign the number of POIs in the vicinity surrounding the paths, buffers of 50 m were created around the POIs and intersected with the paths. Percentiles are used for the classification.
[6]To assign the number of benches in the vicinity surrounding the paths, buffers of 30 m were created around the benches and intersected with the paths.
[7]To assign the number of public toilets in the vicinity surrounding the paths, buffers of 300 m were created around the toilets and intersected with the paths.

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