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Living and Walking in Cities

New challenges for sustainable urban mobility

This Special Issue intended to wonder about the new challenges for sustainable urban mobility, aligning with the European Sustainable & Smart Mobility Strategy. Contributions come from selected papers of the XXVI International Conference "Living and Walking in Cities" and have been collected around two main topics: the relationship between transport systems and pedestrian mobility and the transformative potential of temporary urban changes. Reflections and suggestions elaborated underline a collective great leap forward to reshaping urban mobility paradigms.

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Living and walking in cities: new challenges for sustainable urban mobility

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Cover photo: Herrengasse street in Graz (Austria), baroque pedestrian avenue and centre of public life, provided by Michela Tiboni (June, 2024)

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Special Issue 3.2024

Living and walking in cities: new challenges for sustainable urban mobility

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Role of new technologies on pedestrian walking behaviour research

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Abstract

Walking behaviour has been considered one of the fundamental values of healthy, sustainable and liveable city concepts, various techniques for gathering, analysing and assessing data have been developed. More recently, new technologies have affected both individuals' walking experiences and how researchers assess walkability. Accordingly, traditional approaches have tended to be digitalized through technologies and systems such as Global Positioning System, Geographic Information System, video-based techniques, machine learning, laser scanning, Bluetooth, Radio Frequency Identification and so on. In this context, this research aims to understand the role of new technologies on pedestrian walking behaviour research for analysing/supporting walking behaviour. Through a literature review, the research firstly summarizes the literature on pedestrian behaviour in the public space, examining the potential and limitations of traditional tools. Secondly it analyzes studies examining pedestrian behaviour-walking-technology, to identify different types, general characteristics and interrelations of new technologies. By putting in relation the two domains, the paper reveals (1) the relations between technologies and traditional tools, (2) the role of these technologies in walking behaviour research and which of them are used to detect/assess/support specific walking variables and (3) limitations of these technological approaches. The results showed that technologies have different capacities in understanding walkability and collecting/measuring datasets. Usage of them depends on the scale and purpose; related studies often use them in an integrated form.

Keywords

Pedestrian behaviour; Walkability; Technologies.

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1. Introduction

Pedestrians' behaviour in public spaces and public life is essential to understanding urban dynamics and reading the relationship between human-built environments. After 1960, automobile-oriented urban space production, modernist planning principles and monotype urbanization were criticized, and the necessity of prioritizing the needs of pedestrians in cities and the importance of pedestrian-friendly urban-street life were emphasized (Calthorpe, 1999; Jacobs, 1961). In this direction, well-accepted studies have been carried out by experts such as Jacobs (1961), Whyte (1980), and Gehl (2007, 2010), and socio-spatial patterns related to pedestrian behaviour in urban space have been trying to be understood.

Since the 90s, rapidly developing technologies have changed pedestrian behaviour in a socio-spatial manner and diversified analysis/assessment tools of behaviours in public space through digitalization. With these shifts, the popularity of new technologies has increased in pedestrian behaviour studies, and computer-based tools, location-based approaches, and sensors have been used to replace or complete traditional tools for analysing/supporting walking behaviour. However, studies that subjective these are mostly scattered, and only a few of them deal with the effect of new technologies on pedestrian behaviour research holistically through different perspectives (Conticelli et al., 2018; Feng et al., 2021; Hanzl & Ledwon, 2017; Millonig et al., 2009). Accordingly, the paper would investigate the role of new technologies in walking behaviour research in public spaces by addressing the following research questions:

SQ1: What are the relations between technologies and traditional tools in pedestrian behaviour research?

SQ2: How are these technologies used in walking behaviour research, and what specific walking variables do they detect?

SQ3: What are the limitations of these technologies on walking behaviour research?

The final aim is to highlight the potential of these technologies in better supporting more walkable places planning and design.

2. Methodology

This research adopts a descriptive approach to analyze new technologies' role in walking behaviour research. After summarizing the traditional techniques to detect pedestrian behaviours in urban spaces, the research analyses the role of new technologies through the following three steps: 1) examining the relations between traditional tools and new technologies used in walking behaviour research, by reviewing similar articles/proceedings; 2) categorizing the different types of new technologies in pedestrian walking behaviour research against their usage; 3) trying to open up the limitations of these new technologies in walking behaviour research and how some researchers overcome them via models or multi-layered approaches.

3. Pedestrian walking behaviour research: an overview

3.1 The multifaceted relationship between pedestrian behaviour and public spaces

Pedestrian behaviour and public spaces are multidimensional issues in developing more vibrant urban spaces (Project for Public Spaces, 2012). Since the second half of the twentieth century, a wide range of different studies has been developed, highlighting the complex and multifaceted nature of pedestrian behaviours and public spaces relationship, dealing with the promotion of more walkable spaces. Accessibility and activity levels are some of the primary concerns to reach and use of public spaces that are studied through different approaches, such as observation of human behaviours or by classifying outdoor activities (Gehl, 2011) or by adopting more automated approaches. More recently, the new urbanism wave posed the attention also on, mix-use, human-scale environment, walkable neighbourhoods as key elements to consider for ensuring

liveable places (Calthorpe, 1999; Fulton, 1996), and several cases have used new urbanism principles to provide strategies or evaluate neighborhoods, such as Zali et al. (2016)'s study.

In this context, creating walkable spaces requires an understanding of walking from a multi-layered perspective, but even walking behaviour is a complex mechanism in itself. It can be elaborated as a physical activity, sensorial and experiential issue or mode of transport (Mehta, 2008), and it has different types and characteristics such as utilitarian, social, and recreational, that affect needs, route choices and pedestrian attitudes (Choi, 2014). Based on the importance of walkability, evaluation of it has also been discussed and modelled by several researchers with different lenses. Overall, in the relevant literature, "walkability" is frequently studied with respect to three different lines: physical and built environment factors; perceptual approaches, subjective values and preferences; and human capabilities and quality of life (Blečić et al., 2020). Notably, Fonseca et al. (2022) listed main categories related to walkability and built environment attributes through a review: land use (density & diversity), accessibility, street network connectivity, streetscape design, safety and security, pedestrian facility and comfort. Regarding these, several walkability assessment methods are conducted partly or holistically on different scales considering these approaches and represent walkability scores spatially, such as WalkScore, Walkshed etc. (Blečić et al., 2020).

This first overview highlights the complexity and the variety of factors and approaches that have been identified to investigate the correlations between walking behaviours and the urban environment. In the following sections we firstly consider the traditional techniques adopted for analyzing walking behaviours and secondly, we highlight the role covered by new technologies in supporting an effective investigation.

3.2 Traditional approaches for analysing pedestrian behaviour in public space

Analysing pedestrian movement is critical to understand urban dynamics and developing better mobility policies (Emmons, 1965). Pedestrian behaviours have been analysed for a long time through direct observations, interviews and questionnaires (Millonig & Gartner, 2008). Relevant to this matter, Gehl & Svarre (2013) listed tools based on observation such as counting, mapping, tracing, shadowing, looking for traces, photographing, diaries, test walking. Interviews are used to resolve individual patterns, motivational and perceptual factors etc. and questionnaires have advantages in terms of reaching large samples to capture habits, motives or intentions (Millonig & Gartner, 2008). On the other hand, experts mostly integrate different tools and techniques (Millonig & Gartner, 2008), depending on the research's purpose, budget, time, and local conditions (Gehl & Svarre, 2013, p. 22). In addition, Blečić et al. (2020) also mentioned that methodological preferences are affected by the objective and subjective nature of variables in walkability assessments. Although manual techniques and statistics have been widely used since the 60s and have many advantages, they also have some limitations in examining and controlling data quality and representation, in understanding crowd movement (Stanitsa et al., 2023) or in effectively managing a large amount of data (Gehl & Svarre, 2013). Detailed explanations about the advantages & disadvantages of traditional tools are listed in Tab.1.

Traditional Tools	Advantages	Disadvantages
Counting	Provides statistical data, supports comparisons, allows observer to detect other properties about pedestrians (Gehl & Svarre, 2013). Simple process, effective in temporally limited and small-cross sections (Bauer et al., 2009).	Time consuming, labour intensive to analyse (Gehl & Svarre, 2013), counting accuracy may differ based on observer and complexity (Bauer et al., 2009).
Mapping	Supports plotting activities, captures well staying activity patterns, works like aerial photo (Gehl & Svarre, 2013)	Labour intensive, observers can be distracted during marking process which effect the data accuracy (Gehl & Svarre, 2013).

Traditional Tools	Advantages	Disadvantages
Tracing	Determines movement patterns, gather information about walking sequence, choice direction flow etc. (Gehl & Svarre, 2013).	It is a representation, not exact; dividing space into small zones can be required to analyse manually (Gehl & Svarre, 2013).
Tracking/Shadowing	Unaware pedestrians support capturing natural use of public space (Millonig & Gartner, 2008; Stanitsa et al., 2023).	Manual shadowing has limited sample and accuracy (Bauer et al., 2009).
Photographing	Support before/after comparisons, it can expand observers' perspective, provides time-lapse evidence to observation (Gehl & Svarre, 2013; Hanzl & Ledwon, 2017).	Provides an instant view if it is not repetitive, this could be insufficient data for detecting pedestrian movements.
Diaries	Different types of diaries (kept by observer, trip) have their own potentials (Gehl & Svarre, 2013; Millonig et al., 2009).	Diaries may depend on the observer's selective judgments.
Test Walks	Provides an understanding of real-time/distance dynamics, good for detecting waiting times, potential obstacles etc. (Gehl & Svarre, 2013).	Observation in motion can become less systematic and hard to capture overall movements in a public space.
Interviews	Supports capturing underlying motivations, choices, individual patterns (Millonig & Gartner, 2008)	Depends on response accuracy, distortions in self-assessment (Millonig & Gartner, 2008).
Questionnaire surveys	Reaching large samples, being low-cost, capturing motives, intentions, habits (Millonig & Gartner, 2008)	Depends on response accuracy (Millonig & Gartner, 2008), standardized nature may limit capturing insights.

Tab.1 Advantages and disadvantages of traditional approaches for analysing pedestrian behaviour in public space

3.3 The role of new technologies on pedestrian walking behaviour research

Information and Communication Technology (ICT) and walking behaviours: main application domains

Concerning urban space and human behaviour, developing technologies have affected our daily life routines and public space uses, and have hybridized relations between the city and citizens (De Souza E Silva, 2006). Consequently, observation and other research techniques regarding pedestrian behaviour analysis have tended to become more digitalized, with the development of ICT and other tools (Gehl & Svarre, 2013). According to Conticelli et al. (2018) walkability-oriented application areas of ICT can comprise three main domains: real-time information and data gathering, assessing and measuring walkability, supporting walking behaviour.

- *Data gathering/collection* is a fundamental but complex task for understanding walking presence and patterns. Several studies highlight the added value of using new technologies to increase data richness, validity and quality in capturing variables such as pedestrian numbers, duration and length of the journey, pedestrian flows, etc;
- *Assessing/measuring walkability* is essential to urban decisions and design processes. Accordingly, ICT and Geographic Information Systems (GIS) have an essential impact for automatizing the calculation of assessing, and measuring systems;
- *Supporting walking behaviours*: walking habits of pedestrians have changed, especially with smartphones. Even though it is stated that these devices are seen as a distraction in terms of pedestrian safety (Siuhi & Mwakalonge, 2016; Reynolds Walsh et al., 2019), there is also evidence that they can support the walking experience, favouring this means of transport. Mobile applications especially have lots of potential for pedestrians, who use mobile apps for route planning connected with distance, time predictions, optimal route choices, navigation, wayfinding, travel information (Conticelli et al., 2018; Siuhi & Mwakalonge, 2016), encouraging pedestrian mobility.

ICT and walking behaviours: main technologies

As anticipated, technological advancements have directly affected analysis in pedestrian studies data collection and assessment/measuring manners (Conticelli et al., 2018). In the data-gathering process, Global Positioning System (GPS), Global System for Mobile Communications (GSM)/ Universal Mobile Telecommunications System (UMTS), Bluetooth, Wireless Local Area Network (WLAN), Radio-Frequency Identification (RFID), and laser scanning, are tools that come to the fore and are used for counting or tracking purposes with various devices (Conticelli et al., 2018; Hanzl & Ledwon, 2017; Millonig et al., 2009). In addition, mobile phones (MP) integrated with other technologies (Toch et al., 2019) are also another popular, cost-effective product to collect data on variables such as number, mobility, speed, and distance of pedestrians (Siuhi & Mwakalonge, 2016). In terms of assessment/measuring, GIS based applications are one of the most popular tools (Conticelli et al., 2018; Wang & Yang, 2019); also, lately, technological approaches toward machine learning (ML), and computer vision improve urban analytics by analyzing a massive amount of data; and these improvements also open new perspectives in walkability assessment studies such as using of street-level imagery (Biljecki & Ito, 2021; Telega et al., 2021). Related to these, some experts analyzed technologies that listed up in considering their effects on pedestrian behaviour or relation to walkability. For example, Millonig et al. (2009) considered technologies through pedestrian behaviour monitoring abilities, and Bauer et al. (2009) examined them through measurements of pedestrian movements related to counting/tracking. Hanzl & Ledwon (2017) detailed technologies used to analyze human behaviour in public spaces, and Conticelli et al. (2018) showed available technologies for walkable cities. In the following part a detailed analysis of the most relevant technologies used in pedestrian behaviour research are analyzed in detail, with the aim to highlight main features and applications in analysing and supporting pedestrian mobility.

Global Position System

Global navigation satellite system (GNSS) is the general definition for satellite-based position determination systems, and GPS is the system owned by USA. Systems that provide outdoor high-frequency and continuous location information are often essential to pedestrian mobility technologies, as they can be served on personal mobile devices (Millonig et al., 2009). It is common for geospatial technologies to work integrated with many different technologies such as sensors, wi-fi, and Bluetooth, to raise data accuracy (Hidaka et al., 2019; Rout et al., 2021). They are effective in providing real-time data collection and are a good option for outdoor detections (Alia et al., 2022), but data from GPS is often raw therefore needs to be further elaborated and then mapped (Wielebski et al., 2020).

a) Relations with traditional tools: GPS has been used in many studies to collect data (Hahm et al., 2019) through counting and tracing spatial mobility patterns of pedestrians, for the short or long term in different areas, from the urban to the neighbourhood scale, together with different devices (Feng et al., 2021).

b) Relations with walking behaviour research: GPS (with receivers, smartphones, lodger etc.) is used for data collection purposes in pedestrian behaviour studies (Hahm et al., 2019; Moiseeva & Timmermans, 2010). In addition to that, GPS-based applications in smartphones also support walking behaviour in terms of wayfinding, route planning, etc. Depending on receiver and signal quality, GPS can provide information about route, distance, duration, travel areas, mobility classification (Moiseeva & Timmermans, 2010; Rout et al., 2021). Several cases can be found in the literature related to GPS experiments with different themes considering walking behaviour. For instance, Hahm et al. (2019) conducted GPS experiment to understand choice of walking routes in the retail district; Khanal et al. (2019) used a GPS-based mobility survey to reveal the walking behaviours of older adults; Yun et al. (2018) used data from GPS-based smartphone app to determine urban walking tourist' spatial distributions and seasonal differences between them with integrated with other techniques, and so on...

c) Limitations: Obstructed satellite signals, weak signals, shadows in urban areas and other technological limitations can affect data accuracy (Millonig et al., 2009; Moiseeva & Timmermans, 2010). Although it is used to monitor pedestrian mobility, GPS records may have more errors in high-density environments encircled by tall buildings (Hahm et al., 2019, p. 5). The uncertainty of GPS data may require the use of additional methods (Hahm et al., 2019), and some smoothing techniques can help to fix measurement errors (Hidaka & Yamamoto, 2021). In studies that often relate to city-scale big and anonymous data, limitations on travel type and travel purpose detection are highlighted, as users cannot be identified (Basu & Sevtsuk, 2022).

Geographical Information System

GIS, related functions and data are essential tools for planning practices in terms of analytics and performing tasks through elaboration of different kinds of geospatial data. In the 60s, the first examples of GIS were used; after the 90s, services that included GIS functions, such as web-based services, aerial photography, and three-dimensional views, became more widespread. Nowadays the ongoing process involving GIS pushes towards an integrated use of GIS and other technologies, especially GPS, Internet, Remote sensing etc., thus increasing its potential and supporting its use in different fields (Drummond & French, 2008).

a) Relations with traditional tools: GIS has advanced interfaces for coding, processing and analyzing spatial data. Accordingly, the use of GIS-based interfaces for keeping records, mapping of the observation processes has become more common in field studies of human behaviour in public spaces (Ghavampour et al., 2017).

b) Relations with walking behaviour research: GIS techniques are objective tools that can ensure to assess walkability (Wang & Yang, 2019). Some parameters that are widely examined to assess walkability through GIS can be listed as density, land use, accessibility of urban services/green facilities, street layout and so on (Lee & Talen, 2014; Telega et al., 2021). Moreover, 3D GIS techniques can be useful for street-level walkability urban design assessments (Wang & Yang, 2019). In addition to these, GIS-related interfaces (mobile or web-based) allow the collection of various types of data by multiple users. Relevant to these, several examples can be found in the literature related to walkability and walking behaviour through GIS tools; for instance, Telega et al. (2021) detailed methods to measure walkability with GIS and applied their proposal for Krakow; Blečić et al. (2014) introduced Walkability Explorer which is a walkability evaluation tool that contains GIS features; Manfredini & Di Rosa (2018) used GIS tools to reveal spatial accessibility for the elderly through pedestrian road networks in Milan; Al Shammas et al. (2023) proposed GIS-based algorithm for walking route planner considering specific pedestrian comfort parameters, within some limitations; Laatikainen et al. (2019) collected data about older adults travel behaviour with public participatory GIS (PPGIS) via an online mapping survey and post-processed them with additional techniques.

c) Limitations: GIS-based walkability assessments perform depending on data availability, accuracy and reliability. On the other hand, many cities still suffer from a lack of up-to-date comprehensive datasets (Lee & Talen, 2014).

Video-based (VB) methods

VB techniques include gathering visual data via camera(s) and are often associated with computer vision. Automated video systems in pedestrian research have advantages in capturing the natural mode of pedestrians, data accuracy & consistency (Alsaleh et al., 2018). Borges et al. (2013) categorise video-based human detection methods into three groups: appearance-based, motion-based and hybrid. Relatedly, VB methods can be used for action recognition, gait analysis, defining trajectories, and interaction analysis related to pedestrian behaviour, and several models/algorithms/datasets can be used to conduct and improve the abilities of analysis (Borges et al., 2013).

a) Relations with traditional tools: Video-based approaches have already been used for observational studies to understand public space dynamics for a long time manually. However, in the last two decades, they have

tended to be automated with computer vision techniques. Via video-based monitoring, counting and tracking of pedestrians can be performed within some limitations (Malinovskiy et al., 2008).

b) Relations with walking behaviour research: It can be used for data collection purposes in pedestrian behaviour studies in relation with application areas and to detect pedestrian numbers, pedestrian trajectories, etc. Several studies are conducted through video-based analysis to understand pedestrian walking behaviour by integrating additional techniques or algorithms based on research purposes. For instance, Willis et al. (2004) used video-based techniques with motion software and other measurement techniques to understand the microscopic movement patterns of pedestrians and some other features related to their walking behaviours; Alsaleh et al. (2018) analysed the impacts of cell phones on walking behaviour with using automated video analysis with using computer vision techniques; Liang et al. (2020) examined effects of climate on pedestrian walking through video-based observational study that use computer vision technology.

c) Limitations: Viewing angles, environmental conditions, positioning, calibration problems can affect analysis and data accuracy (Millonig et al., 2009). Different techniques and algorithms for pedestrian detection and tracking have their own constraints as mentioned in Malinovskiy et al. (2008)'s study.

Machine Learning Approaches (ML)

Interest in ML methods in urban studies is rising thanks to their ability to perform various tasks through a large amount and different types of data. ML methods (supervised/unsupervised) can be differ based on descriptive and predictive capabilities and different models can be used to analyse or model pedestrian mobility through different datasets (Toch et al., 2019).

a) Relations with traditional tools: ML can perform analyses for detection of pedestrian volume (Chen et al., 2020) or tracking (Toch et al., 2019) through location-based or visual data (photo/street view etc.) obtained/integrated with different technologies (Wifi, GPS, Bluetooth, GIS etc.).

b) Relations with walking behaviour research: In this research, ML approaches are considered one of the tools that support walkability assessment/measurements, but it is an emerging area with the potential to evolve. Literature concerning ML and walking show that depending on the dataset's characteristics. Several operations can be served to support walkability assessments through different models. For example, Blečić et al. (2018) use trained images by humans to understand perceived walkability, Zhou et al., (2019) use deep learning techniques to segment the physical environment through street view imagery and score visual walkability. Similarly, some other studies use street imagery through ML to detect pedestrian volume (Chen et al., 2020), to understand visual enclosure for street walkability (Yin & Wang, 2016) etc.

c) Limitations: Not all machine learning models perform in the same way, this depends on the task to be undertaken (Blečić et al., 2018); accordingly, the selection of the right ML tool for a given task can be challenging (Toch et al., 2019). Data bias, over/underfitting issues, and lack of data are some limitations that may occur related to ML approaches.

Augmented Reality (AR)

Augmented Reality is a technology that creates virtual views in real scenes (Isoyama et al., 2021; Mahapatra et al., 2023; Narzt et al., 2006), and lately its usability with different devices has increased. On the other hand, AR can positively/negatively affect pedestrians' walking behaviour depending on display positioning and characteristic of the content created (Isoyama et al., 2021). It has different indoor applications such as displaying routes in museums, commercial stores (Isoyama et al., 2021), and outdoor, as walkable AR experiences or games (Reilly et al., 2020), guides, navigation (Dong et al., 2021) etc. It works with other technologies such as Bluetooth, GPS etc (Amirian & Basiri, 2016; Mahapatra et al., 2023).

- a) Relations with traditional tools: AR is still used in more experimental ways in research dealing with pedestrian behaviours in urban spaces. Most studies are conducted through outdoor experiments in which test-walk groups use devices/software to understand AR's effect on walking/perceiving/playing.
- b) Relations with walking behaviour research: Although AR can be used in several contexts, it is often associated with pedestrian navigation systems in pedestrian studies (Amirian & Basiri, 2016; Mahapatra et al., 2023; Narzt et al., 2006), supporting walking behaviour in terms of route, wayfinding, and guidance. Relevant to these, Dong et al. (2021) tested the difference between 2D digital maps and AR-based navigation to understand the usability of AR navigation, considering wayfinding and spatial memory issues.
- c) Limitations: AR has still not reached its full potential in the context of urban applications. Different viewing angles and resolution capacities in some devices and positioning problems may limit the user experience (Isoyama et al., 2021).

Laser Scanning

"The laser scanner measures distances of nearby objects by emitting eye-safe laser beams at controlled directions and computing their time of flight" (Shao et al., 2007, p. 2174). Lately, interest in laser range scanners is rising related to tracking issues, and they have advantages in measurements and position determination (Shao et al., 2007). Some studies use multiple scanners for better results, and data gathered by various clients can be integrated to cover larger space (Shao et al., 2007). Relatedly, several algorithms/techniques have been proposed by experts to support the process of pedestrian detection and tracking process based on research purposes.

- a) Relations with traditional tools: Pedestrian detection, counting and tracking can be done using laser scanning data (Bauer et al., 2009; Shao et al., 2007; Xiao et al., 2016). However, these practices via laser scanning may require different implementation procedures depending on scanner type, positioning, scene etc. (Bauer et al., 2009).
- b) Relations with walking behaviour research: Laser scanners are mostly used for data collection, and there are several approaches that use those data in training models or supportive purposes in walking behaviour research. For example, Xiao et al. (2016) have proposed an algorithm for simultaneous detection and tracking of pedestrians using data captured with panoramic laser scanning and found out that these kinds of approaches can be efficient for flow estimations; Shao et al. (2007) have focused on detection and tracking of pedestrians in crowd scene using laser range scanners; Gate & Nashashibi (2009) are interested with pedestrian detection with laser scanning in dense urban spaces from moving vehicles; Maruyama et al. (2016) has created 3D environment models using laser scanners to support walking simulation.
- c) Limitations: Laser scanners are costly, especially in scenarios requiring multiple scanners, equipment may not be affordable (Hanzl & Ledwon, 2017; Millonig et al., 2009). Also, bad weather conditions can affect devices in outdoor experiments, and the detection range may not be sufficient (Kidono et al., 2011) depending on the tasks.

Bluetooth

Bluetooth is used for data exchange between devices located in short-distance, therefore has a big potential in proximity-based detection related to pedestrian behaviour (Hanzl & Ledwon, 2017), and ensuring information. It is used for "device-device communications" with several sensors, internet, smartphones etc. (Malinovskiy et al., 2012, p. 137), and it has passive and active forms. It can support real-time data collection in pedestrian studies integrated with other technologies, like Wi-Fi systems and is considered a low-cost approach for pedestrian detection (Kurkcu & Ozbay 2017).

- a) Relations with traditional tools: Bluetooth has potential in small-medium scale analysis in pedestrian studies; it can perform counting and tracking within limitations (Millonig et al., 2009).

b) Relations with walking behaviour research: Bluetooth can be used for data collection purposes in pedestrian oriented studies (Kurkcu & Ozbay, 2017; Malinovskiy et al., 2012). Sample sizes can be limited, and the travel time of pedestrians can be calculated through positioned devices (Malinovskiy et al., 2012). Accordingly, different studies have benefited from Bluetooth sensors related to their research dynamics. For instance, Angel et al. (2023) have been interested in the impact of policies during the pandemic on walking behaviour using datasets related to pedestrian movements documented via Bluetooth sensors; Malinovskiy et al. (2012) have conducted outdoor experiments to analyse pedestrian travel via Bluetooth; Davies et al. (2009) have benefited from Bluetooth in their experiments to support the interaction of users with public screens in a campus and so on.

c) Limitations: Users that actively use Bluetooth are limited and thus can result in insufficient sample size. In the experiments, privacy and bias concerns may exist (Malinovskiy et al., 2012).

Radio-Frequency Identification (RFID)

RFID is an AUTO-ID technology (Pang et al., 2010, p. 389) and an intrusive localization method for pedestrian studies (Bauer et al., 2009, p. 341), supporting identification and tracking. It works through tags and readers via different objects (smart cards, labels, wristbands etc.), and has passive and active tag types (Bauer et al., 2009; Chen, 2010; Pang et al., 2010), can be used with several technologies like Wireless sensors, GPS, etc. and has advantages like being low-cost, easy to use, verifying and providing automated real-time information. In urban planning, it is used to detect pedestrian movements, and understand transit behaviour, and vehicular movements (Pang et al., 2010).

a) Relations with traditional tools: RFID is used for pedestrian counting and tracking both indoors and outdoors (more experimental phase) within some limitations (Hanzl & Ledwon, 2017; Millonig et al., 2009).

b) Relations with walking behaviour research: Usually, it is used for data collection purposes in pedestrian behaviour research. There are different experiments in the literature, from "child localization system" in a theme park with RFID and wireless sensors (Chen, 2010) to "positioning estimation" for the visually impaired people (Yamashita et al., 2017). Related tags can support the determination of pedestrian density, movements, and flows (Conticelli et al., 2018).

c) Limitations: Privacy concerns are the most relevant limitations, and these problems must be fixed before the implementation of research experiments (Conticelli et al., 2018). Costs depend on RFID types and numbers (Pang et al., 2010).

Wireless Local Area Network (WLAN)

WLAN systems are networks that can connect several devices; in general, they offer access to the internet with access points (Santi, 2012). Relatedly, Conticelli et al. (2018) have mentioned Wi-Fi, one of the most common WLAN types, considering its linkage with smart pedestrian mobility systems, and Stanitsa et al. (2023) have addressed potential of data gathered from Wi-Fi tracking thanks to its cost-effectiveness and wide coverage.

a) Relations with traditional tools: WLAN data can be used for counting and tracking purposes in pedestrian studies within some limitations (Hanzl & Ledwon, 2017).

b) Relations with walking behaviour research: WLAN is used for data collection purposes in pedestrian studies (Millonig et al., 2009). In relation to these, Stanitsa et al. (2023) have tabulated variables used in their study, and the ones based on Wi-Fi tracking sources are listed through coordinates, date and time, time spent, distance, and walk speed. Also, Feng et al. (2021), in their study reviewing data collection methods considering pedestrian behaviour, investigated various research that used Wi-Fi. In addition, pedestrians can reach other services via these networks, so it indirectly affects walking behaviour with data exchange based on content.

c) Limitations: Position accuracy is one of the main disadvantages in Wi-Fi based location approaches, so research purposes must be considered accordingly and signal accuracy can differ in space (Stanitsa et al., 2023), gathered data may need processing procedures based on task.

Global System for Mobile Communications / Universal Mobile Telecommunications System (GSM/UMTS)

Mobile device usage is increasing, which triggers an understanding of the potential use of GSM/UMTS data. It is considered one of the alternatives for location data sources within limitations.

a) Relations with traditional tools: GSM/UMTS data and related localization methods can be used for approx. counting, and tracking. Tracking ability may not perform well in public space studies related to accuracy (Hanzl & Ledwon, 2017) but its capacity can be raised with custom applications or integration with other technologies such as GPS, Wifi etc.

b) Relations with walking behaviour research: It usually provides the data collection phase of walking behavior research. Feng et al. (2021, p. 5) have highlighted the role of GSM data in detecting mobility patterns, crowd densities, described in some studies. In addition, Sohn et al. (2006) show that GSM data can be used for mobility detection in a way integrated with custom applications.

c) Limitations: Regarding cell-based approaches, the data obtained depends on user activity, access permissions, and cell network providers and network density; user privacy and security are critical issues (Millonig et al., 2009). Relatedly, Toch et al. (2019) have mentioned that call detail records can not perform well in analyzing small-scale movements.

	Relation with traditional tools	Analyze (data collection / assess) & Support	Walking / walkability indicators that capture	Limitations
GPS	Counting, tracking	Analysis/mostly data collection, supporting walking behaviour*	Route, distance, duration, speed, time stamps, location...	May need additional smoothing techniques for signal interruption...
GIS	Mapping, Questionnaires*	Analysis/mostly assessment, collection*, supporting via GIS-based applications*	Walkability assess/ land use, accessibility of urban services& facilities, street layout...	Lack of data problems in terms of availability and accuracy ..
VB-tec.	Counting, tracking	Analysis/mostly data collection	Walking/ gaits, activities, routes ...	Depending on viewing angles, environmental conditions, calibration, etc.
ML	Use datasets to count and track	Analysis/mostly assessment	Walkability assess/ built environment & perceptual features	Expert knowledge, different models for different tasks...
AR	Test walks	Supporting walking behavior*	Support walking in terms of route, wayfinding, guide...	Limited experience, changing attitude depends content/ positioning...
Laser Scan	Counting, tracking	Analysis/mostly data collection	Walking/ time stamps, location related to device...	Costly, affected from environmental conditions, may need multiple device use..
Bluetooth	Counting, tracking	Analysis/mostly data collection	Walking/ travel time...	Active users can be limited, privacy and bias concerns...
RFID	Counting, tracking	Analysis/mostly data collection	Walking/density, flows...	Privacy concerns etc.
WLAN	Counting, tracking	Analysis/mostly data collection	Walking/ time stamps, distance...	Signal accuracy, may need multiple access points etc.
GSM/UMTS	Counting, tracking*	Analysis/mostly data collection	Walking/ pedestrian density, time stamp...	Depending on user activity, permissions, network providers, privacy issues ...

* may need additional technologies/ interfaces

Tab.2 Summary of technologies related to pedestrian walking behaviour studies

Technologies differ in their role in pedestrian walking behaviour research. In that sense, GPS, VB-tech, laser scanning, Bluetooth, RFID, WLAN, and GSM/UMTS are mostly related to data collection; counting and tracking purposes within limitations; as mentioned in (Hanzl & Ledwon, 2017; Millonig et al., 2009); GIS and ML perform/assist walkability assessments depending on the task; AR, GPS or GIS-based applications can be used to support walking behavior (Tab.2).

4. Conclusion

Within the scope of this research, the relationship between different technologies and traditional tools for analyzing and supporting pedestrian behaviour, has been examined in terms of usage patterns, and limitations thus giving an updated and comprehensive perspective. Similar reviews have been undertaken but they are few and partial: this review goes beyond by including relevant technologies, such as GIS, machine learning, and augmented reality technologies that can support pedestrian behaviour and walkability analysis. As a result of this paper, it has been detected that technologies have different capacities in understanding the dynamics of accessibility & walkability and collecting/measuring data sets that are difficult to cope with manual tools. Usage&choice of them mainly depends on the scale and purpose of the research. Therefore further research is needed to understand the real potential and usability of these tools, thus easing their usage and supporting users and practitioners in selecting the most suitable and relevant ones depending on their skills and research and application purposes.

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