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Perceived accessibility: What it is and why it differs from calculated accessibility measures based on spatial data

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A R T I C L E I N F O

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A B S T R A C T

Accessibility is usually evaluated using indicators calculated from spatial data. However, perceived accessibility, defined as the perceived potential to participate in spatially dispersed opportunities, is often poorly reflected by these calculated measures. This paper sets out to explain the mechanisms that lead to these mismatches. A conceptual model is constructed to establish what factors shape perceived accessibility. A schematic framework shows that mismatches between a calculated indicator and perceptions can stem from inaccuracies in awareness as well as from inaccuracies in the measure if the measure fails to take account of the subjective evaluations of accessibility components. When evaluating the performance of land-use and transport system configurations, calculated measures based on spatial and transport data only serve as proxies for how accessibility is actually experienced. This paper argues that bringing perceived accessibility to the fore of accessibility-based planning, by acknowledging and evaluating potential mismatches with calculated accessibility indicators, will advance the evolution from mobility-based to accessibility-based planning.

1. Introduction

The key role of a transportation system is to provide people with the opportunity to engage in spatially dispersed activities of all kinds (Miller, 2018). This potential to interact is often referred to as accessibility. It is increasingly acknowledged that having sufficient accessibility is a crucial factor for social inclusion and, therefore, potentially for wellbeing (De Vos et al., 2013; Lucas, 2012; Preston and Rajé, 2007; Van Wee, 2016). Consequently, goals linked to accessibility rather than to only increasing potential mobility are gaining prominence in transportation plans around the globe (Boisjoly and El-Geneidy, 2017a; European Commission, 2015; Handy, 2020; Proffitt et al., 2019).

However, the evolution from mobility-based to accessibility-based planning faces many barriers, including the operationalization, interpretation and communication of accessibility indicators (Boisjoly and El-Geneidy, 2017a, 2017b; Handy, 2020; Martens, 2017; Silva et al., 2017). Usually, accessibility is evaluated using calculated indicators based on spatial data (from now on: 'calculated accessibility'). However, the relationship between the land-use and transport systems and potential individual behaviour is mediated by how the environment is perceived (Downs and Stea, 1973; Golledge et al., 1972; Ma and Cao, 2019; Ma et al., 2014; Ma and Dill, 2015; Morris et al., 1979; Wang et al., 2015b). Each individual has their own 'mental map' of what is within reach and what are suitable activity locations, which ultimately acts as the basis for decisions regarding spatial behaviour (Downs and Stea, 1973; Morris et al., 1979; Van Wee, 2016, p. 11).

Studies on perceived accessibility indicate that self-reported evaluations of accessibility are often a poor match with calculated accessibility measures (see, for example, Comber et al., 2011; Curl et al., 2015; Curl, 2018; Dewulf et al., 2012; Fone et al., 2006; Gebel et al., 2011; Gim, 2011; Lättman et al., 2018; Lotfi and Koohsari, 2009; Macintyre et al., 2008; McCormack et al., 2008; Scott et al., 2015; Van der Vlugt et al., 2019). As perceived accessibility can be viewed as the real basis for decisions regarding participating in spatially dispersed opportunities (Kirk, 1963; Gold, 1980; Morris et al., 1979), any mismatches with calculated accessibility indicators may undermine policy strategies regarding accessibility. To reduce this risk, it is necessary to understand the mechanisms that lead to these mismatches.

In response, this paper sets out to explain the mechanisms that lead to mismatches between calculated and perceived accessibility. This

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paper first establishes what perceived accessibility actually is by discussing why perceptions of the environment may differ from the actual observable physical environment. This discussion is exemplified through a conceptual model of perceived accessibility building on the theoretical components of accessibility established by Geurs and Van Wee (2004). Following the identification of factors that contribute to perceived accessibility, this paper provides a schematic framework of how mismatches can occur between calculated indicators of accessibility and perceived accessibility. Based on this, the paper then discusses implications of perceptions on the interpretation of conventional accessibility indicators used in transport planning. Finally, suggestions are provided regarding the integration of perceived accessibility into accessibility-based planning, along with a research agenda.

Integrating subjectivity into transportation research has gained popularity in recent decades. Inspired by insights from sociology and social psychology, De Witte et al. (2013) and Van Acker et al. (2010) established frameworks for travel behaviour that incorporated travel and residential attitudes. Within the same field, Lanzini and Kahn (2017) presented a meta-analysis of psychological determinants of travel mode choice. Further, Metcalfe and Dolan (2012) presented an overview of contextual factors derived from behavioural economics influencing travel behaviour changes. On the journey level, Di and Liu (2016) reviewed bounded rational route choice behaviour. In the social health sciences, several reviews have highlighted the role of neighbourhood perceptions in active travel behaviour (Duncan et al., 2005; Owen et al., 2004). The reviews referred to here have all focused on subjective determinants of actual travel behaviour to reach activities. However, no attempt has yet been made to generalize these insights to address the perceived potential to participate in activities (i.e. perceived accessibility). This paper aims to fill this gap by providing an appropriate framework.

The paper is structured as follows. Section 2 provides a short conceptualization of perceived accessibility in relation to traditional accessibility conceptualizations. Section 3 considers how perceptions of the environment are shaped and mediate the relationship between the environment and potential behaviour. Based on this argumentation, a conceptual model of perceived accessibility is established. Section 4 then turns to explaining how mismatches occur between calculated accessibility indicators and perceptions of accessibility. Section 5 discusses the implications for the interpretation of conventional accessibility measures, presents practical implications for incorporating perceived accessibility in evaluations and a research agenda to further advance this topic. Finally, Section 6 summarizes the main conclusions regarding accessibility-based transport policymaking.

2. Perceived accessibility

A myriad of conceptualizations of accessibility have emerged after the seminal work by Hansen (1959). It is generally agreed that accessibility is a combination of the magnitude of opportunities provided at destinations and the resistance associated with reaching these locations (Miller, 2018; Van Wee, 2016). Much of the literature on conceptualizing accessibility has focussed on how to measure accessibility based on spatial data (for overviews of accessibility indicators see, for example, Handy and Niemeier, 1997 or Geurs and Van Wee, 2004). Such calculated indicators, which stem from the dominant approach to transport as a rational discipline rooted in engineering (Kębłowski and Bassens, 2018), may suggest that accessibility constitutes an objective quantifiable reality. However, it has long been recognized that perceived accessibility, as the actual determinant of decisions regarding activity behaviour, may differ from such indicators (Morris et al., 1979). These calculated measures may, therefore, not reflect accessibility as it is actually experienced (Section 5.1 returns to this notion). Yet, only recently, research interest in perceived accessibility has increased (e.g. Curl et al., 2015; Curl, 2018; Lättman et al., 2016, 2018).

In this paper, perceived accessibility is defined as *the perceived potential to participate in spatially dispersed opportunities*. This definition builds on the view that accessibility is most generally about the potential to engage in activities distributed across space (e.g. Burns, 1979; Geurs and Van Wee, 2004; Hansen, 1959; Preston and Rajé, 2007). These activities potentially contribute to social inclusion and well-being, provided that these activities are desired. The opportunity-based definition used here allows for the possibility that positive evaluations of accessibility for a certain type of activity may not always lead to increased levels of participation and, consequently, social inclusion, since not all types of activities are equally desired. This generalizes and complements outcome-based definitions of perceived accessibility, which aim to directly evaluate the benefits derived from accessibility regarding social inclusion and well-being (e.g. "*how easy it is to live a satisfactory life with the help of the transport system*", Lättman et al., 2016, p. 36). As the main interest of this paper is to explain the mediating role of perceptions of accessibility in the relationship between the physical environment and spatial behaviour, which includes the desirability of opportunities, an opportunity-based definition is considered most useful.

3. How perceptions of accessibility are shaped

In Section 3.1 it is reasoned that the cognitive environment in which decisions regarding spatial behaviour take place is different from the actual physical environment. This argumentation is then applied to the concept of accessibility in Section 3.2, where a conceptual model of perceived accessibility is presented.

3.1. The formation of the cognitive environment

Behavioural and cognitive approaches within geography have acknowledged that decisions related to spatial behaviour follow from perceptions of the environment (Kirk, 1963; Gold, 1980). Therefore, spatial behaviour is not only directly influenced by the physical environment but also mediated by how the physical environment is perceived. Different people can perceive the same place in very different ways following heterogeneous processes of gathering, detecting, filtering and interpreting information from their environments (Golledge, 1978). Consequently, decisions, including those related to travel, in relation to the context in which an individual lives are rarely made in a fully rational way (Metcalfe and Dolan, 2012; Simon, 1957; Tversky and Kahneman, 1974). Here, a distinction can be made between an actual and a cognitive environment, where the latter is seen as the basis for spatial decision-making (Downs and Stea, 1973; Gold, 1980; Kirk, 1963).

An influential, albeit simplified, representation of the cognitive processes involved in shaping perceptions of the environment is displayed in Fig. 1. Information on the *actual environment* can be gathered and detected directly through interaction with the physical environment itself as well as indirectly through representations of the environment (maps, media, descriptions by other people etc.) (Thorndyke and Hayes-Roth, 1982). In recent years, digital representations may be increasingly important following the growing presence of ICTs in many aspects of daily life (e.g. information on the existence, availability and feasibility of opportunities through online maps, GPS, social media). When it comes to detecting and gathering information, strategies may differ from person to person, especially between satisficing and maximizing individuals (Bovy, 2009; Conlisk, 1996; Di and Liu, 2016; Schwarz et al., 2002). 'Satisficers' are expected to cease their information searching once a satisfying alternative has been found, while 'maximizers'

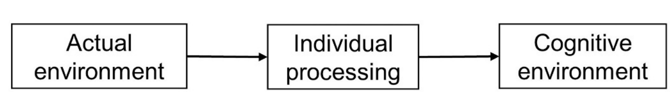

Fig. 1. Formation of the cognitive behavioural environment (based on: Downs, 1970 in Holloway and Hubbard, 2001, p. 45).

continue to find the best alternative.

Translating information on the environment into a mental image of the environment is subject to *individual processing*. As psychologists have extensively argued, our brains are often 'overloaded' by the amount of information they receive (i.e. sights, sounds, smells, textures and even tastes). Even in seemingly simple environments, some information that is relatively unimportant to the task at hand may be filtered out. The extent to which information can be detected and correctly memorized is linked to individual spatial abilities, which relate to the ability to imagine and mentally transform spatial information (Hegarty et al., 2006; Tversky, 1992; Uttal et al., 2013). When information is gathered from representations, note that these representations of the environment may themselves be filtered, distorted and coloured as a result of incomplete knowledge and/or the intentions of their creators (for example, a public transport company may not display taxi stands on their maps).

What one consequently knows about the environment can be termed *spatial knowledge*. Golledge and Stimson (1997) identified three components of spatial knowledge: i) a *declarative* component encompassing knowledge about the existence and attributes of places; ii) a *relational* component concerning spatial relationships between the individual and these places, as well as among known places, including concepts such as direction, proximity and hierarchy; and iii) a final *procedural* component associated with understanding about how to move towards and between places.

Finally, knowledge is interpreted and evaluated following one's own value system that reflects the attitudes and beliefs held by an individual. Consequently, sources of information may be appreciated and interpreted in various ways (Metcalfe and Dolan, 2012). These individual processing mechanisms result in a mental image of the environment. This *cognitive environment*, often incomplete, distorted and coloured through filtering and biased processing, was notably examined empirically by Lynch (1960) using mental sketch-mapping techniques and is widely considered to act as the real basis of spatial decision-making (Gärling et al., 1984; Tolman, 1948; Tversky, 1981, 1992; Wolpert, 1964). Based on such arguments, it can be inferred that one's mental image of accessibility in a certain environment may also be incomplete and coloured. This notion is elaborated further in the next section.

3.2. A conceptual model for perceived accessibility

Translating the discussion on how perceptions of the environment mediate the environment–behaviour relationship to the concept of accessibility, this section analytically derives a conceptual model of perceived accessibility (Fig. 2). The framework draws heavily on the work of Geurs and Van Wee (2004) by adopting their accessibility components as a starting point.

In line with the discussion presented in Section 3.1 there is an indirect link between the environment and spatial decision-making mediated by perceptions of the environment. These perceptions are a function of spatial knowledge and individual valuations of components of the environment of which one is aware of. When considering accessibility, the physical environment consists of the land-use and transport systems. Perceived accessibility in this model is formulated as a function of perceptions of the distribution and characteristics of activity locations (land-use), of the transport system and of the temporal feasibility of engaging in these opportunities via the transport system. This is equivalent to the 'cognitive environment' shown in Fig. 1. The mechanism behind the formation of these perceptions is captured in the overarching individual component, since this determines the environment with which an individual is confronted and how accessibility information is received and processed.

In terms of the *land-use component*, perceptions may relate to the distribution and characteristics of activity locations. As such, this involves knowledge of available opportunities and their locations (i.e. the declarative and relational components of spatial knowledge). For example, one may not know an activity location in one's surroundings or incorrectly estimate the distance to it (Cadwallader, 1979; Witlox, 2007). Also, the perceived attributes of these activity locations matter: it could be that one perceives an activity location to be near but not suitable based on certain quality attributes. For example, a person may have an expensive grocery shop nearby but, because of one's income, might consider that shop to be not suitable, and prefer to shop at a cheaper supermarket further away. So, despite the expensive shop may be perceived as easy to reach, it is not perceived as a possibility for engaging in the desired activity (i.e. grocery shopping). Therefore, its

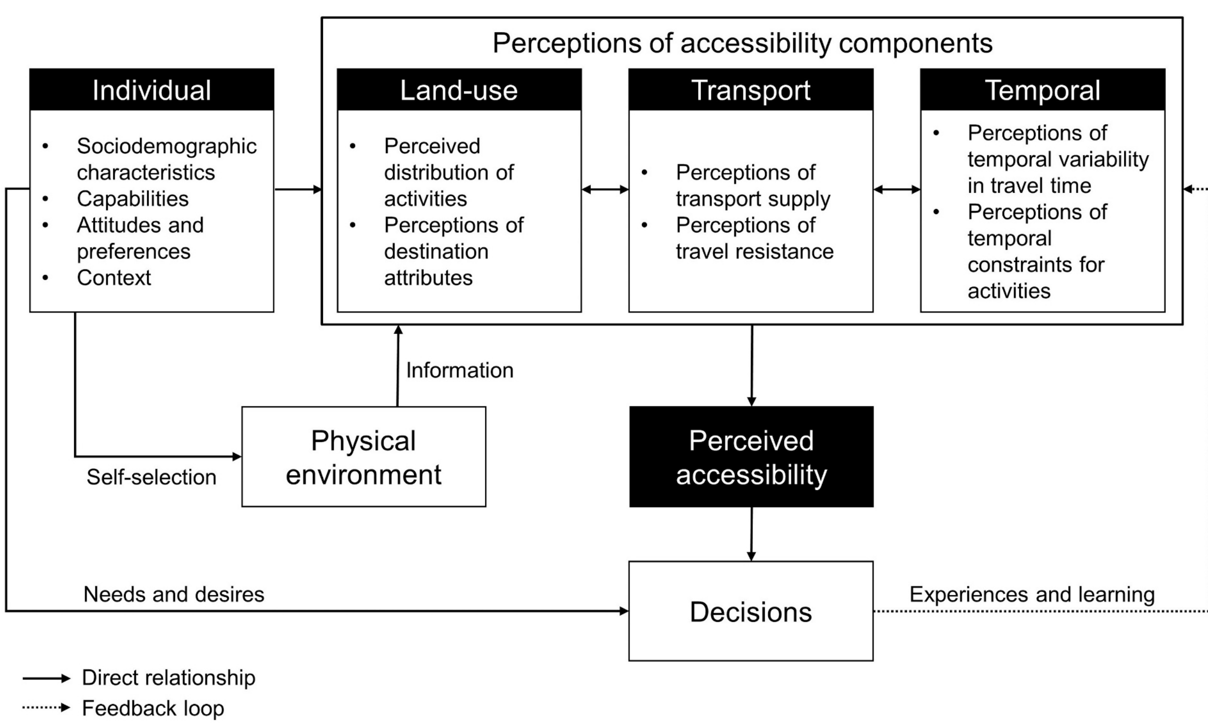

Fig. 2. A model of perceived accessibility.

perceived accessibility would be low.

Similar reasoning holds for the *transport component* of accessibility. First, one may have incomplete awareness of the supply of transport options, including transport modes and possible routes to a considered activity location (i.e. the procedural component of spatial knowledge). Second, travel resistance can be perceived and evaluated in very heterogeneous ways in terms of all the components of generalized transport costs (GTC) such as comfort, costs, safety and convenience (Sadalla and Staplin, 1980).

Finally, perceptions can relate to the *temporal component* of accessibility. For example, one may incorrectly estimate the time needed to get to an activity location or to conduct an activity at a certain location, and consequently perceive it as inaccessible. Further, perceptions of the temporal availability of an activity location, such as opening hours, will also determine whether someone deems the activity feasible.

The perceptions of these spatial accessibility components will also interact. For example, perceptions of distances (land-use) are likely to influence perceptions related to travel resistance (transport system). When distances are perceived to be long, travel resistance may also be perceived as high. In turn, this would also influence the perceived temporal feasibility of activity patterns.

When discussing what constitutes perceived accessibility, public transport services are a special case. These services can be seen as part of the accessibility of a certain activity location, and thus part of the transport component, but they can also be seen as activity locations in their own right, which can be perceived as accessible or not (bus stops, train stations etc.). Then one can speak of the perceived accessibility of a public transport service (Hess, 2012; La Paix and Geurs, 2016). The reasoning from the previous paragraphs still applies, the land-use component now relates to the perceived location of public transport services, the transport component to perceptions of getting to the public transport service, and the temporal component to the temporal feasibility of using it.

Turning to how these perceptions of components of accessibility are shaped, there are personal factors, as defined in the *individual component* of accessibility, that will influence how information on components of accessibility are gathered and processed. The sources of these mechanisms, which link to *sociodemographic characteristics* (age, gender, income etc.), include capabilities, attitudes and the geographical and social contexts. Personal *capabilities*, including spatial abilities, will influence the ways in which information is gathered and interpreted. For example, some are better able to interpret maps, to use online travel planners, to estimate distances, and to identify opportunities and remember directions while travelling than others (Witlox, 2007). Also, for some, high travel costs may matter less than for individuals with limited incomes. Whether certain activity locations are perceived as feasible will be influenced by *attitudes* and *preferences* related to these locations as well as to travel options (Van Acker et al., 2010). Personal attitudes towards transport modes and which activity patterns are perceived feasible are in part shaped by the geographical and/or social *context* and one's position within this context (Avineri, 2012; Pot et al., 2020). This occurs on multiple scales such as countries, local communities and households (Smirnov and Egan, 2012; Van Acker et al., 2010; Wang et al., 2015a). The social environment can for example provide information on experiences with certain travel modes or activity locations, which will shape personal attitudes towards them. Moreover, the social and geographical contexts may prescribe norms related to accessibility and travel behaviour to which an individual wants to comply (Ababio-Donkor et al., 2020; Van Wee, 2021). In rural areas, for example, the use of the private car may be associated with an autonomous lifestyle leaving other transport options burdened with negative social stigmas (Ahern and Hine, 2012). On the household level, parents may not allow their children to travel independently by certain modes, leading to lower evaluations of the feasibility to engage in activities at certain locations (Lopes et al., 2014).

The individual component also determines the environment with which an individual is confronted. It has been extensively documented that people may *self-select* into areas that correspond with their travel preferences (Cao et al., 2009; Van Wee, 2009). Consequently, when a region is characterized by low accessibility by public transport, this may not be perceived as a problem by people who like to travel by car and have self-selected themselves into such an area.

However, people may also experience residential dissonance in terms of accessibility (Fone et al., 2006; Lin et al., 2017). Not everyone is able to self-select themselves due to financial or other constraints that limit people's freedom to choose where to live (Lin et al., 2017; Schwanen and Mokhtarian, 2004). This also depends on an individual's position in the household, as where to live is often the result of a household decision-making process (Molin et al., 1999). Furthermore, characteristics of the transport system and accessibility may not be the dominant decision factors in choosing where to live, and people will not have perfect information on accessibility before choosing a new residential location, potentially leading to an unanticipated mismatch between preferences and the actual accessibility situation (Næss, 2014). Moreover, the physical environment as well as preferences regarding the environment may change over time (e.g. following a certain life course event) potentially leading to a mismatch between the preferred and actual environment (Gao et al., 2019; Janke and Handy, 2019).

Perceptions may also change over time through interactions with the environment (De Vos, 2019; De Vos et al., 2018; Van Wee et al., 2019a). This process is shown in the feedback loop running from behaviour towards perceptions of accessibility in Fig. 2. It has even been suggested that behaviour has a stronger influence on travel attitudes than vice versa (Kroesen et al., 2017). An obvious case is when a decision is made following perceptions of the environment, but the actual physical environment does not allow such behaviour. For example, an individual may decide to use the bus to get to some activity, while the service does not run anymore. In this sense, the actual environment directly influences behaviour and through experiences and learning, perceptions may be adjusted. This also means that perceptions and preferences could change to match the environment alleviating residential dissonance with respect to accessibility (De Vos and Singleton, 2020; Haartsen and Van Wissen, 2012).

Finally, the individual component also directly influences decisions regarding activity participation. Someone may perceive the accessibility of a certain location as very good: that the location is suitable for engaging in a certain activity and is perceived as easy to get to. However, there may be no need or desire to engage in that type of activity, resulting in no travelling to that location, despite its high perceived accessibility.

4. Mismatches between calculated accessibility measures and perceived accessibility

Following from the discussion above on how perceptions of accessibility are shaped, this section discusses how calculated accessibility measures can differ from perceived accessibility. A schematic framework is presented after which an illustrative example is given.

4.1. Schematic framework

Two broad strands of reasoning (see Fig. 3) can be identified as to why accessibility may be experienced very differently than calculated indicators using 'real world' land-use and transport data would suggest (see, for example, Comber et al., 2011; Curl et al., 2015; Curl, 2018; Gebel et al., 2011; Lättman et al., 2018; Lotfi and Koohsari, 2009; Van der Vlugt et al., 2019). First, people may have *inaccuracies in awareness* regarding the outside world's realities that calculated accessibility indicators aim to represent. *Spatial knowledge* can cover all spatial components of accessibility including the spatial distribution of opportunities, the functioning of the transport system, and how temporally feasible these opportunities are given certain ways of travel.

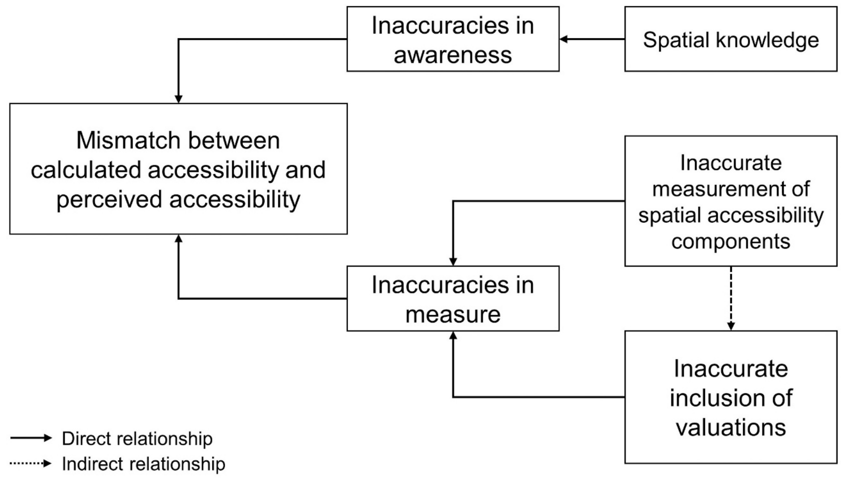

Fig. 3. Schematic framework on how mismatches can occur between accessibility measures using land-use and transport data and self-reported perceptions of accessibility.

When individuals do not have complete knowledge of this potential, measures using spatial data that incorporate the full accessibility potential may easily differ significantly from perceived accessibility.

Adopting the mechanisms described in Section 3.1, information on components of accessibility will be sought for and handled in heterogeneous ways. Different searching strategies to gather information (such as those matching ‘satisficers’ vs. ‘maximizers’) and their related searching costs will lead to different levels of spatial knowledge. For example, people generally overestimate travel times by modes they are less familiar with (Van Exel and Rietveld, 2009; Vreeswijk et al., 2014). Given the habitual character of spatial behaviour, learning about new alternatives may be a rather slow process (Chorus and Timmermans, 2009; Verplanken et al., 1997). The willingness to look for new alternatives may also be subject to attitudes. A person who likes to travel by car may simply not search for public transport alternatives to certain destinations. Clearly, searching outcomes also relates to capabilities, including spatial abilities. For example, someone who does not have access to the internet may not be able to acquire the same amount of information (such as public transport timetables) as someone who does. As such, an individual's spatial knowledge with respect to accessibility will to a greater or lesser extent be incomplete. People may not know of activity locations and ways of getting there, or incorrectly assess characteristics (such as GTC components) of these options.

The second way in which mismatches can arise is that calculated measures may contain *measurement inaccuracies*. These errors can be split into two categories. First, measures may, possibly intentionally in the interest of ease of operationalization, *inaccurately cover components of accessibility*. This is clearly the case when components are omitted from the measure altogether. For example, a measure may not account for temporal constraints such as time of day variations in travel times or the temporal feasibility of an individual to conduct activities. Additionally, components can be reflected incorrectly due to flaws in the data used. For example, transport modes and activity locations may be mistakenly omitted or included, or GTC may not be measured accurately with respect to travel times (e.g. some people may cycle faster than others). This is especially likely when spatial data are outdated and not frequently updated.

Measurement inaccuracies can also be the result of *imprecisely reflecting evaluations of accessibility components* following individual preferences and capabilities. Once information on the environment has been filtered, it is interpreted and valued on the individual level (see Section 3.1). These individual interpretations may involve all aspects of accessibility. They may relate to whether known opportunities are perceived to be suitable, and whether the GTC to these opportunities are perceived as acceptable. A specific issue in this respect is the relevance of having multiple options available. For example, measures of cumulative opportunities often assign a similar value to each additional alternative. However, it seems highly possible that an additional sixth alternative is perceived to add less to accessibility than the addition of a second alternative to a single alternative. The law of diminishing returns probably applies.

Connected to the issue of how to handle multiple options, the way activity locations are categorized and aggregated may also matter. Some destinations can be substituted by other destinations offering, to some extent, comparable opportunities (Van Wee et al., 2019b). For example, when analysing accessibility to doctors, large distances to general practitioners (GPs) may be perceived as less problematic if a large hospital is nearby. An aggregated indicator which includes all health facilities and, therefore, accounts for interactions between destinations (general practitioners and hospitals) may better reflect how doctor accessibility is perceived than a disaggregated measure that only includes GPs. However, going to see a doctor in a hospital may be less favoured than going to a GP (i.e. it is not perceived as a good substitute). In this case aggregation would lead to additional measurement inaccuracies.

Further complicating things is that these perceptions will be different for each individual. This means that the level of aggregation with respect to different categories of individuals will influence how well perceptions may be covered. At one extreme there are indicators expressed for the whole population, while on the other hand there are person-based measures. Later, in Section 5.3, we return to the issue of how disaggregated accessibility indicators should be constructed in order to serve as valid proxies for perceived accessibility. Note that if the measures employed exclude some components of accessibility altogether then any cognitive evaluations of these components will be inaccurately captured by the indicator (as reflected in the indirect relationship in the scheme shown in Fig. 2).

Using the building blocks of this schematic framework, Table 1 summarizes the possible reasons for mismatches between calculated and perceived accessibility. There will only be no mismatch between perceived accessibility and a calculated indicator if accessibility is measured perfectly (including abilities and preferences of individuals) and spatial knowledge is complete. The extent of the mismatch will be positively related to the number of activity locations under consideration, as well as ways of getting to them; the heterogeneity in characteristics of these options; and the heterogeneity in characteristics and preferences of individuals. For example, calculating a single individual's accessibility to a local bakery is less prone to a mismatch with individual

Table 1
Overview of reasons for mismatches between calculated accessibility measures and perceived accessibility.

Inaccuracies in awareness	Inaccuracies in measures
Spatial knowledge	*Inaccurate inclusion of components*
• Unawareness of activity locations and/or ways of getting there	• Components are omitted
	• Components are represented incorrectly
• Unawareness of characteristics of options	Subject to:
Subject to:	o Difficulty of operationalization
o Searching strategies	
	o Flaws in data
o Search costs	*Inaccurate inclusion of valuations*
	• Inaccurate inclusion of individual valuations of GTC
o Habitual behaviour	
o Attitudes	• Inaccurate inclusion of the relevance of opportunities
o Capabilities	Subject to:
	o Individual cognitive evaluations on the environment
	o Level of aggregation

perceptions of accessibility than calculating an entire city's accessibility to food.

4.2. An illustrative example

It may be helpful to illustrate the framework outlined in the previous section with an example. Consider the scenario of accessibility on foot to postal services. Using data on the location of post offices, including other stores that include a post counter, and the street network, a contour measure could indicate that from a certain location, one post office as well as another store where letters and packages can be sent and received are within a ten-minute walk. When using such a measure in an evaluation, this may be considered as good accessibility to postal services on foot (although such an evaluation will depend on the perceptions of the analyst, see Section 5.4). However, from an individual perspective, such accessibility may be perceived very differently. With a lack of spatial knowledge, one may not be familiar with both of these opportunities, and perhaps be only aware of the dedicated post office. Further, one may not be aware of certain footpaths resulting in inaccurate distance and travel time estimates.

The measure itself is also prone to measurement flaws. By using the street network as input data, the measure may overlook footpaths leading to inaccurate travel time calculations. Also, the measure does not account for individual preferences and capabilities. Some might favour the services offered by a dedicated post office, making other options less or not suitable to their needs. Also, there may be individuals who due to personal preferences and/or physical capabilities do not want to walk for more than five minutes, making the ten-minute threshold set by the evaluator inaccurate. It could also be that walking is perceived as more dangerous and/or unpleasant during certain times of the day. As there is no temporal component in the measure, this is automatically overlooked (the indirect link in Fig. 2). Consequently, the accessibility of postal services on foot may not be perceived to be as good as the measure suggests.

5. Implications for evaluating accessibility

As argued in the previous theoretical sections, perceptions of accessibility can be very different from what measures suggest. This section provides an attempt to translate the theoretical discussion to implications for accessibility evaluations. Section 5.1 starts by arguing that there is no such thing as 'objective' accessibility in contrast to 'subjective' accessibility. In addition to the general sources of mismatches between accessibility indicators and perceived accessibility highlighted in the previous sections, Section 5.2 section highlights some specific strengths and limitations of conventionally used measures when it comes to representing how accessibility is perceived. Further, some examples are provided showing how these measures could be modified to better match perceptions. Based on the limitations of accessibility indicators in terms of reflecting perceived accessibility, Section 5.3 presents implications for policy practice. Finally, some avenues for future research to advance the evaluation of accessibility with regard to perceptions are presented in Section 5.4.

5.1. Terminology: 'objective' accessibility does not exist

Resulting from the theoretical argument in Sections 3 and 4, accessibility to opportunities is not solely a function of land-use and transport system configurations. The actual potential for spatial interaction is conditioned by how the environment is perceived. Therefore, accessibility is an individual trait which is actively fostered by cognitive processes related to how the built environment and travel behaviour are experienced and made sense of. Consequently, there is no such thing as 'objective' accessibility, which could then be implicitly assumed to be the 'real' accessibility, in contrast to 'subjective' accessibility. Instead, 'objective' accessibility, which relates to measures using transport and land-use data should be seen as no more than attempts to create a proxy for the actual experienced potential to interact with spatially dispersed activities. It is therefore suggested that terms like 'objective' accessibility should be avoided and more honest terminology such as 'accessibility based on land-use and transport data' should be employed.

5.2. Perceptions and conventional accessibility measures

It is impossible to evaluate how every accessibility measure ever constructed relates to perceived accessibility, and so the discussion here is limited to some broad implications for the categories of measures based on the widely cited conceptualization by Geurs and Van Wee (2004). Table 2 summarizes some main challenges facing these categories of measures. These challenges are discussed in greater depth in the subsequent subsections.

5.2.1. Infrastructure-based

Infrastructure-based measures aim to represent the performance or service level of transport infrastructure (e.g. congestion, speed, reliability). Here it can be problematic to identify at which performance level it is perceived as good or bad. People will have different perceptions of what travel times and/or levels of congestion are acceptable. Travel time in itself may not always be experienced as a disutility, as it is suggested that activities inhabit an optimal non-zero travel time (Milakis et al., 2015; Redmond and Mokhtarian, 2001). This relationship will likely differ among geographical contexts and types of activities (Milakis and Van Wee, 2018). This can lead to misleading conclusions with respect to how accessibility is perceived. A remedial action could be to

Table 2
Major potential challenges related to perceptions for categories of accessibility indicators.

Category	Potential challenges
Infrastructure	Choice of relevant performance measure; relationship between level of service and perceptions
Location	Inclusion of perceived quality and/or relevance of opportunities; establishing distance thresholds and/or decay parameters that correspond with perceptions
Person	Variability of travel times and how this is perceived; incorporating flexibility to adapt activity patterns to space-time constraints
Utility	Correlated error terms across alternatives; perceived option values; expected rather than experienced utility is measured; evaluated choice set may not match perceived choice set

incorporate some information on satisfaction with the performance of the network (e.g. Chaloux et al., 2019). This may, in some way, correct the indicator for perceptions.

5.2.2. Location-based

By including a land-use component, location-based measures are theoretically more robust than purely infrastructure-based measures. Such measures take the form of a quantity of opportunities that can be reached from a given location. However, it is hard to determine the perceived relevance of activity locations, and thus to determine how to include these opportunities. One way to capture the relevance of opportunities would be to use weights based on some measurable characteristic (e.g. size, number of jobs, floorspace) and possibly to correct for competition effects on the demand side for these opportunities (e.g. population within a catchment area) (Van Wee et al., 2001). However, relating such proxies to the perceived attractiveness of activity locations would involve assumptions by the analyst.

Another way to add weighting to the various opportunities is to assume that the relevance of activities decreases with travel resistance. However, the analyst would then need to determine the shape of this travel resistance function. Further, it is likely that there is high variability in this function linked to preferences and capabilities. These preferences will also be linked to the type of activity and local context. Consequently, it would be difficult to set distance or travel-time thresholds for contour measures as well as to specify distance-decay functions to match the perceptions of the people these measures aim to represent. Making a priori assumptions may be problematic as these are often normative without it being clear whether these thresholds or decay parameters match perceptions. Positivist measures try to overcome this by setting thresholds based on actual travel behaviour data. However, such a procedure can also be problematic as it is not always clear whether behaviour results from choice or from constraints (Páez et al., 2012).

Some remedial measures have been proposed for location-based indicators to better incorporate perceptions. Chaloux et al. (2019) estimate impedance functions only using journeys where the traveller was satisfied with the travel time. In this way, long travel times as a result of constraint rather than choice, and hence dissatisfying, are filtered out. Also, in an attempt to incorporate perceptions in impedance functions, Martínez and Viegas (2013) approximate distance decay curves based on what distances are coded as 'near' and as 'far' in a survey of a wide range of destinations. Focussing on slow travel modes, Guimpert and Hurtubia (2018) estimate boundaries for the area perceived as suitable for walking based on the built environment and sociodemographic characteristics. Sundling et al. (2015) also try to account for perceptions regarding travel. In measuring accessibility to railway stations, they include the joint probability of encountering and overcoming travel barriers, which are weighted for importance, on the way to the station.

5.2.3. Person-based

With person-based measures, accessibility is analysed at the individual level based on a 'space-time prism' that determines the locations that can be accessed within fixed space–time constraints (Hägerstrand, 1970; Neutens et al., 2007). As these measures are calculated on the individual level, at least part of the individual heterogeneity in potential accessibility should be captured and, as such, the gap with perceived accessibility should be narrowed.

However, the disaggregation efforts required mean that these very precise measures are very data-demanding and, as a consequence, are particularly sensitive to measurement errors. The classical space–time prism allows only deterministic travel speeds, ignoring the stochastic nature of travel environments. In reality, travel times are subject to uncertainty as a consequence of variability in the reliability of the transport system. Travelers will anticipate this uncertainty in coming to possibly inaccurate perceptions of the travel-time distribution (Ettema and Timmermans, 2007). Furthermore, the possibility of rescheduling activities to cope with time-constraints is not captured by these measures. For example, one might decide to leave work early to be able to participate in a leisure activity outside one's space-time prism. Such limitations can easily lead to mismatches between calculated space-time prisms and how they are perceived.

In this regard, less rigid space-time prisms that allow for flexibility in travel times and activity durations may be less sensitive to mismatches with perceptions (Chen et al., 2013; Ettema and Timmermans, 2007; Kuijpers et al., 2010). Also, within the class of person-based indicators, Cascetta et al. (2016) propose a set of measures that define accessibility as the joint probability that an opportunity location is known and fits within one's space-time constraints.

5.2.4. Utility-based

Utility-based measures capture the benefits that are derived from the opportunities that the environment provides using discrete choice modelling. The *expected* maximum utility is calculated as the summed utility derived from each option weighted by their estimated choice probabilities, also known as the Logsum (Ben-Akiva and Lerman, 1985).

When using a choice model, the coefficients estimated for the attributes of an alternative represent the values attached to those attributes in the utility derived from that option. From this, one can derive how important certain attributes are perceived when choosing an alternative. Hence, there is no need to make a priori assumptions on how important certain attributes are perceived when evaluating accessibility. All other weights regarding unobserved attributes and the heterogeneity in preferences, which is assumed to be random, are captured in an error term. Provided this error term has a mean of zero and is symmetrically distributed, Logsum values can be expected to be close to how accessibility is actually perceived.

However, there are also challenges attached to utility-based measures with respect to perceived accessibility. First, all the unobserved attributes and their associated weights are assumed to be independent of all the other alternatives. However, there is a possibility that the unobserved components of utility are correlated across some alternatives (e.g. perceptions related to comfort between bus and train alternatives). If this is the case, error terms of a choice model are correlated across alternatives resulting in a flawed Logsum indicator.

Second, it is debatable whether the so-called 'option value' of having multiple options is adequately captured by the Logsum (Geurs et al., 2006). One could argue that the valuation of non-chosen alternatives, and their associated choice probabilities, can be interpreted as the value of having these alternatives. For example, when considering residential choice, one may value having multiple activity locations or transport options to one's display for future use. However, such reasoning seems less applicable when considering travel mode choices. Intuitively, there is no option value of having another mode available when choosing a certain travel mode in a given situation.

Third, when using choice data based on stated preferences, it is *expected* (or *decision*) utility rather than *experienced* utility that is captured. Perspectives found in behavioural economics postulate that the weights placed on various attributes when making a choice leading to an anticipated level of utility may be very different to how the execution and outcome of the choice is eventually experienced and remembered (Ettema et al., 2010; Kahneman et al., 1997; Lichtenstein and Slovic, 2006). This may result in rather weak correlations between Logsums and how accessibility is perceived in stated-choice settings (Chorus, 2012).

Finally, when using revealed-choice data, it is not clear to what extent subjects had a complete knowledge of the choice set. The generation of choice sets is influenced by cognitive processes related to learning from the environment. Accordingly, when evaluating the benefits of changes in accessibility based on the difference between the Logsums before and after a certain intervention, the benefits can, especially in the short-term, be overestimated since initial awareness of the change in accessibility may be limited (Chorus and Timmermans, 2009).

Some attempts have been made to deal with these problems of utility-based measures with respect to perceived accessibility. Addressing the limited awareness of decision-makers, Chorus and Timmermans (2009) propose a model where user benefits of an improvement in accessibility are a function of time by incorporating the probability that an individual experiences a new alternative, or a change in attributes, at a given moment. Nevertheless, an empirical underpinning of how to set the model's parameters is still lacking. In an attempt to bridge the gap between decision and experienced utility, Chorus and de Jong (2011) extended the Logsum measure to allow for volatility in preferences between moments of choice and of experience by adding an additional random error term reflecting unobserved preferences during the evaluation of a choice. However, it is unclear how this specification relates to self-reported utility measures as advocated by, for example, Ettema et al. (2010).

5.3. Policy implications

When attempting to understand people's potential spatial behaviour, predict actual behaviour and/or assess the potential utility derived from accessibility based on calculated accessibility indicators, one should acknowledge the potential mismatch with perceived accessibility and the mechanisms that may contribute to this mismatch. Integrating perceptions in conventional accessibility indicators as described in Section 5.2 fits the trend towards developing complex and disaggregated measures that include a combination of the theoretical components of accessibility outlined above (Silva et al., 2017). While such efforts are conceptually and empirically insightful for understanding the relationship between the environment and behaviour, more complex measures usually place heavier demands on data, modelling techniques, time and budget and are more difficult to interpret by practitioners (Geurs and Van Wee, 2004; Silva et al., 2017). Therefore, accessibility-based planning may benefit more from indicators that are easy to construct and understand, especially considering that the dominance of the mobility-based paradigm is in part fuelled by the fact that it allows for easy evaluations based on standardized 'level of service' indicators (Handy, 2020). Consequently, results from academic efforts of constructing complex measures that better account for perceptions are regarding policy practice likely to be most valuable for enriching the interpretation of simpler indicators. It is beyond the scope of this paper to provide detailed methodological and prescriptive steps on how perceived accessibility can be integrated in policymaking and it is suggested that further research is needed to advance this issue (see Section 5.4). In what follows, some general considerations for practice are presented with respect to accounting for perceived accessibility when using conventional indicators. Also, to complement the use of traditional indicators, methods to directly incorporate perceived accessibility in evaluations are explored.

The scheme in Fig. 3 accompanied by Table 1 may provide guidance on where to look for mismatches between calculated indicators and perceptions. First, it can be assessed to what extent spatial knowledge of the opportunities the accessibility measure describes can be assumed to be complete. This may involve assessing levels of spatial knowledge as well as evaluating ways in which information is gathered. This may be especially important when evaluating the impacts of future policies as people may, in the short-term, not be aware of changes in accessibility (Chorus and Timmermans, 2009). If a lack of spatial knowledge is identified as a source of a mismatch between a calculated accessibility indicator and perceptions, efforts to increase awareness can be very important to close this gap.

The second source of mismatches relates to measurement inaccuracies. Issues related to specific measures that may be valuable with regard to evaluating perceived accessibility are summarized in Section 5.2. From the scheme in Fig. 3, it can be expected that using theoretically more sound indicators including more components at a disaggregated level may narrow the gap with perceived accessibility. For example, while perceptions are by definition individual, stratifying calculated indicators by population groups based on sociodemographic characteristics may already lead to more realistic representations of perceived accessibility when perceptions can expected to be comparable within these groups.

The extent to which accessibility evaluations may be sensitive to differences between perceptions and calculated indicators, and, therefore, the extent to which perceptions actually need to be taken into account, will depend on the level of aggregation required for the task at hand. If accessibility is to be evaluated for a large group of people, results may be less sensitive to very specific individual perceptions, because as long as the distribution of the differences between perceived and calculated accessibility is random, these differences cancel out at the aggregate level. For example, if one was considering a national plan to increase accessibility by public transport, it is more efficient to take account of general perceptions related to the use of public transport rather than individual-level perceptions for specific train routes to specific destinations at specific times. Similarly, when considering an intervention on a specific train route to make it more feasible for a specific group of users in a specific region, perceptions on a more disaggregated level will become more relevant.

In addition to the evaluation of calculated accessibility indicators in terms of potential mismatches with perceived accessibility along the lines of the theoretical discussion presented in this paper, perceived accessibility could also explicitly be evaluated. This can be done as a standalone exercise or as a means to support the construction and/or interpretation of calculated measures. Perceived accessibility can be assessed quantitatively as well as qualitatively. Quantitative approaches such as self-reported measures of accessibility may especially be helpful in providing an alternative evaluation tool to conventional indicators (e.g. Curl et al., 2015; Lättman et al., 2016; Van der Vlugt et al., 2019). This approach may also allow for an explicit comparison between a given calculated indicator and self-reported accessibility, which should add to the interpretation of such an indicator and/or assist in setting parameters of an indicator to better match perceptions. Additionally, the nuanced mechanisms shaping perceived accessibility, which may not be captured by quantitative assessments, may be uncovered by qualitative approaches, such as focus group meetings, interviews with target groups, mental map sketching exercises in the spirit of Lynch (1960) or ethnographic methods (e.g. Porter et al., 2010; Pot et al., 2020; Tiznado-Aitken et al., 2020).

5.4. Future research directions

Considering the current lack of consensus on the use of accessibility measures (Handy, 2020), explicitly interpreting these measures in terms of how these measures represent perceived accessibility may clear out some of the ambiguity associated with using these measures. While Section 5.3 presents some high level implications by opting for a more holistic way of understanding accessibility beyond crude spatial indicators, further research is needed to look into providing specific procedural proposals on how to efficiently include percieved accessibility in designing responsive spatial policies.

Specifically, research on perceived accessibility can assist in determining what levels of a certain indicator are likely to constitute 'sufficient' accessibility as perceived by the people the measure aims to represent. This may especially be relevant for efforts regarding designing inclusive transport systems (Lucas, 2012; Martens, 2017), which currently rely on a normative practice of setting minimum thresholds for accessibility without an explicit link to individual perceptions.

Empirical research on the factors shaping perceived accessibility may inform the interpretation and use of accessibility measures, for example to validate minimum thresholds. The discussion in Section 3.2 proposes possible mechanisms, although the associated framework in Fig. 2 is yet to be empirically validated. Also, research could focus on to the ways in which information on environment regarding accessibility is presented, gathered and eventually cognitively understood (Mondschein et al., 2010). The growing presence of ICTs in many aspects of everyday life arguably influences the way information on accessibility is gathered and activities are chosen and planned. Therefore, special attention should be given to the impact of digital representations on the provision and interpretation of accessibility information. Research could also focus on assessing mismatches between calculated and perceived accessibility. Following the scheme in Fig. 3 and the accompanying Table 1, analyses can be conducted to find patterns regarding how spatial configurations as described by traditional calculated indicators relate to perceived accessibility in different situations (e.g. Lättman et al., 2018; Ryan et al., 2016; Van der Vlugt et al., 2019).

Connected to this, research should also be devoted to how perceived accessibility could be measured. Analogous to traditional calculated indicators, a multitude of measures could be appropriate depending on the goal of the analysis (Geurs and Van Wee, 2004), including opportunity-based measures relating to the perceived interaction potential (e.g. Curl et al., 2015; Ma and Cao, 2019) as well as outcome-based self-reported measures referring to the benefits that individuals derive from accessibility (e.g. Lättman et al., 2016; Van der Vlugt et al., 2019).

Policymakers are in the end the ones who implement and interpret accessibility measures in planning. Therefore, it is needed to understand policymakers' views of such indicators in terms of the ability of these measures to reflect perceived accessibility. In setting accessibility goals and evaluating outcomes of accessibility-based planning, policymakers will likely do so based on their own perceptions of accessibility. These may be different from the perceptions of the people they design plans for, since the role of being a policymaker may inherit specific understandings of the functioning of the land-use and transport system that differ from target groups. In this regard, it may also be valuable to study differences between perceptions of accessibility of policymakers and the people they design plans for.

6. Conclusion

The correct use and interpretation of accessibility indicators serves as a barrier to the adoption of accessibility goals in transport planning (Handy, 2020; Silva et al., 2017). As Gould (1969, p. 64) points out, "*accessibility is a slippery notion* [...] *one of those common terms that everyone uses until faced with the problem of defining and measuring it.*" This paper has demonstrated that the accessibility to opportunities that the environment provides is conditioned by individual perceptions. As such, there is no such thing as 'objective accessibility', that can be perfectly captured by calculated accessibility measures using spatial data, as an alternative to 'subjective accessibility'. Rather, one should speak of calculated measures, that aim to serve as a proxy for how accessibility is actually perceived and eventually utilized by individuals. It is, after all, the cognitive environment that is the real basis for spatial decision-making (Kirk, 1963; Gold, 1980; Morris et al., 1979).

The main takeaway here is that regardless of the indicator used, it should not be taken at face value without any nuance in terms of its limitations with respect to how accessibility is perceived by the individuals it aims to represent. The observation that accessibility measures are prone to mismatches with perceptions may suggest that the concept of accessibility becomes even more 'slippery'. However, bringing perceived accessibility to the fore of accessibility-based planning by acknowledging and evaluating potential mismatches with accessibility indicators should take away some of this 'slipperiness' associated with measuring and interpreting accessibility. Therefore, thinking about accessibility in terms of how it is perceived rather than how it can best be measured will advance the evolution from mobility-based to accessibility-based planning.

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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