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Measuring Neighborhood Walkability
: Scope Review of Recent 20 Audit Instruments

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Abstract

The interest in measuring neighborhood pedestrian environment has grown in recent years owing to its relevance to health, transportation, and urban planning. As the relationship between the neighborhood environment and walking has gained greater attention, researchers have developed diverse observational audit instruments to collect information on neighborhood walkability. This scope review aims to concisely inventory and examine these instruments, characterizing their data collection methods, unit of analysis, purpose, measured items, and the intended users, to gain a comprehensive understanding of the current stage of research on quantifying neighborhood walkability. This review was conducted through a literature search and examination of 65 articles, identifying 20 relevant audit instruments. The result of the analysis led to three conclusions. First, observational methods for measuring walkable built environments evolved from in-person audits to virtual data collection methods, using new technologies such as Google Street View (GSV) for cost-efficient data collection. Second, the audit protocols had to enhance explicitness in the instructions. Third, the audit instruments had to improve terminology consistency for reliable audit results. This review synthesizes the current knowledge on walkability audit instruments and provides insights for future researchers seeking to measure walkability of neighborhood environments in more advanced ways.

Keywords Walkability, Walkability Assessment Tool, Walkability Audit

Ⅰ. Introduction

1. Background

In recent years, the relationship between the characteristics of the built environment and walking has gained attention from various disciplines. The accumulated evidence suggests that the built environment is associated with physical activity. As a result, there is a corresponding need to measure the quality of the built environment for walking and identify built environmental determinants that can potentially create a walkable built environment. This need has gained growing interest among researchers, practitioners, and planners who aim to establish strategies targeting walking to increase physical activity (Moudon and Lee, 2003). A proliferation of methods has been incorporated into neighborhood research to measure a neighborhood's walkability, and each empirical study varies its measuring approach because researchers have different built environmental determinants that affect walkability measurements (Clifton et al., 2006).

Neighborhood research has developed a variety of

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measuring methods, each with its own strengths and limitations (Schaefer-McDaniel et al., 2010). Surveys, GIS, and audits are some of the approaches used, but there is no consensus among researchers on the most appropriate method (Lee and Talen, 2014). With the proliferation of walkability measurements, it has become increasingly difficult for researchers to choose suitable measuring methods and tools for their empirical studies. Given the various walkability measuring methodologies available, this paper focuses on the audit methodology, which assesses the pedestrian safety, accessibility, and comfort of a neighborhood's built environment via observation by raters.

Several earlier studies have reviewed the methods of walkability audit tools to understand the various types of walkability measurements. Nickelson et al. (2013) identified 31 audit instruments and thoroughly examined the domains and subdomains associated with each instrument. Similarly, Schaefer-McDaniel et al. (2010) reviewed 51 empirical studies that involved neighborhood observations, focusing on methodological rigor, geographical boundaries, and the relationship between neighborhood observations and the health of residents. Moudon and Lee (2003) reviewed built environment variables of existing audit instruments used to measure the bikeability and walkability of environments. In addition, Rzotkiewicz et al. (2018) systematically reviewed 51 English-language studies to analyze the current use of Google Street View (GSV) in health research, characterizing major themes, strengths, and weaknesses. Existing literature reviews inventory the fundamental information to aid auditors' selection and development process of audit instruments. (Nickelson et al., 2013; Schaefer-McDaniel et al., 2010). Despite existing research efforts, there is a scarcity of reviews dedicated to the in-depth interpretation of walkability audits, especially their diverse objectives, unit of analysis, and user perspectives, to highlight the development trend of audit instruments. Additionally, several reviews conducted approximately a decade ago, which focused on neighborhood audit tools, lack the inclusion of up-to-date information regarding the latest tools available for assessing neighborhood walkability. Therefore, there is a critical need for a comprehensive review that thoroughly examines both in-person and virtual audits, elucidating the transition from traditional in-person methodologies to virtual alternatives within the context of walkability literature. With these backgrounds, this study aims to fill the gap in the literature on neighborhood audit instruments by providing a critical review of the current state of research on walkability audit tools, specifically those available for quantifying the walkability of neighborhood pedestrian environments.

To this aim, this paper identified commonly used walkability audit instruments and analyzed the characteristics of each audit tool to provide an essential overview of the key factors of walkability audits. We first analyzed the trend of walkability measurement research by documenting the flow of research in measuring the walkability of a neighborhood. Subsequently, we conducted a thorough review of 65 studies and 20 tools, examining data collection methods, geographical scale, purpose, measured domains, and the primary users of each audit instrument. By providing the inventory of available neighborhood audit tools, this study is expected to aid researchers in understanding the nature of each audit tool and finding adequate tools for their neighborhood walkability studies.

2. Method

1) Collecting Relevant Publications

We conducted a database search to collect scholarly publications on keywords related to neighborhood walkability audits. We conducted a preliminary search on Google Scholar to collect both academic records and grey literature. We then searched on Scopus and Web of Science to collect journal articles relevant to neighborhood walkability audits. Search terms were determined based on those used in relevant publications in neighborhood research and modified to be as inclusive as possible. In order to collect as many relevant academic publications as possible, when searched on Scopus and Web of Science, we used methodological terms that can be interchangeable, which are 'Walkability Audit,' and 'Measuring Walkability'. With search terms 'Measuring AND Walkability' OR 'Walkability AND Audit,' we obtained 331 documents, when searched within article, title, abstract, and keywords on Scopus. With the same search terms and search criteria, a total of 1,450 citations were obtained from Web of Science. As a result, we retrieved a total of 1,781 records from Scopus and Web of Science. We then removed duplicate 202 citations from these results and screened the remaining citations' titles and abstracts that include the term 'walkability' for relevance. To ensure that we only included articles that pertained specifically to the topic of walkability, we eliminated any articles that expanded upon the topic to include measurements such as bikeability or wheelability. As a result, 65 articles were retrieved in full-text and further screened to identify audit tools mentioned in the selected articles. The literature selection process is illustrated in 〈Figure 1〉.

2) Selection of Relevant Instruments

After identifying the final list of 65 articles from the initial literature search, we thoroughly screened each one in full-text in order to catalog the audit instruments used for this review. To ensure that we were including the most reputable and widely used tools in measuring neighborhood walkability, we also conducted a careful review of existing literature. This included cross-referencing literature reviews on walkability measurements, selecting those audits that are simultaneously mentioned more than once among prior literature reviews (Brownson et al., 2009; Lee and Talen, 2014; Moudon and Lee, 2003; Nickelson et al., 2013; Schaefer-McDaniel et al., 2010). This step of our search process was important to ensure that we included well-established and reputable audit tools. Second, we selected audits from literature that explained the development process of the audit, specifically articles written by the original developer of the audit. This step was important as it ensured that the audits we included had a clear and well-documented development process. Finally, we selected audits utilized by empirical studies that measure walkability, as these studies provide evidence of the effectiveness of the audit in measuring walkability. This step was important as it ensured that the audits we included had been used in scientific studies and have been proven to be valid and reliable. The selection process resulted total 20 instruments for the analysis.

3) Analysis

For the 20 selected audits, we meticulously performed data abstraction on 20 selected audit instruments to gain a comprehensive understanding of their characteristics. We extracted the following information from each audit instrument: the name of the instrument, developer, year of development, countries of use, data collection method, unit of analysis, purpose, scale of measurement, domains measured, and intended users. To ensure the reliability of the information obtained from each audit, we initially sourced data from publications authored by the creators of the instruments, including empirical studies, supplementary materials, and internet resources. Furthermore, we cross-referenced the data obtained from multiple sources to increase the accuracy and credibility of our findings. The characteristics of each instrument are summarized in 〈Table 1〉.

Ⅱ. Walkability Audit Tool

1. Concept and Definition

The development of walkability audit tools is underpinned by a conceptual framework that addresses the challenge of translating the quality of the pedestrian environ-

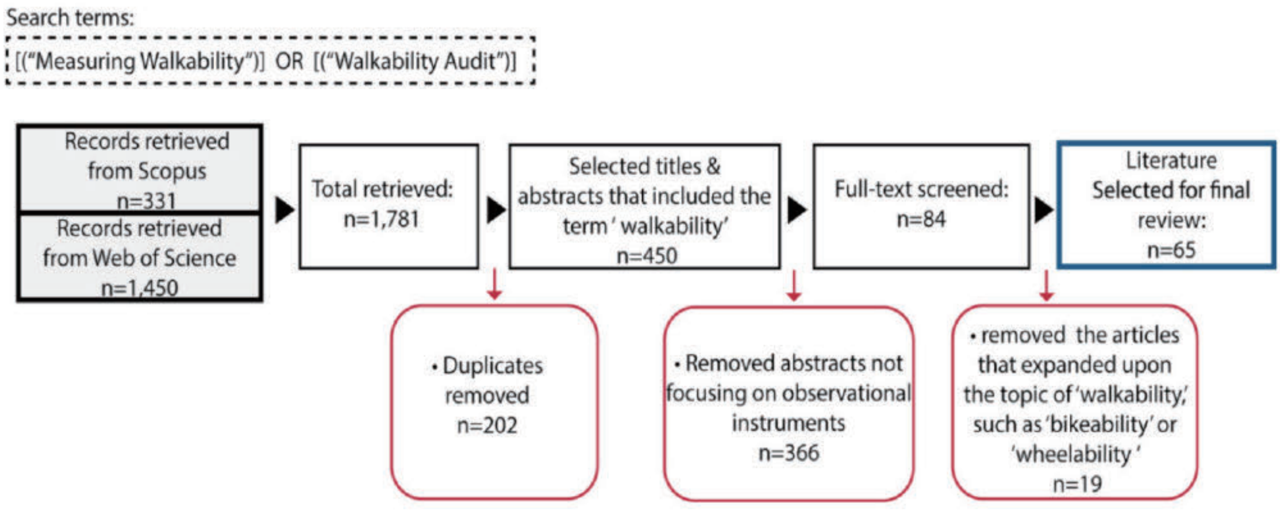

Figure 1. Literature selection process

Table 1. Comparison of audit instruments

A. In-person audits							
Name of the instrument	**Developer**	**Countries of use**	**Data collection methods**	**Unit of analysis**	**Purpose**	**Scale of measurement**	**Intended users**
Systematic pedestrian and cycling environmental scan instrument (SPACES)	Pikora et al. (2002)	Australia	In-person	Street segment	To measure the physical environmental determinants that affect walking and cycling in neighborhoods	Microscale	Researchers, practitioners
Pedestrian environment data scan (PEDS)	Clifton et al. (2006)	United States	In-person	Street segment	To measure environmental features that relate to walking in varied environments in the U.S.	Macroscale, Microscale	Researchers, practitioners
Irvine-minnesota inventory (IMI)	Day et al. (2006)	United States	In-person	Street segment	To measure a wide range of built environment features that are potentially lined to active living, especially walking or bicycling	Macroscale, Microscale	Researchers, practitioners
Senior walking environmental audit tool (SWEAT)	Cunningham et al. (2005)	United States	In-person	Street segment	To assist researchers in analyzing data collected in the service of understanding the influence of the physical environment on physical activity of older adults	Microscale	Pesearchers, practitioners
Senior walking environmental assessment tool-revised (SWEAT-R)	Michael et al. (2009)	United States	In-person	Street segment	To measure built environmental features associated with physical activity of older adults	Microscale	Researchers, practitioners, community members
Pedestrian bicycle information center checklist (PBIC)	PWA (2023)	United States	In-person	Street segment	To collect information about the environment for use in evaluating residents' satisfaction with their walking environment	Microscale	Community members
Walking suitability assessment form (WSAF)	Emery et al. (2003)	United States	In-person	Street segment	To examine features associated with pedestrian safety	Microscale	Researchers, practitioners
St. Louis analytic audit tool (SLU)-checklist version	Brownson et al. (2004)	United States	In-person	Street segment	To assess walkability and bikeability of street-scale environments and physical behavior	Macroscale, Microscale	Practitioners, community members
Active neighborhood checklist (ANC)	Hoehner et al. (2007)	United States	In-person	Street segment	To assess the activity friendliness of neighborhood streets	Macroscale, Microscale	Researchers, practitioners, community members
Analytic Audit Tool—St Louis University (SLU)-Analytic version	Brownson et al. (2004)	United States	In-person	Street segment	To measure walkability and bikeability of street-scale environments and physical activity behavior	Macroscale, Microscale	Researchers
Rural active living assessment (RALA)	Yousefian et al. (2010)	United States	In-person	Street segment	To evaluate the activity-friendliness including walkability of rural communities	Macroscale, Microscale	Researchers, practitioners
Microscale audit of pedestrian streetscapes (MAPS)	Cain et al. (2014)	United States	In-person	Street segment	To measure microscale environmental attributes correlated with physical activity	Macroscale, Microscale	Researchers, practitioners
AARP walk audit	AARP (2023)	United States	In-person	Street segment	To identify roads for improving safety	Microscale	Practitioners, community members

Table 1. (Continued)

B. Virtual audits							
Name of the instrument	**Developer**	**Countries of use**	**Data collection methods**	**Unit of analysis**	**Purpose**	**Scale of measurement**	**Intended users**
Computer assisted neighborhood visual assessment system (CANVAS)	Bader et al. (2015)	United States	Virtual	Street segment	To provide an online application with an efficient and user-friendly interface for measuring walkability and physical disorder in neighborhood environment	Macroscale, microscale	Researchers
SPOTLIGHT-virtual (S-VAT)	Bethlehem et al. (2014)	Netherlands	Virtual	Street segment	To assess the dietary and physical-activity-related environmental characteristics within neighborhoods	Microscale	Researchers
Forty area study street VIEW (FASTVIEW)	Griew et al. (2013)	United Kingdom	Virtual	Street segment	To examine the degree to which built environment characteristics influence adult's physical activity behaviors across a broad range of social and environmental settings in Northwest England	Microscale	Researchers
Drop-and-spin	Plascak et al. (2020)	United States	Virtual	Street segment	To develop a method where a GSV scene is rated by spinning 360° around a point location, using a modified version of the virtual Computer Assisted Neighborhood Visual Assessment System	Microscale	Researchers
Virtual systematic tool for evaluating pedestrian streetscapes (Virtual-STEPS)	Steinmetz-Wood et al. (2019)	Canada	Virtual	Street segment	To assess micro-scale features of neighborhood environments that may promote active living	Microscale	Researchers
Street walkability audit tool for route choice (SWATCH)	Shatu and Yigitcanlar (2018)	Australia	Virtual	Street segment	To assess street environment for route choice analysis of pedestrians	Microscale	Researchers

ment into quantifiable measures suitable for empirical research (Forsyth et al., 2006). As a walkability audit instrument is defined as a tool used to inventory or assess the physical environmental conditions associated with walking, its main objective is to measure walkability by analyzing the quality of pedestrian environment features and aggregating them into a singular walkability index or a composite score that encompass various factors of walkability (Baobied et al., 2021; Moudon and Lee, 2003). The fundamental purpose of the walkability audit tools is to provide a set of quantitative measures that practitioners or community members can use to assess the suitability of the neighborhood environment for walking. (Moudon and Lee, 2003).

Based on this conceptual framework, the early developed walkability audit instruments were conducted by in-person observation, in which a person observes the street segment by direct observation. Later, the "remote" approaches that can measure built environment variables using GIS or aerial photos have been incorporated into audit instruments (Brownson et al., 2009). These walkability audit instruments that can remotely measure built environments, are alternatively called as virtual audit tools (Steinmetz-Wood et al., 2019).

2. Process

The process of walkability audit instruments unfolds as follows: selecting sites, defining and sampling street segments within sites, training for auditors, collecting data, entering data, and synthesizing variables from the raw data to compute the walkability score (Brownson et al., 2009). The in-person and virtual audit procedures are similar, except for the data collection method. When using the in-person audit instruments, the auditors collect data by walking through sampled street segments and entering data directly into a Tablet PC or paper version of audit instruments (Day et al., 2006). Whereas when using the virtual audit tools, the auditors locate the street segments using the QGIS map, which allows the auditors to navigate through streets to view GSV images (Steinmetz-Wood et al., 2019). The detailed processes of the in-person and virtual audits are further explained in Chapter Ⅲ.

Ⅲ. Findings from 20 Audit Instruments

In order to provide a comprehensive understanding of the nature of walkability audits, we identified 20 commonly used audit instruments through a literature review and listed them in 〈Table 1〉. Based on the findings from the review, we organized the information into categories including purposes, data collection methods, unit of analysis, scale of measurements, measured items, and neighborhood boundaries. 〈Table 1〉 provides a comprehensive overview of all the reviewed audits and their characteristics.

1. Audits' Purposes

The primary objective of walkability audits in 〈Table 1〉 is to measure the walkability of different population groups. The audit tools are often tailored to measure the specific walking experience of different types of pedestrians, as environmental features that affect walking vary among them due to differences in their physical activity level. For instance, several audit tools have been developed to measure the built environment features associated with older adults' physical activity (Michael et al., 2009). These specific audit instruments are crucial in measuring the environmental obstacles for older adults in the neighborhood, which is essential for planning livable communities and enhancing the quality of life for seniors (Cunningham et al., 2005). These audits address the specific considerations of senior pedestrians, such as their sensitivity to loud noises and bright lights, cognitive ability and memory, slower walking pace, and susceptibility to steep inclines (World Health Organization, 2023). Senior specific audit tools measure the domains that potentially affect seniors' walking, such as signage accessibility, traffic and pedestrian signal timing lengths, and crosswalk lengths (Cunningham et al., 2005). The purpose of each audit instrument is explained in the columns of 〈Table 1〉.

Different intended users can also explain the purpose of walkability audit instruments. For instance, Moudon and Lee (2003) explained the audits into categories based on user groups. The first category is the audits designed to assess the built environment for research purposes. Audits for research usually inventory the environmental features that need to be observed during the data collection phase (Moudon and Lee, 2003). The audits are often called checklists because they provide an index of environmental variables for walkability assessment (Moudon and Lee, 2003). The primary purpose of the audits for the first category is to provide a standardized protocol for empirical research. The second category is the audits for transportation engineers, who measure the safety of road segments and rank the roads based on the pedestrians' perception of safety and comfort (Moudon and Lee, 2003). The audits from the third category are for the planners and policymakers, who identify the pedestrian concentrated area and ensure pedestrians' safety and comfort (Moudon and Lee, 2003). Lastly, the audit, such as the AARP walk audit, is intended to be used by the community members. The audits for community members are often accessible online and can be easily conducted by non-professionals. The training session is minimal compared to the other categories' audits, and the protocols are relatively simplified. The intended users of each audit instrument are specified in the columns of 〈Table 1〉.

2. Audits' Data Collection Methods

The data collection methods of walkability audit tools in 〈Table 1〉 have gone through various stages. Primary data collection methods used in walkability audit tools include collecting data in-person and using virtual methods such as Google Street View. Several audits in 〈Table 1〉 use in-person data collection methods, where the auditors characterize the quality of walkability by directly observing the built environmental features using a checklist while walking through the neighborhood (Pikora et al., 2002; Clifton et al., 2006; Day et al., 2006; Cunningham et al., 2005). The data collected in-person refers to the data collected by the auditors who visit the streets and directly observe the street infrastructure and conditions. This process begins with preparing the auditors by familiarizing them with the walking route and the audit instructions based on a manual (Pikora et al., 2003). In-person audits can be carried out by local participants, working with a trained coordinator who consults with them throughout the audit process. The in-person audit methods generally require tools such as a pen or pencil to complete the responses, a personal digital assistant (PDA) recording device, and a pedometer (National Transport Authority, 2021). The audit session requires a minimum 30 minutes of walking usually with a team of two auditors for each audit session (Emery et al., 2003). While observing the street, the auditors record the responses for each question on the audit form asking about the quality or presence of environmental attributes. The auditors then utilize a rating scale such as 1 to 10 to evaluate the overall quality of each environmental feature. The rating numbers are then combined to derive a composite score that indicates the overall quality of the environment's walkability (Lee and Talen, 2014; Partnership for a Walkable America, 2023). Additionally, in-person audit tools often incorporate qualitative measurements of the walking environment, allowing auditors to provide subjective assessments of their satisfaction with the environment (Pikora et al., 2003). The early auditing process relied heavily on manual input, which involved direct observation of a given neighborhood area or a street segment.

The use of virtual auditing methods has revolutionized the process of conducting audits by allowing researchers to perform audits at their desk (Steinmetz-Wood et al., 2019). Virtual audits generally employ more intricate protocols than in-person audits, including different interfaces to improve the inter-reliability of the audit results. For example, the Computer Assisted Neighborhood Visual Assessment System (CANVAS) classified the process according to the different interfaces, such as the 'study deployment interface' and the 'analytics interface' to improve inter-reliability of the audit results (Bader et al., 2015). Researchers are able to specify the street locations to be audited, audit items, and assign the street segments to auditors using the 'study deployment interface' (Bader et al., 2015). Locations can be either identified in 'manual-confirm' mode or 'auto-select' mode, where the virtual audit program displays the map with nearest viewable streets by issuing calls to Google's API. After designating the street segments, auditors select items to rate from the existing audit form or adjust the items in the list. Several virtual audits include the 'analytics' interface, in which study manager maintains the data of auditor's progress, inter-rater kappa statistics, and rating times for each audit session. This interface is particularly useful in handling data in the future, as these data can be downloaded in text files and imported into statistical software for further analysis (Bader et al., 2015). In addition, the virtual audit with different interfaces allows researchers to modify audit protocols to their specific research needs without deviating from the audit protocol (Bader et al., 2015). Therefore, the introduction of virtual audits using GSV has brought promising advantage for expediting the audit procedure, by enabling researchers to audit remotely, which dramatically reduced the time and cost of visiting street segments. The data collection method of each audit instrument is described in the columns of 〈Table 1〉.

3. Audits' Unit of Analysis

The audits summarized in 〈Table 1〉 employ street segments as the fundamental unit of analysis. To provide clarity, the audits operationalize a street segment as the "section of street or road between two intersections within each street" (Pikora, 2002). Within this context, a street or road encompasses one or more segments. For instance, segments A-B and C-D are treated as distinct entities, necessitating separate evaluations (Figure 2). Each segment is uniquely identified and assigned an ID number prior to data collection. The length of each street segment exhibits variability. According to WSAF, a typical street segment is generally under 2 miles in length, while SLU specifies a range of 1/4 mile or less. Depending on the audit protocol, observers

Figure 2. Definition of a street segment

may be tasked with assessing either one or both sides of a segment. For example, PEDS requires auditors to evaluate both sides of the segment for low-volume roads. On the other hand, for high-volume roads, auditors are directed to focus on the side with the greater traffic volume. Auditors are responsible for observing and recording various attributes of each street segment on an audit form. These attributes encompass elements such as the slope, number of intersections, types of pedestrian facilities, and materials used for pathways. In some cases, a segment may be represented by a cul-de-sac or another street variant lacking two intersections within 1/4 mile radius from each other (Prevention Research Center, 2020). It is pertinent to note that in the IMI protocol, a street segment is alternatively referred to as a "block face". As defined in the IMI instrument codebook, a "block face," encompasses both sides of a street (Day et al., 2006).

The sampling protocols differ across various studies. Some studies employed random segment sampling, while others conducted observations for entire neighborhoods. The IMI protocol suggests a sampling range of around 15-20 blocks within a neighborhood consisting of 60-80 blocks (Day et al., 2006). For instance, 36 segments were randomly selected to assess the inter-rater reliability of SWEAT (Cunningham et al., 2005). In contrast, all segments within a neighborhood were evaluated to ensure the inclusion of a significant number of segments with sidewalks, a crucial attribute for evaluating the reliability of PEDS (Clifton et al., 2006). It is important to note that this study recognizes several limitations. The small sample size may have an impact on limited variability and result in diminished reliability (Clifton et al., 2006). However, when dealing with neighborhoods characterized by homogeneous street attributes, sampling specific streets can significantly reduce observation time while providing a sufficient characterization of neighborhood walkability. To address the question of whether a sample size less than 100% of street segments adequately represents the pedestrian-built environment of a neighborhood, McMillan et al (2010) conducted a comparison of audit results using PEDS across eleven neighborhoods in Houston TX. Their findings indicated that the sampling 25% of residential street segments within a 400m radius of a neighborhood sufficiently represented the pedestrian-built environment (McMillan et al., 2010).

4. Audits' Scale of Measurements

The audits in 〈Table 1〉 measure diverse environmental features because there are no universal measures that can capture all significant factors of walkability due to the variety of built environments (Baobied et al., 2021). However, researchers have developed categorical terms to classify the measured attributes based on the scale of the measured attributes. Macroscale features refer to the wider pedestrian network and urban scale, including pedestrian network connectivity, land-use mix, and population density (Shields et al., 2021). Microscale elements refer to environmental features that potentially influence walking behavior on a human scale, such as the presence and conditions of sidewalks, benches, trees, and the level of crime (Shields et al., 2021). Several GIS-based audits, such as Walkability Index, consider macroscale elements in measuring neighborhood walkability. Audits that mainly assess macroscale components rely on the understanding of walkability as a quality that derives from urban-scale characteristics (Shields et al., 2021). However, walkability audits have increasingly measured microscale environmental elements based on accumulating evidence that such factors influence walking behavior in the neighborhood environment (Sallis et al., 2022). This consideration of microscale audits reflects an interest in creating street environments and neighborhoods that increase walking by enhancing pedestrian environments at the human scale (Shields et al., 2021).

5. Audits' Neighborhood Boundaries

The definition of neighborhood boundaries varies across studies, often being described as the spatial extent of the study area. Establishing the neighborhood within circular boundaries presents several advantages. First, circular boundaries encompass all areas to which a resident may be exposed during daily travels, whether on foot or by automobile (McMillan et al., 2010). Second, the use of straight-line distance enables the inclusion of foot travel distances and "shortcut" routes that may not be accounted for when employing a street network or aerial satellite photography strategy (McMillan et al., 2010). One approach to determining neighborhood boundaries involve specifying a radius distance from residents' homes. For example, streets were selected within a 400-meter radius of each participant's residence to test the reliability of the SPACES instrument (Pikora et al., 2002). This 400-meter radius is chosen based on the walkable neighborhood boundaries defined by the Western Australian Planning Commission (Pikora et al., 2002). Similarly, Lee et al. (2008) established a neighborhood buffer using a 0.25-mile radius from the school's location as the epicenter, approximately equating to a 5-min walk. In a different context, Mraz (2005) assessed street connectivity in suburban Tucson, AZ, considering the distance from the neighborhood center to a point on its perimeter, up to a distance of two miles and its bikeability. It is noteworthy that these studies align with the prevailing urbanist concept of the walkable neighborhood boundary, often approximated as a 1/4 mile radius, estimated as the distance an individual could walk in about 5 minutes (Pikora et al., 2002).

Census tracts serve as widely adopted delineations for defining neighborhood boundaries, particularly in studies encompassing the United States and Canada. These tracts constitute compact, relatively stable geographic zones within census metropolitan areas, with an average population typically around 4000 individuals (Statistics Canada, 2018). To illustrate, Chaudhury et al. (2011) used census tracts (CTs) to identify neighborhoods consisting of individuals aged 65 and older, constituting at least 13% of the total population in Portland and Metro Vancouver. In a similar vein, Brownson et al. (2004) used 2000 US Census Bureau data to assess the number of households and the percentage of population below poverty line in 1999. Drawing from this data, they selected both higher and lower-income neighborhoods in St. Louis, MO, representing a "low walkable" neighborhood, and Savanna, GA, representing a "high walkable" neighborhood. These examples underscore the applicability of census tracts as neighborhood boundaries, particularly in studies evaluating walkability based on diverse socio-economic characteristics. CTs offer a consistent, nationwide standard for delineation and furnish socio-economic insights within each census tract (Chaudhury et al., 2011). Analogous to the concept of the Census Tracts, in areas beyond North American regions, studies frequently adopt their country's standardized administrative boundaries. As an illustration, research conducted in the Netherlands employs the nation's administrative division boundaries.

Some studies establish unique neighborhood boundaries tailored to their research objectives. For example, Boarnet et al. (2011) employed a distinctive approach, sampling 716 subjects from 36 square focus areas measuring half a mile by half a mile (805×805 m). From these square focus areas, street segments were selected. Additionally, street segments were chosen from square study areas measuring one mile by one mile (1,609×1,609 m) (Boarnet et al., 2011). In another study, street segments were carefully selected from four distinct "zones" encompassing the "Town Center," Thoroughfare," "Neighborhood Cluster," and "Isolated School." These "zones" were conceived to encompass all accessible streets outside of the town center, including areas adjacent to schools located on the town's periphery or along highways, remote residential zones, and thoroughfares (Yousefian et al., 2010). 〈Table 2〉 summarizes the definition of neighborhood boundaries of the reviewed studies and audit instruments.

6. Audits' Measured Items

Many walkability audits employ a hierarchical system to organize physical environmental items and clearly state the factors of walkability they intend to measure. One such framework is the system of domains, and subdomains, where domains refer to the prominent categories consisting of minor environmental attributes. In line with the commonly measured domains identified by Nickelson et al. (2013) the most frequently measured domains were Functionality, Safety, Aesthetics and Land Uses. The Functionality domain includes subdomains, such as 'walking/cycling surface,' 'streets,' and 'traffic' (Pikora et al., 2003), while the Safety domain comprise components such as stop signs that potentially enhance the perception of safety (Chaudhury et al., 2011). The Aesthetics domain assesses the visual appeal and the quality of the streetscape (Cunningham et al., 2005; Chaudhury et al., 2011), while the Land Uses domain measures the functional usage of the land in the street segments (Nickelson et al., 2013). The categorical terms used to describe the domains may vary among the walkability audits, as each researcher who develops the audits considers different factors when capturing neighborhood walkability. Another example is the system of features, elements, and items where features align with the same hierarchical definition as domains, elements align with subdomains, and

Table 2. Definitions of neighborhood boundaries

Studies	Audit name	Definition of neighborhood boundaries
Pikora (2002)	SPACES	Radius distance
Clifton (2006)	PEDS	Census tracts
Boarnet et al. (2011)	IMI	Focus areas
Cunningham et al. (2005)	SWEAT	Census tracts
Chaudhury et al. (2011)	SWEAT-R	Census tracts
Mraz (2005)	PBIC	Census tracts
Lee et al. (2008)	WSAF	Radius distance
Brownson et al. (2004)	SLU-Checklist	Census tracts
Hoener et al. (2007)	ANC	Census tracts
Brownson et al. (2004)	SLU-analytic version	Census tracts
Yousefian et al. (2010)	RALA	Others
Cain et al. (2014)	MAPS	Census tracts
Hansen et al. (2009)	WABSA	Census tracts
Barragan and Wladkowski (2019)	AARP Walk Audit	Others
Bader et al. (2015)	CANVAS	Census tracts
Bethlehem et al. (2014)	S-VAT	Others
Griew et al. (2013)	FASTVIEW	Radius distance
Plascak et al. (2020)	Drop-and-spin	Census tracts
Steinmetz-Wood et al. (2019)	Virtual-STEPS	Others
Shatu and Yigitcanlar (2018)	SWATCH	Radius distance

items align with individual built environmental factors (Pikora et al., 2003). Although audits may use different terminology to describe the attributes, they all describe the same concept of the built environment factors that correlate to walkability (Nickelson et al., 2013). 〈Table 3〉 summarizes the differences in measured items of the audits listed in 〈Table 1〉, based on the six categories and attributes.

Ⅳ. Discussion and Conclusion

A considerable body of audit instruments assessing the built environment's impact on physical activity holds significance for researchers, practitioners, and community members. The audit instruments have spurred significant progress from in-person methodology to virtual methods in comprehending how environmental factors influence physical activity across diverse populations and settings. The core characteristics that highlight differences in audit instruments are the diverse purposes of audit instruments that aim to measure the walkability of different population groups.

Based on the findings described in the previous chapter, this paper identified three discussion points. First, notable trends have been observed in the development of audit tools, characterized by a transition from in-person observations to virtual data collection methods. Our findings substantiate a discernible increase in the adoption of virtual data collection methods, such as Google Street View, in recent years. This shift can be attributed to their cost-effectiveness and time-saving advantages (Rzotkiewicz et al., 2018). Accordingly, some studies have been conducted to evaluate the reliability of virtual audits as a viable alternative to traditional in-person audits, with a majority indicating a high degree of correlation between the two approaches (Lee and Talen, 2014). This prevalence of virtual audits has significant implications for researchers, as it facilitates more efficient and effective measurement of neighborhood walkability (Bader et al., 2015; Steinmetz-Wood et al., 2019). This underscores the necessity for researchers to consider the advantages and disadvantages associated with these different methods when designing studies and measuring walkability.

In the future, the progression of virtual audits is expected

Table 3. Category and variables of measured items

Category		Variables	SPACES	PEDS	IMI	SWEAT	SWEAT-R	PBIC	WSAF	SLU-Check.	ANC	SLU-Analy.
1. Land use	1-1. Density	Housing density	X	X	X	X	X	X	X	X	X	X
		Population density	X	X	X	X	√	X	X	X	X	X
	1-2. Type	Land use types (residential, commercial)	√	√	√	√	√	X	X	√	√	√
2. Environments along the street segment	2-1. Buildings	Architectural style (variety)	√	X	X	X	√	X	X	√	X	X
		Building height	X	√	√	√	√	X	X	X	X	X
		Building setback	X	√	X	X	X	X	X	X	X	X
		Building features (windows etc.)	X	√	√	√	√	X	X	X	X	X
		Frontage yard conditions	√	X	√	X	√	X	X	√	√	X
	2-2. Lighting	Presence of lighting	√	√	√	√	√	X	√	√	√	√
		Lighting quality	√	X	X	√	√	X	X	X	X	X
	2-3. Street furniture	Benches	√	√	√	√	√	X	X	√	√	X
		Other street furniture (tables, parklets etc.)	√	√	√	√	√	X	X	X	X	X
	2-4. Litter	Presence of litter	√	√	√	√	√	√	X	√	√	√
	2-5. Trees	Presence of trees	√	√	√	√	√	√	X	√	√	√
		Presence of shades	√	√	√	X	X	X	X	√	√	X
3. Sidewalk	3-1. Presence of sidewalk	Presence of sidewalk	√	√	√	√	√	√	√	√	√	√
	3-2. Sidewalk quality	Materials	√	√	X	√	√	X	√	X	X	X
		Conditions or maintenance of sidewalk	√	√	√	√	√	√	√	√	√	X
	3-3. Slope	Slope of the sidewalk	√	√	√	√	√	X	X	X	√	√
	3-4. Width	Sidewalk width	X	√	X	√	X	√	√	X	√	√
4. Road/ Sidewalk connectivity	4-1. Street crossing	Presence of crossings	√	√	X	√	√	X	X	√	√	√
		Crossing aids	√	√	X	√	√	X	X	√	√	√
		Crossing width	X	X	X	X	X	X	X	X	X	X
		Types of crossings (marked, unmarked)	√	√	√	X	√	X	X	X	X	√
	4-2. Pedestrian signalization	Presence of traffic/ pedestrian signals	√	√	√	√	√	√	X	√	√	√
	4-3. Buffer	Presence of barriers between road and sidewalk (trees, grass)	X	√	√	√	√	X	√	X	√	X
	4-4. Curb	Presence of curb	√	√	√	√	√	√	X	√	√	√
5. Safety	5-1. Surveillance	Presence of surveillance system	√	X	X	X	X	X	X	√	X	X
	5-2. Crime	Exposure to crime	√	X	X	X	X	X	X	√	√	X
6. Aesthetics	6-1. Appeal	Visual attractiveness of a streets and buildings	√	X	√	√	X	X	X	√	X	X
	6-2. Memorability	Unique markers	X	X	X	X	X	X	X	X	X	X

to advance further, embracing more innovative approaches that integrate computer vision and deep learning techniques. While virtual audits employing computer vision techniques using Google Street View images have already surmounted numerous limitations of traditional in-person audits, such as mitigating travel and audit time, and reducing exposure to crime, the utilization of Google Street View still necessitates substantial manual input from auditors, rendering the auditing process time-consuming (Adams et al., 2022; Badland et al., 2010; Wilson et al., 2012; Yi et al., 2019). To address this challenge, the hybrid approach of combining computer vision techniques with deep learning holds promise. By training neural network models to recognize patterns in pedestrian environments depicted in GSV images, this approach has the potential to automate the auditing process without human intervention. Consequently, researchers anticipate that this approach will expedite the audit time and yield many advantages, such as reducing the need for travel and labor cost since fewer auditors would be required. As these methods continue to evolve, researchers will persistently seek more efficient methods to conduct streetscape audits, ultimately leading to the advancement of the walkability audit system.

Second, there exists a pressing need for explicit guidelines within the audit process itself. This includes addressing issues such as unclear instructions regarding the number of segments required for auditing and discrepancies in defining the neighborhood and geographical area assessed across different audits (Schaefer-McDaniel et al., 2010). Ambiguity regarding the required number of observed segments can result in low interrater reliability when the audit is conducted in different regions (Chaudhury et al., 2011). Such inconsistencies and imprecisions in audit manuals can lead to decreased reliability in audit results and hinder comparisons between different audit tools (Nickelson et al., 2013). In future audit development, it is crucial to provide explicit operational details and rationale behind the development process to facilitate better comparisons between studies (Brownson et al., 2009; Schaefer-McDaniel et al., 2010).

Lastly, there is a need to maintain consistency in the use of terminology. For instance, various audit instruments employ different terms to describe the same measured items. For example, as noted by Nickelson et al. (2013), the space between a street and a sidewalk is referred to as sidewalk buffer in several audit instruments, whereas others refer to it as a verge (Pikora et al., 2002). To comprehend the intricate methodological and analytical processes of audit instruments across a wide range of disciplines, it would be advantageous to maintain terminology consistency on important variables such as the geographical scale, measured items, required observation time, and protocols for analysis (Schaefer-McDaniel et al., 2010). Such terminology consistency would enhance the understanding of audit instruments' complexity and promote comparability across studies.

This paper aimed to be as comprehensive as possible in the selection of audits for review. However, given the continuous evolution of audit tools across various fields, periodic updates of this review will be necessary to ensure accurate representation of the available audit tools. It is plausible that certain aspects of walkability audit characteristics may have been covered in our analysis due to the dynamic nature of audit tools. It is crucial to note that the 20 audits included in our study, which are widely used and consistently referenced in the literature, can be considered representative of the overall landscape of walkability audit tools. Instead of establishing definitive standards for measuring neighborhood walkability, the objective of this paper is to provide researchers with information on the available methods for measuring walkability and help them select the appropriate audit tools for their research.

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