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A perception-based cognitive map of the pedestrian perceived quality of service on urban sidewalks

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ABSTRACT

A better understanding of what walking entails is important in sustainable transportation planning. Recent research has shown that perceptions have a higher power to explain the quality of service (QoS) than objective measures have; the latter being typically used in the pedestrian level of service methodologies. Despite the existing research on perceptions and QoS in other transportation fields, very little information has been found in the literature that can explain a clear cognitive structure that defines the pedestrian QoS. In this research, we propose a cognitive map to make it possible to understand and explain pedestrian sidewalk QoS of a given infrastructure when walking, based on perceptions. We gathered the perceptions of 1056 pedestrians on-site, regarding the attributes (indicators) identified in the literature review in 30 locations in Bogotá, Colombia. Based on an Exploratory Factor Analysis, we developed a conceptual model through Structural Equation Modeling. We found that seven latent variables (LVs) (i.e., *Sidewalk characteristics, Externalities, Surrounding, Discomfort, Bike hassles, Protection,* and *Amenities*) interrelate to each other, forming a pedestrian cognitive map. QoS is directly explained by how pedestrians perceive the LVs *sidewalk characteristics* and *surrounding* and indirectly by the rest of LVs. The cognitive map shows three LVs related to the interaction between pedestrians and other transportation modes (i.e., *externalities, discomfort,* and *bike hassles*) that impact the perceived QoS negatively, and four LVs related to the interaction between pedestrians and different elements of the sidewalk (i.e., *sidewalk characteristics, surrounding, amenities,* and *protection*) that impact the perceived QoS positively. To understand pedestrian perceptions when walking and the path that these perceptions follow to develop a QoS perception provides an accurate tool by which to improve the QoS from the useŕs perspective, generating a new opportunity to provide better pedestrian facilities.

1. Introduction

A better understating of what walking entails is critical in sustainable transportation planning. Walking implies a sensorial experience given by pedestrian interaction with infrastructure, other individuals, and the surroundings; thus, perceived

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QoS is affected by more than just traffic flow or on-site measurable attributes. Indeed, recent studies have shown that perceptions have a higher power to explain the quality of service (QoS) than objective measures (Rodriguez-Valencia, Barrero, Ortiz-Ramirez, & Vallejo-Borda, 2020). For this reason, pedestrians' feedback about their walking activity is a valuable input that can help us understand the real meaning of QoS from the user's point of view.

Inquiring about the Quality of Service (QoS) in transportation is frequent, especially on service-oriented industries such as carriers and public transport. QoS serves to measure the performance of a service or infrastructure. QoS is a transportation concern that is continually being improved to persuade or attract users to any service (Jahan, Al, Hadiuzzaman, Mashrur, & Neaz, 2020). Drucker (2006) points out that the service is not what is offered, but what the users receive. Thus, understanding QoS requires users to be asked about their perception of what is relevant to them.

Designing appropriate policies aimed at improving pedestrian activity requires a previous understanding of pedestrian perceptions considering subjective attributes to explain the perceived QoS (Jahan et al., 2020). Besides this, there is a consensus on the use of latent variable (LV) models when considering subjective attributes, related to the interaction between pedestrians and the different elements around them (Ashok, Dillon, & Yuan, 2002; Cantillo, Arellana, & Rolong, 2015; Márquez, Cantillo, & Arellana, 2014; Yáñez, Raveau, & Ortúzar, 2010). For the case of pedestrian modeling, the use of LVs to consider subjective attributes to evaluate sidewalks is a nascent approach that has only recently been addressed (Geetha Rajendran Bivina & Parida, 2019; Jahan et al., 2020; Vallejo-Borda, Ortiz-Ramirez, Rodriguez-Valencia, Hurtubia, & Ortúzar, 2020).

Structural Equation Modeling (SEM) approaches have been used to study perceptions of modes of transport in studies that were mostly based on understanding and quantifying user satisfaction at airports (Bezerra & Gomes, 2016) and on public transport (Eboli & Mazzulla, 2015). However, for pedestrians, it is not common to use SEM models to understand their perception of QoS in relation to the attributes they interact with when walking on urban sidewalks. Given the above, in this paper, we use a continuous SEM, which includes the use of LVs to explain how the pedestrian perception of the attributes affects their perception of the QoS when walking on urban sidewalks. SEM models let us identify the direct and indirect effects that LVs can have on the QoS perceived by pedestrians (Vallejo-Borda et al., 2020). Considering that LVs are identified based on pedestrian perceptions (Ortúzar & Willumsen, 2011; Vallejo-Borda et al., 2020), the above-mentioned effects can be understood as a representation of more complex cognitive pedestrian processes defining a cognitive map (Behrens et al., 2018; Eichenbaum, 2015).

Thus, this study proposes a cognitive map based on which to understand and explain, using perceptions, pedestrians' sidewalk QoS of a given infrastructure when walking. We developed an SEM model from 1056 pedestrian perception surveys applied in 30 locations in Bogotá, Colombia. Using the SEM approach, we will develop a pedestrian cognitive map that explains the perceived QoS and the effects on the QoS perception considering only the pedestrian perceptions represented on different LVs. On-site objective attributes are not considered in this study, given our interest in understanding the phenomenon behind the pedestrian perceived QoS only from pedestrian perceptions in different real walking scenarios.

This rest of the paper contains, first, a literature review that presents the most relevant studies related to pedestrian QoS. Second, a methodology section that explains the data collection techniques and the modeling framework. Then, a section which presents the results showing LV identification and model estimation. This is followed by a discussion and analysis section, where the LVs and their interactions are explained in terms of their relationship with the QoS. Finally, the last section presents the study's conclusions.

2. Review of factors influencing the urban sidewalk service being provided for users

For more than 50 years, researchers on transportation engineering and urban planning have inquired about the variables that positively or negatively influence QoS or satisfaction rendered by pedestrian infrastructure. In the early 1970 s, the level of service (LOS) was defined as the service that transport infrastructure was rendering to its users (Roess & Prassas, 2014). Specifically for pedestrians, initial pedestrian LOS (PLOS), introduced by Fruin (1971), considered only flow and geometry attributes, considered as the only ones to evaluate pedestrian infrastructure (e.g., urban sidewalks) until the end of the 1980 s (Mōri & Tsukaguchi, 1987; Polus, Schofer, & Ushpiz, 1983; Tanaboriboon & Guyano, 1989; Transportation Research Board, 1985). In the 1990s, the evolution of methodologies to evaluate urban sidewalks began with a consideration of new attributes recognizing pedestrian interactions when walking. Initially, surrounding attributes were added to support the urban sidewalks evaluation, along with flow and geometry attributes (Jaskiewicz, 1999; Mozer, 1994). This evolution continued at the beginning of the new century by adding attributes present in the environment (Pikora, Giles-Corti, Bull, Jamrozik, & Donovan, 2003; Sarkar, 2003) and experts' perceptions of sidewalk attributes (Gallin, 2001; Pikora et al., 2003; Sarkar, 2003) to assess the urban sidewalk service being provided for users.

Many methodologies have been proposed to assess urban sidewalks where the pedestrian level of service (PLOS) is the first proposed. PLOS can be understood as a qualitative stratification of performance measures that represent the service that pedestrian infrastructure is rendering at a particular time in a six-point ordinal scale (Roess & Prassas, 2014; Transportation Research Board, 1985, 2000, 2010, 2016). This approach considered density attributes (i.e., pedestrian flow, sidewalk width, and sidewalk length) to evaluate sidewalks and was used for many years without modifying any of the attributes (Fruin, 1971; Mōri & Tsukaguchi, 1987; Polus et al., 1983; Tanaboriboon & Guyano, 1989; Transportation Research Board, 1985). In the new century, studies on PLOS found that other attributes beyond operational performance (e.g., built environment) also explain the pedestrian-perceived quality of service (QoS) when walking. Most of these attributes are objectively measured on-site (e.g., buffer width, bus stops).

After the year 2000, the importance of land use and population structure made it essential to evaluate urban sidewalks. From 2005 to 2009, only land use was added to the attributes mentioned above to improve the evaluation of urban sidewalks (Jensen, 2007); then, from 2010 to 2014, population structure was considered, but land use was omitted (Kang, Xiong, & Mannering, 2013). However, in the literature written from 2015 until today, all the attributes mentioned above have been considered in the evaluation of urban sidewalks. Some methodologies consider both expert judgment and on-site measurable attributes (G. R. Bivina, Parida, Advani, & Parida, 2018), land use (Choi, Kim, Min, Lee, & Kim, 2016), population structure (Kang & Fricker, 2016), physical attributes (Macdonald, Szibbo, Eisenstein, & Mozingo, 2018; Marisamynathan & Lakshmi, 2016; Sahani, Ojha, & Bhuyan, 2017; Talavera-Garcia & Soria-Lara, 2015; Transportation Research Board, 2016), and environmental attributes (Motamed & Bitaraf, 2016) to assess urban sidewalk service being provided for pedestrians.

When the users' perspective is considered, there is not much information in the literature to identify a clear cognitive structure that explains the pedestrian perception of the sidewalk service when walking. Geetha Rajendran Bivina & Parida (2019) proposed an SEM approach to explain the direct influences that the built environment has on the perceived PLOS in India. This approach was based on pedestrian perceptions and found four LVs (i.e., *safety*, *security*, *mobility and infrastructure*, and *comfort and convenience*) that had a direct positive impact on the perceived PLOS (Geetha Rajendran Bivina & Parida, 2019). Similarly, Jahan et al. (2020) also proposed an SEM approach that, in this case, is used to explain the direct influences that three LVs (i.e., *physical aspects*, *security system*, and *side friction*) have on the overall sidewalk QoS. Recently, Vallejo-Borda et al. (2020) proposed a model to forecast the perceived QoS from the direct and indirect effects of four LVs (i.e., *sidewalk characteristics*, *surrounding*, *discomfort*, and *externalities*) on the pedestrian perception of the sidewalk QoS.

Previous studies identified different LVs from pedestrian perceptions that could impact the urban sidewalk service being provided for users. They suggested that an LV related to pedestrian perception of different sidewalk characteristics (e.g., width, surface) is the one with the highest impact on the sidewalk evaluation, without considering amenities (Geetha Rajendran Bivina & Parida, 2019; Jahan et al., 2020; Vallejo-Borda et al., 2020). Besides, Geetha Rajendran Bivina & Parida (2019) also proposed to consider pedestrian comfort through an LV identified from the pedestrian perceived accessibility to the sidewalk, which can also be seen as a part of the LV related to sidewalk elements (Jahan et al., 2020; Vallejo-Borda et al., 2020). Some studies have even suggested several LVs that consider the pedestrian interaction in general with other modes (Jahan et al., 2020) and, in particular, with motor vehicles (Geetha Rajendran Bivina & Parida, 2019; Vallejo-Borda et al., 2020), and with other pedestrians (Vallejo-Borda et al., 2020), leaving aside the sole interaction with bicyclists. Finally, LVs have been proposed that capture pedestrian perceptions of the surroundings (Vallejo-Borda et al., 2020) and the impact that perceived security has on urban sidewalk evaluation (Geetha Rajendran Bivina & Parida, 2019; Jahan et al., 2020).

When the satisfaction theories are considered, the literature has established that perceived QoS directly and positively affects user satisfaction. The literature also establishes that user perceptions of the different elements with which they interact can have positive or negative effects on their perception of QoS (Aliman, Hashim, Wahid, & Harudin, 2016; Badara et al., 2013; Nilplub, Khang, & Krairit, 2016; Subramanian, Gunasekaran, Yu, Cheng, & Ning, 2014) and satisfaction (Fig. 1).

The relationship proposed in Fig. 1 from satisfaction theories between on-site measurable attributes and the QoS is the most frequently referred to in the literature (Asadi-Shekari, Moeinaddini, & Zaly Shah, 2013; Banerjee, Maurya, & Lämmel, 2018; Raad & Burke, 2018). For example, there is sufficient evidence supporting the fact that sidewalk elements have a positive effect on pedestrian QoS (e.g., sidewalk width, sidewalk condition, furniture, trees, public transport access, and signage) (Asadi-Shekari et al., 2013; Banerjee et al., 2018; Raad & Burke, 2018). Meanwhile, the relationship between pedestrian perceptions and their QoS is still nascent (Geetha Rajendran Bivina & Parida, 2019; Jahan et al., 2020; Vallejo-Borda et al., 2020). In sum, the literature provides plenty of evidence of different attributes affecting the sidewalk service or performance being provided for pedestrians. Although physical attributes have frequently been used throughout history to explain pedestrian QoS (Asadi-Shekari et al., 2013; Banerjee et al., 2018; Raad & Burke, 2018), the use of pedestrian perceptions to explain the pedestrian perceptions of QoS has been less studied. For instance, there are no previous studies that consider the interactions between pedestrians and bicyclists in a specific LV from the pedestrian perspective or the effect that amenities on sidewalks have on the pedestrian perception about sidewalk QoS. Also, there is not much information considering the indirect and adverse effects of pedestrian perceived QoS by using LVs identified from pedestrian perceptions. To help close this gap, we present a more in-depth examination of urban sidewalk QoS using pedestrian perceptions on the development of a cognitive map to reveal direct and indirect effects, both positive and negative, on pedestrian perceived QoS when walking on urban sidewalks.

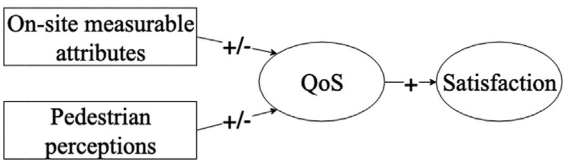

Fig. 1. General structure of pedestrian QoS and satisfaction.

3. Methodology

3.1. Data collection

A pedestrian intercept survey was applied in 30 different locations in Bogota, Colombia, covering different zones to attain a diverse population and a diversity of sidewalks in terms of QoS and characteristics (see examples in Fig. 2). The number of surveys at each point was equally distributed. Following depuration, we obtained 1056 valid surveys from a sample distributed by age, sex, and income level into groups that may be considered to reflect the population of Bogota. Surveys were conducted in 2018, between June 2 and June 19, during working days, from 08:00 to 18:00. Each survey lasted eight minutes approximately, and the overall response rate was 33.2%. Surveyors picked respondents on a one-out-of-three passing pedestrians basis to attain randomness.

The questionnaire was based on the work of Rodriguez-Valencia, Paris, & Vallejo-Borda (2017), which has been used to develop other pedestrian studies (Bellizzi, Eboli, & Forciniti, 2019; Rossetti & Hurtubia, 2020; Vallejo-Borda et al., 2020). The design process included consulting experts and focus groups to obtain information about the variables considered relevant by pedestrians. Before launching the definitive survey, a pilot was applied. The questionnaire inquired about the overall perceived sidewalk QoS, in a 0 to 10 Likert scale, rating from 0 (poor) to 10 (excellent). The questionnaire also included questions on the perceptions of the infrastructure, attributes, interaction with other modes, safety, and the emotions produced (see Table 1).

3.2. Modeling approach

We proposed a cognitive map using the SEM approach, where we identified and quantified pedestrian perceptions on interactions when walking and the effects on their QoS perception. The LVs approaches have been applied in the past in transport studies such as for airports (Bezerra & Gomes, 2016), pedestrian infrastructure (Geetha Rajendran Bivina &

Fig. 2. Audited sidewalk examples.

Table 1
On-site measured pedestrian perceptions (indicators).

Indicator	Question/Statement
Width	On a scale where 0 = poor and 10 = excellent, rate this point on the sidewalk for the following.
Condition	
Furniture	
Trees	
Public transit access	
Signage	
Road width	Where 0 = it does not bother me at all and 10 = it bothers me a lot, rate how much the following characteristics at this point on the sidewalk bother you.
Lanes	
HGV flow	
Vehicular speed	
Noise	
Weather	Where 0 = totally uncomfortable and 10 = totally comfortable, rate how comfortable you feel at the moment with the following aspects at this point on the sidewalk.
Lighting	
Odor	
Environment	
Cleanliness	
Landscape	
Bike flow	Where 0 = it does not bother me at all and 10 = it bothers me a lot, rate to what extent, the presence on the sidewalk of the following bothers you when walking.
Bike speed	
Opposite direction flow	
Same direction flow	
Security	Where 0 = totally unprotected and 10 = fully protected, rate how protected you feel at this time regarding the following aspects at this point on the sidewalk.
Sidewalk safety	
Road safety	
Restrooms	Where 0 = totally uncomfortable and 10 = totally comfortable, rate how comfortable you would feel with the general presence of the following would be when walking.
Shops	
Shade	
Where 0 = I totally disagree and 10 = I totally agree, rate the following statements	
Pedestrians far from me	When walking on this sidewalk, I prefer for there to be a distance between other pedestrians and myself.
Stress	Walking on this sidewalk is stressful.
Too many pedestrians	On this sidewalk, the number of pedestrians does not let me walk freely.
I prefer not to walk here	I would rather not walk on this sidewalk.

Parida, 2019; Cantillo et al., 2015), and public transport (Eboli & Mazzulla, 2015). SEM is a statistical modeling tool that can be used as an extension of linear models (Lei & Wu, 2007). Notation in SEM can be defined, as shown in Fig. 3 and equations (1) to (3).

$$Y = \alpha_Y + \lambda_{Y1}\eta_1 + \lambda_{Y2}\eta_2 + \varepsilon_Y \tag{1}$$

$$\begin{aligned} x_i &= \alpha_i + \lambda_i\eta_1 + \varepsilon_i \\ x_j &= \alpha_j + \lambda_j\eta_2 + \varepsilon_j \end{aligned} \tag{2}$$

$$\eta_1 = \beta\eta_2 + \zeta_1 \tag{3}$$

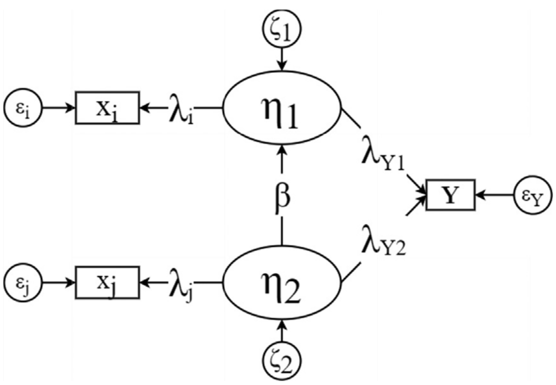

Fig. 3. SEM generic model structure.

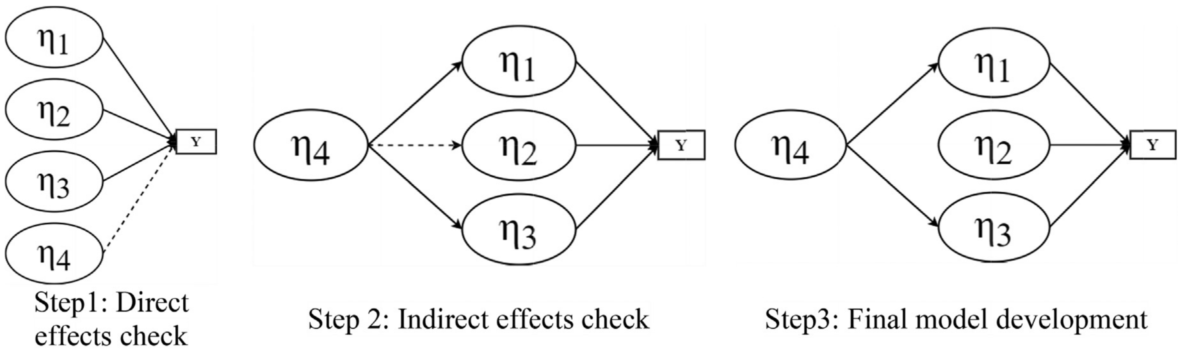

Fig. 4. Model development process.

In Eqs. (1) to (3), Y represents the dependent variable (i.e., perceived quality of service for this paper); α_Y is the intercept term (constant) associated with the dependent variable; λ_{Y1} and λ_{Y2} are the coefficients that indicate the change in the value of the dependent variable if there is a unit change in the respectively LV; η_1 and η_2 are the LVs; ε_Y is the error associated with the dependent variable presented in Eq. (1); x_i and x_j are the indicators (i.e., pedestrian perceptions presented in Table 1) that identify the LVs, where i and j discrete counters represent the number of indicators needed to identify such LVs, which have to be a minimum of three; α_i and α_j are the intercept terms (constant) associated with the indicators; λ_i and λ_j are the coefficients that indicate the change in the value of the indicators if there is a change of one unit in the respective LV; ε_i and ε_j are the errors associated to the indicators presented in Eq. (2); β is the structural parameter coefficient that indicates the marginal change in the value of η_1 regarding η_2; and ζ_1 and ζ_2 are the random error terms for the LVs presented in Eq. (3). For this study, all the errors were assumed to be normally distributed with an expected value of zero. To test the generic model, all the assumed relations are considered simultaneously, and the complete model is fit evaluated to ensure that the estimated covariance matrix is significant and similar to the observed covariance (Lei & Wu, 2007; McDonald & Bollen, 2006).

3.3. Model development

We initially developed an exploratory factor analysis (EFA) using the attributes identified in Table 1, which helped us to identify the LVs that explain the different indicators. For the EFA, a VARIMAX orthogonal rotation method was assumed, and the number of factors was determined using the scree test criterion (i.e., only the factors with eigenvalues greater than 1). Then, based on the EFA results and the SEM assumption of temporal precedence between the established relations (Hoyle, 2012), we specified an SEM model that represents the pedestrian cognitive map where the presumed causes occur before the presumed effects. The SEM analysis was carried out for thirty-two 0 to 10-scale questions considering a maximum likelihood estimation and was estimated using the R function "sem" of the "lavaan" package (R Core Team, 2019; Rosseel, 2012). For the SEM analysis, the measurement model (i.e., relations between LVs and their indicators) was initially verified, considering only the indicators with significant parameters (i.e., absolute t-statistic values higher than 1.64). We then established the direct effects of the LVs on the perceived QoS, keeping only the effects with significant parameters (i.e., absolute t-statistic values greater than 1.64). In the cases that direct effects were not statistically significant, we also tested the indirect effect that the LVs could have on perceived QoS through the LVs with statistically significant direct effects. This process was repeated until all LV relations were tested (see Fig. 4).

4. Results

Following the procedure described in the methodology section, from thirty-one attributes related to pedestrians' perceptions, we identified seven potential LVs: *sidewalk characteristics, externalities, surrounding, discomfort, bike hassles, protection,* and *amenities*. The most robust LVs, in terms of the number of indicators, are those related to the perception of *sidewalk characteristics* (explains user perceptions of sidewalk width, condition, furniture, trees, signage, and public transit access.) and *surrounding* (explains user perceptions of the weather, lighting, odor, environment, cleanliness, and landscape present on a sidewalk), with six indicators each. The LV *externalities* (explains user perceptions of the road width, the number of vehicular lanes, HGV flow, vehicular speed, and noise) is composed of five indicators, followed by the LVs related to perceptions of *discomfort* (explains user perceptions of the interaction with other pedestrians and the perceived stress on the infrastructure) and *bike hassles* (explains user perceptions of bike speed and flow in both directions), which comprises four indicators each. Finally, the LVs related to user perceptions of *protection* (explained based on user perceptions of safety and security on a sidewalk) and *amenities* (explains pedestrian perceptions of restrooms, shops, and shade on the sidewalk) are composed of three indicators each. LVs were tested using an SEM model by obtaining statistically significant results for the measurement model (see Table 2).

We also tested the structural model, and here too, obtained statistically significant results (see Table 3 and Fig. 5). From the cognitive map presented in Fig. 5, we inferred that QoS perception is directly explained by how pedestrians perceive the LVs *sidewalk characteristics* and *surrounding*. It also shows that how the LV *sidewalk characteristics* is perceived, is affected by the perception of the LVs *surrounding*, *externalities*, *discomfort*, and *protection*. Similarly, the perception of the LV *surrounding* is affected by how pedestrians perceive the LVs *externalities*, *discomfort*, and *protection*. The perception of the LV *externalities* affects how pedestrians perceive the LVs *discomfort* and *protection*. In the same way, the perception of the LV *discomfort* also affects the perception of the LV *protection*. Finally, the way that pedestrians perceive the LVs *bike hassles* and *amenities* also affects the perception of the LVs *externalities* and *protection*.

Perceived QoS is directly affected by two LVs: *sidewalk characteristics* and *surrounding* while it is indirectly affected by six LVs: *surrounding*, *externalities*, *discomfort*, *protection*, *bike hassles*, and *amenities*. In the case of direct effects, QoS perception is directly and positively affected by the perception of the *sidewalk characteristics* ($\lambda = 0.689$). Similarly, the perception of *surrounding* is directly and positively related to the perceived QoS ($\lambda = 0.149$). When considering indirect effects, QoS perception was also positively affected by the perception of the *surrounding* using *sidewalk characteristics* as a mediator ($w = 0.121$). Likewise, the perceived QoS is also affected positively and indirectly by how pedestrians perceive *protection* ($w = 0.222$) and *amenities* ($w = 0.145$) using the perceptions of *surrounding* and *sidewalk characteristics* as final mediators. On the other hand, the perception of *externalities* also indirectly but negatively affects the QoS perception with the final mediation by the perceptions of *surrounding* and *sidewalk characteristics* ($w = -0.412$). In the same way, the perceived QoS is also affected indirectly and negatively by how pedestrians perceive *discomfort* ($w = -0.128$) and *bike hassles* ($w = -0.091$) using the perceptions of *surrounding* and *sidewalk characteristics* as final mediators.

The resulting structural model presents a satisfactory adjustment, and no modifications were made after the evaluation of the resulting model given its good data fit (see Table 4). The response rate for the survey and the fact that it was applied during the daytime poses limitations for this study, as perceptions may change at night. On the other hand, the cognitive map presents exciting results that might be worthy of validation or replication in other cities or by considering personal emotional states (e.g., daily stress).

Table 2
Standardized parameters of the measurement model.

Attribute	Latent variable	α	λ	t-statistic
Quality of service	–	2.383	–	39.068
Width	*Sidewalk characteristics*	1.771	0.708	35.702
Condition		1.550	0.731	33.871
Furniture		1.473	0.640	28.736
Trees		1.225	0.586	24.424
Public transit access		1.650	0.422	14.636
Signage		1.363	0.625	28.392
Road width	*Externalities*	1.016	0.619	21.854
Lanes		1.034	0.621	21.677
HGV flow		1.315	0.636	21.593
Vehicular speed		1.428	0.629	21.480
Noise		2.489	0.381	11.631
Weather	*Surrounding*	2.671	0.373	12.448
Lighting		3.451	0.418	14.042
Odor		1.971	0.665	25.665
Environment		2.568	0.778	41.976
Cleanliness		1.711	0.713	35.363
Landscape		2.184	0.679	31.912
Pedestrians far from me	*Discomfort*	1.137	0.462	15.880
Stress		1.033	0.750	35.082
Too many pedestrians		1.071	0.704	31.410
I prefer not to walk here		0.942	0.631	25.918
Bike flow	*Bike hassles*	2.289	0.753	41.244
Bike speed		3.737	0.851	53.889
Opposite direction flow		2.690	0.627	27.970
Same direction flow		2.868	0.647	29.798
Security	*Protection*	1.039	0.653	28.704
Sidewalk safety		1.325	0.824	42.785
Road safety		1.401	0.726	34.565
Restrooms	*Amenities*	1.530	0.433	10.305
Shops		2.887	0.589	12.451
Shade		3.148	0.471	10.947

Table 3
SEM infrastructure QoS final model results.

Model	βandλ						
	Sidewalk characteristics	Surrounding	Externalities	Discomfort	Protection	Bike hassles	Amenities
Direct							
Quality of service	0.689	0.149					
(t-statistic)	(29.040)	(5.114)					
Sidewalk characteristics		0.176	−0.363	−0.088	0.185		
(t-statistic)		(4.229)	(-7.621)	(-1.952)	(4.838)		
Surrounding			−0.196	−0.170	0.350		
(t-statistic)			(-3.940)	(-3.690)	(9.973)		
Externalities						0.156	−0.304
(t-statistic)						(3.890)	(-6.068)
Discomfort			0.527				
(t-statistic)			(14.590)				
Protection			−0.186	−0.100		−0.117	0.088
(t-statistic)			(-3.217)	(-1.972)		(-3.088)	(1.707)
Indirect							
Quality of service		0.121	−0.412	−0.128	0.222	−0.091	0.145
(t-statistic)		(4.153)	(-14.736)	(-3.659)	(8.375)	(-4.839)	(6.021)
Sidewalk characteristics			−0.155	−0.055	0.062	−0.110	0.179
(t-statistic)			(-5.696)	(-3.237)	(3.868)	(-4.784)	(6.067)
Surrounding			−0.173	−0.035		−0.099	0.143
(t-statistic)			(-5.776)	(-1.933)		(-4.912)	(5.433)
Discomfort						0.083	−0.160
(t-statistic)						(3.747)	(-5.561)
Protection			−0.053			−0.037	0.072
(t-statistic)			(-1.972)			(-3.126)	(3.992)
Total							
Quality of service	0.689	0.270	−0.412	−0.128	0.222	−0.091	0.145
(t-statistic)	(29.040)	(7.747)	(-14.736)	(-3.659)	(8.375)	(-4.839)	(6.021)
Sidewalk characteristics		0.176	−0.519	−0.142	0.247	−0.110	0.179
(t-statistic)		(4.229)	(-15.009)	(-3.035)	(7.009)	(-4.784)	(6.067)
Surrounding			−0.369	−0.205	0.350	−0.099	0.143
(t-statistic)			(-9.482)	(-4.256)	(9.973)	(-4.912)	(5.433)
Externalities						0.156	−0.304
(t-statistic)						(3.890)	(-6.068)
Discomfort			0.527			0.083	−0.160
(t-statistic)			(14.590)			(3.747)	(5.561)
Protection			−0.238	−0.100		−0.155	0.161
(t-statistic)			(-5.224)	(-1.972)		(-4.119)	(3.348)

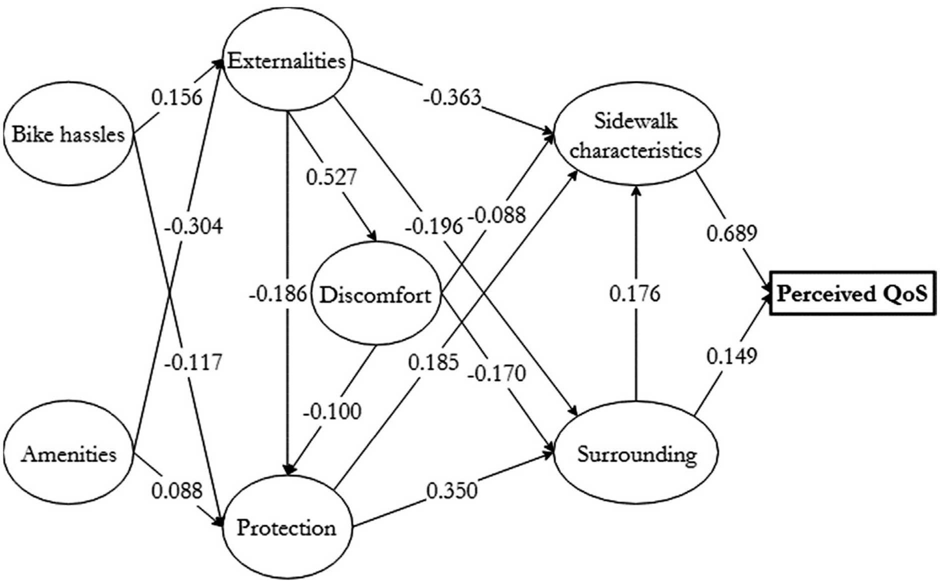

Fig. 5. SEM infrastructure QoS final model.

Table 4
The goodness of fit indicators of the final model.

Indicator	Explanation	Model result	Threshold accepted
χ^2/DF	This indicator measures the discrepancy between the sample and model covariance matrices corrected for degrees of freedom.	2.124	< 3.000
RMSEA	This indicator determines the model fit to the sample's covariance matrix with unknown coefficients.	0.033	< 0.060
CFI	This indicator compares the proposed model χ^2 with a non-correlated model between latent variables.	0.953	> 0.950
SRMR	This indicator calculates the square root of the difference between the sample and the hypothesized model's covariance matrix residuals.	0.038	< 0.080

5. Analysis and discussion

Perceptions have been used to better understand the world. Since the early 1960 s, with publications such as the Image of the City (Lynch, 1960), the use of perceptions to explain and understand urban environments has been key. In the field of pedestrians, who are those that interact directly with urban environments, it is only recently that perceptions have been acknowledged and actively applied to understand preferences and the behavior of non-motorized modes. Geetha Rajendran Bivina & Parida (2019) very recently conducted a study considering pedestrian perceptions and an SEM approach to explain PLOS. This study indicated the positive effects that the LVs *safety, security, mobility and infrastructure,* and *comfort and convenience* have on the PLOS. Meanwhile, Vallejo-Borda et al. (2020) and Jahan et al. (2020) proposed a similar study but this time to explain QoS using an LV approach. The results of the present study also identified the positive effects presented by Geetha Rajendran Bivina & Parida (2019) and Jahan et al. (2020), and the negative effects presented by Vallejo-Borda et al. (2020). Based on the results of this study, we identified the way in which pedestrians perceived QoS when walking by uncovering a useful pedestrian cognitive map that uncovers two additional LVs (i.e., *bike hassles* and *amenities*) to the ones reported in the literature (see Fig. 5).

According to our model, pedestrians initially begin by focusing on *bike hassles* and *amenities* (see Fig. 5). The literature provides evidence that the interaction of pedestrians with bicycles on their infrastructure decreases infrastructure QoS (Muraleetharan, Adachi, Hagiwara, & Kagaya, 2005; Muraleetharan & Hagiwara, 2007; Sahani et al., 2017). The results of this study can support these previous findings; however, the negative impact of *bike hassles* on perceived QoS is not direct and needs the mediation of other LVs (see Fig. 5). In the case of the *amenities* LV, the impacts, presented here, that this has on the perceived QoS is supported by the literature. The literature also shows that the presence and good rate of public restrooms on sidewalks impact the *amenities* of a sidewalk positively, generating better QoS for an urban sidewalk (Motamed & Bitaraf, 2016), while shops on the infrastructure or close to the infrastructure provide a safe and secure sidewalk (Motamed & Bitaraf, 2016) where pedestrians are more likely to walk (Choi et al., 2016; Pikora et al., 2003). Finally, having shade on the sidewalks also contributes to increasing pedestrian comfort when walking (Jaskiewicz, 1999) and improving the visual quality of the environment (Macdonald et al., 2018).

Externalities is the LV with the higher indirect impact that decreases the perceived QoS and is one of the LVs that help to mediate the effect of the LVs *bike hassles* and *amenities* on perceived QoS. In line with our result, previous research has shown that the interaction of pedestrians with traffic attributes like *HGV flow* increases stress levels, and thus decreases PLOS (Mozer, 1994). Pedestrians' interaction with high vehicular speed values, also increases stress levels, affecting their experience (Mozer, 1994), decreasing perceived pedestrian safety (Jaskiewicz, 1999; Landis, Vattikuti, Ottenberg, McLeod, & Guttenplan, 2001; Motamed & Bitaraf, 2016; State of Florida Department of Transportation, 2009; Talavera-Garcia & Soria-Lara, 2015), PLOS (S. Kim, Choi, & Kim, 2013; Landis et al., 2001; Mozer, 1994; Sahani et al., 2017; State of Florida Department of Transportation, 2009) , level of comfort (Pikora et al., 2003), satisfaction (Jensen, 2007), and QoS (Vallejo-Borda et al., 2020). The literature also mentions that vehicle infrastructure with a wide road width and large number of lanes also increases pedestrian stress levels (Macdonald et al., 2018; Mozer, 1994), and decreases pedestrian satisfaction (Choi et al., 2016; Jensen, 2007). High noise levels on the sidewalk decrease perceived pedestrian pleasure (Motamed & Bitaraf, 2016), the QoS for pedestrians (Sarkar, 2003), and PLOS (Christopoulou & Pitsiava-Latinopoulou, 2012).

One of the LVs that help to mediate the negative effect of the *externalities* LV on perceived QoS is *discomfort*. According to our results, the interaction of pedestrians with other pedestrians and the stress felt on the sidewalk, produce a negative impact on how they are perceiving the sidewalk QoS. Previous research reveals that pedestrian interaction with other pedestrians decreases their PLOS (Asadi-Shekari et al., 2013; Banerjee et al., 2018; Raad & Burke, 2018) and QoS (Vallejo-Borda et al., 2020). Moreover, stress levels are understood as being opposite to PLOS. In other words, when stress levels go up, PLOS goes down (Mozer, 1994).

Another LV that helps to mediate the effect of the LVs *discomfort*, *externalities*, *bike hassles*, and *amenities* on the perceived QoS is *protection*. *Protection* on sidewalks was measured from two perspectives: road safety and personal security. A positive impact on the perceived QoS was found when perceived *protection* increases. Similar results were obtained by Geetha Rajendran Bivina & Parida (2019) and Jahan et al. (2020), who stated a positive effect of the LVs related to the LV *protection* on PLOS. There is also evidence to show that increasing the level of safety (Christopoulou & Pitsiava-Latinopoulou, 2012;

Ewing, Handy, Brownson, Clemente, & Winston, 2006; Pikora et al., 2003) and security (G. R. Bivina et al., 2018; Gallin, 2001; Jahan et al., 2020; Motamed & Bitaraf, 2016), also increases pedestrian QoS.

Similarly, the *surrounding* LV also helps to mediate the effect of LVs *protection*, *discomfort*, and *externalities* on perceived QoS. In this case, the LV *surrounding* can explain the positive impact, both direct and indirect, on the perceived QoS caused by how pedestrians perceive attributes that are not directly related to the infrastructure (i.e., weather, lighting, odor, environment, cleanliness, and landscape). This result is supported in the literature, where this LV has already been proposed (Vallejo-Borda et al., 2020). It is also explained that bad weather conditions like rain can cause pedestrians to express negative attitudes (Kang & Fricker, 2016). Besides, the improvement of built environment characteristics like a good sidewalk, environment, and landscape increases perceived pedestrian comfort (T. Kim, Park, Lim, & Joo, 2011) and satisfaction (Jensen, 2007). The literature also mentions that there are some characteristics of sidewalk *surroundings* such as proper lighting that also increase the perceived sidewalk PLOS (Kang et al., 2013), as do a clean sidewalk with a pleasant odor (Motamed & Bitaraf, 2016; Pikora et al., 2003), which can increase sidewalk quality and improve the pleasure experienced by pedestrians (G. R. Bivina et al., 2018).

Finally, the LV *sidewalk characteristics* also helps to mediate the effect of the LVs *surrounding*, *protection*, *discomfort*, and *externalities* on the perceived QoS. This LV considers the positive and direct impact on perceived QoS, given the perception of the infrastructure elements. These results are supported in the literature, which states that the LV related to the *sidewalk characteristics* is the most relevant when it comes to assessing pedestrian infrastructure (Geetha Rajendran Bivina & Parida, 2019; Jahan et al., 2020; Vallejo-Borda et al., 2020). The literature also states that over time, an increase in the width of a sidewalk increases PLOS (Asadi-Shekari et al., 2013; Banerjee et al., 2018; Raad & Burke, 2018). However, among the *sidewalk characteristics*, width is not the only attribute to consider when trying to understand sidewalk QoS. Pedestrians' interaction with sidewalk elements like the presence of good furniture improves pedestrian comfort (Sarkar, 2003) and pleasure (Motamed & Bitaraf, 2016) when walking. Trees on the sidewalk also increase pedestrian satisfaction (Jensen, 2007), PLOS (Christopoulou & Pitsiava-Latinopoulou, 2012; Talavera-Garcia & Soria-Lara, 2015), and they generate a more attractive infrastructure for walking (Choi et al., 2016; Motamed & Bitaraf, 2016). Also, good pedestrian signaling and support facilities that aid pedestrians increase PLOS (Gallin, 2001) and sidewalk QoS (T. Kim et al., 2011). However, the presence of the above-mentioned elements is not enough; sidewalks must be in good condition to provide a better infrastructure for pedestrians (G. R. Bivina et al., 2018; Christopoulou & Pitsiava-Latinopoulou, 2012; Gallin, 2001; Jaskiewicz, 1999; T. Kim et al., 2011; Marisamynathan & Lakshmi, 2016; Motamed & Bitaraf, 2016; Pikora et al., 2003; Sarkar, 2003). Finally, access to public transport on a sidewalk increases sidewalk PLOS (Christopoulou & Pitsiava-Latinopoulou, 2012) and satisfaction (Choi et al., 2016), providing a more attractive sidewalk to walk on (Pikora et al., 2003).

Our results suggest that pedestrian perceptions of *sidewalk characteristics* are the most relevant for improving perceived QoS. As such, increasing the perceived quality of the *sidewalk characteristics* (i.e., width, condition, furniture, trees, public transport access, and signage) is essential when it comes to improving urban sidewalks. The effect of the other LVs that also influence the perceived QoS positively should not be ignored. Improving pedestrian infrastructure is a necessary condition for consolidating a positive perception of the *surrounding* (weather, lighting, odor, environment, cleanliness, and landscape), *protection* (security, sidewalk safety, and road safety), and *amenities* (restrooms, shops, and shade).

The interaction that generates the greatest negative impact is with non-active modes represented by the LV *externalities,* and to counteract this negative effect will improve the perceived QoS. This counterbalance can be produced in two different ways; first, by improving the pedestrian perception of their *amenities* (restrooms, shops, and shade); and second, by decreasing the negative effect of this LV by designing rights of way with few spaces for non-active vehicles (lower vehicular road width and number of lanes), regulating the HGV flow, vehicular speed, and noise. However, we highly recommend the application of both counteracting actions and a consideration of the negative impact of the other LVs related to pedestrians' interaction with bicyclists (*bike hassles*) and among themselves (*discomfort*). To decrease the negative impact caused by bicyclists, we recommend that the flow and speed of bicyclists close to pedestrians be regulated. Finally, to reduce the negative impact caused by pedestrians' interaction with other pedestrians, we recommend the design and development of more spaces that can be used for walking, reducing pedestrian density and the potential conflicts between them.

6. Conclusions

Perceptions are powerful assets in explaining pedestrians' overall perceived QoS of a given local environment. We propose a cognitive map to understand how perceptions influence pedestrian perceived QoS. The map would show that to generate an overall assessment of the QoS, pedestrians first consider *bike hassles* and infrastructure *amenities*, followed by *externalities*, *discomfort*, *protection*, and *surrounding*, and finally, *sidewalk characteristics*. The cognitive map has great potential to uncover mediations that can be used to reduce barriers (i.e., mitigate the negative effects) or as an opportunity to enhance the positive effects. Better understanding the cognitive process pedestrians undertake to assess QoS, has immense potential in the design, policy, and assessment of pedestrian infrastructure. It is remarkable that the perception of *sidewalk characteristics* is key in explaining QoS. In addition, we also found three LVs related to the interaction between pedestrians and other transportation modes (i.e., *externalities*, *discomfort*, and *bike hassles*) that negatively impact the perceived QoS.

In this study, we explored pedestrians' cognitive processes in perceiving QoS when walking on an urban sidewalk, considering their perceptions. The proposed cognitive map was developed using data from Bogotá without considering time periods or the respondents' emotional states. As such, we highly recommend that future research should test the validity of the model in different contexts to uncover the effects of considering different times of the day or pedestrians' emotional states on their responses. Further research may also include the effect of socioeconomic characteristics of the individuals on the cognitive map.

CRediT authorship contribution statement

Jose Agustin Vallejo-Borda: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing - original draft. **Victor Cantillo:** Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Writing - review & editing. **Alvaro Rodriguez-Valencia:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Project administration, Resources, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trf.2020.06.013.

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