Individuals' perception of walkability

Cities 125 (2022) 103650

Contents lists available at ScienceDirect

Cities

journal homepage: www.elsevier.com/locate/cities

Individuals' perception of walkability: Results of a conjoint experiment using videos of virtual environments

Bojing Liao, Ph.D. *, Pauline E.W. van den Berg, P.J.V. van Wesemael, Theo A. Arentze

Department of the Built Environment, Eindhoven University of Technology, PO Box 513, 5600MB Eindhoven, the Netherlands

ARTICLE INFO

Keywords:
Perceived walkability
Walking emotions
Videos of virtual environments
Conjoint experiment
Latent class model

ABSTRACT

In empirical research there is an increasing interest in the role of visualization techniques combined with conjoint experiments to measure perceptions of walkability at neighbourhood and street levels. However, existing studies still mainly use traditional visualization methods (e.g., images and photos), which cannot provide respondents with a holistic perspective to evaluate the built environment accurately. Virtual reality technology could fill this gap. In this study, we conducted a conjoint experiment using videos of virtual environments to investigate how certain groups of people perceive walkability differently. The experiment was conducted online conjoint experiment involving a sample of 295 respondents. The hypothetical virtual environments were presented using a dynamic 3D virtual video to visualize different street block designs from the viewpoint of a moving pedestrian. Participants were asked to rate each environment viewed based on the feelings evoked during watching the video. We used a latent class regression model and discrete choice analysis to understand how groups of individuals perceive walkability differently, and what emotions of individuals are associated with walkability. Our results confirmed earlier findings from empirical studies that land use mix, connectivity, road size, open space, and green have an influence on individuals' perception of walkability. We further found that perceived walkability is mainly associated with feelings of comfort and feelings of security.

1. Introduction

Research on how physical activity and lifestyle are influenced by the built environment and social context has received increased attention in recent years. Previous studies have shown that the design of the built environment has a significant influence on the extent to which individuals walk (Koschinsky et al., 2017), which is an important element of the active lifestyle of people in the neighbourhood (Liao et al., 2020a, 2020b). Empirical research further points out that walking behaviour is affected by the way people perceive the walking environment (Koschinsky & Talen, 2015; Sung & Lee, 2015).

The majority of existing research uses subjective measurement to understand individuals' perception of walkability on the neighbourhood level. In many cases, studies in this line of research use questionnaires where respondents are asked to rate various aspects of the walking environment of neighbourhoods they live in by rating scales (Cerin et al., 2006). The conjoint experiment has also received attention as a method to identify effects of built-environment attributes on how people perceive walkability of neighbourhoods (Kasraian et al., 2020a, 2020b). In a conjoint experiment, generally, respondents are asked to indicate their preferences in specific hypothetical situations. Commonly, these hypothetical situations are constructed based on attribute profiles that are varied by an experimental design. Traditionally, the attribute profiles are presented either verbally (text) or by using visualisations such as photos, and images. These are by definition static and are only rudimentary representations, which forces respondents to stretch their imagination, and thereby introduce inevitable imagination bias. Compared to these traditional methods of representation, a virtual reality environment could provide a more dynamic and integral impression of the environment and, hence, avoid this pitfall (Birenboim et al., 2019). The use of virtual reality technology in a conjoint experiment will help respondents to perceive the walkability in neighbourhood environments more directly by experiencing it in a more integral and dynamic way. However despite the potential of VR, research on how to combine virtual reality technology with a conjoint experiment has until now received less attention.

The objective of the present study is, therefore, to design a conjoint experiment to measure individuals' perception of walkability using

* Corresponding author at: De Groene Loper 6, 5612 AZ, VRT 8.36, Eindhoven, the Netherlands.
E-mail address: lbj@xmu.edu.cn (B. Liao).

https://doi.org/10.1016/j.cities.2022.103650
Received 19 October 2020; Received in revised form 11 October 2021; Accepted 19 February 2022
Available online 30 March 2022

videos of virtual environments to simulate the neighbourhood environments seen from the eye-level of pedestrians. Although it cannot generate the experience of VR, by watching a video of a virtual environment participants can obtain an integrated view of the environment and create a lively imagination how it would be like to walk in that environment (Kasraian et al., 2020a, 2020b). At the same time, a video can be displayed on the own computer screen of each participant, so that the experiments can be conducted on-line making a larger sample feasible. Considering the scale level, we use the street-block. The street block has been described as the fundamental and appropriate unit to map the urban structure (Bochow et al., 2010). Using the smaller scale level of the street-block compared to the neighbourhood allows for the construction of a 3D model of the environment that provides sufficient spatial and social detail. The data of the conjoint experiment is collected through an online survey. This survey uses dynamic videos of virtual environments to visualize different street block designs from the viewpoint of a moving pedestrian. Participants are asked to watch the videos and rate the environments presented based on the feelings each video evoked. The set-up of the present study also aims to identify groups that differ with regard to their perception of walkability. The results should, thus, contribute to a better understanding of individuals' perception of walkability and the development of tools to connect design theory and design practice through for instance streetscape design guidelines.

The remainder of this article is structured as follows. The next section discusses the literature about the relationship between neighbourhood characteristics and perceived walkability, and the use of virtual reality techniques in conjoint experiments. In Section 3, we explain the experimental design, the data collection, and analysis methods. The results of the analysis and discussion are presented in Section 4. In the last section, the key findings and policy implications are highlighted.

2. Literature review

2.1. The relationship between neighbourhood characteristics and perceived walkability

Various assessment tools to understand how neighbourhood characteristics affect the way people perceive the walkability of neighbourhoods have been developed for empirical studies (Talen & Koschinsky, 2013). These include the Neighbourhood Environment Walkability Scale (NEWS), NEWS-A (Simplified Version), NEWS-Y (Youth Version), International Physical Activity Questionnaire Environmental module (IPAQ-E), Active for Life, and Perceptions of Local Environment (Cerin et al., 2006; Foster et al., 2004; Hagströmer et al., 2006; Rosenberg et al., 2009; Spittaels et al., 2009, 2010; Wallmann et al., 2012). These tools are based on questionnaires asking subjects to rate characteristics of the built environment that are considered important for walkability. Items often recurring in the questionnaires used are: (a) residential density; (b) proximity to nonresidential land uses (land use mix-diversity); (c) ease of access to nonresidential uses (land use mix-access); (d) street connectivity; (e) walking/cycling facilities; (f) aesthetics; (g) pedestrian traffic safety; (h) crime safety; and (i) overall environment (Cerin et al., 2006; Foster et al., 2004; Hagströmer et al., 2006; Harrison et al., 2007; Inoue et al., 2009; Liao et al., 2020a, 2020b; Meusel et al., 2007; Rosenberg et al., 2009; Wang & Yang, 2019).

Application of the different assessment tools in studies has led to mixed findings regarding the associations between built environment characteristics and perceived walkability. Rosenberg et al. (2009) examined the relationship between the neighbourhood environment and adolescents' perception of walkability in the United States using NEWS-Y. Traffic safety, aesthetics, walking/cycling facilities, land use mix, and overall environment were found to be associated with perceived walkability. In China, Cerin et al. (2007, 2010, 2013) used NEWS and NEWS-A to investigate effects of the built environment on perceived walkability of Hong Kong elderly. They found that two attributes (access to services and human and motorized traffic) were both significantly associated with the perceived walkability. Cerin et al. (2013) analyzed the measurement results of NEWS and NEWS-A across twelve countries around the world. They found that land use mix, street connectivity, walking/cycling facilities, aesthetics, and safety have an influence on perception of people of walkability in all twelve countries.

In addition to NEWS, NWES-A, and NEWS-Y, also studies using IPAQ-E have contributed to a growing body of evidence in this area. Inoue et al. (2009) tested the reliability of IPAQ-E in Japan and found that for Japanese adults' residential density, access to shops, access to public transport, and presence of sidewalks are associated with perceived walkability. However, when used in Germany, the results from the IPAQ-E were different than in Japan. In Germany, the IPAQ-E was used by Wallmann et al. (2012) to explain the association between perceived walkability and walking environment. They observed positive associations between perceived walkability and good access to destinations, well-maintained sidewalks, higher residential density, and neighbourhood safety. Other environmental assessment tools, including Active for Life (A4L) and Perceptions of Local Environment (PLE), have also been used to analyze the way people perceive the walkability. Foster et al. (2004) reported A4L investigation results in the United Kingdom, which indicated that street safety, public spaces, and green spaces contributed positively to perceived walkability. Results of the PLE survey in the United Kingdom pointed out that neighbourhood safety and access to leisure facilities had positive effects on the perceived walkability (Harrison et al., 2007).

In the studies reviewed above, divergence in findings originates from differences between the tools as well as the diversity of regions. However, some neighbourhood characteristics were commonly found to contribute to perceived walkability, namely land use mix-diversity, safety, and walking facilities. Although these studies provide perspectives to better understand the interaction between neighbourhood characteristics and perceived walkability, they all relied on revealed preference data making it hard to identify the separate effects of attributes because of the existence of strong correlations. Also, these studies did not involve and explain the relationship between emotions and walking experiences (perceived walkability). While, empirical studies clearly have pointed out that the neighbourhood environment also influences emotions of individuals, colouring their individual perceptions of the walkability in neighbourhoods. For example, Ettema and Smajic (2015) found that in the Netherlands pedestrian experience of individuals was associated with sense of happiness. Furthermore, Birenboim (2018) indicated that sense of comfort and sense of security are associated with walking through experiences in urban environments. And, Resch et al. (2020) found relationships between the walkability and senses of stress and relaxation. Besides, a few studies have reported the association between walking experiences and sense of annoyance in neighbourhood environments (Birenboim, 2018; Paunović et al., 2009; Ulrich et al., 1991).

A conjoint experiment to understand respondents' subjective judgment of the neighbourhood environment, where neighbourhood characteristics can be varied independently, has therefore been considered as an alternative approach (stated preference data). In a conjoint experiment, respondents are asked to answer questions for hypothetical alternatives, which usually involves a choice, ranking, or rating task (Hensher et al., 2005). Recent studies that have used the conjoint experiment to analyze walkability or walking preferences of individuals are: Adkins et al., 2012; Borst et al., 2008; Kaparias et al., 2012; Kasraian et al., 2020a, 2020b; Kelly et al., 2011; Kim et al., 2011; Lusk et al., 2018; Perdomo et al., 2014. Specifically, these studies considered the relationship between the characteristics of a neighbourhood or a street and how it is experienced by individuals who use it. Borst et al. (2008), Kaparias et al. (2012), Kasraian et al. (2020a, 2020b), Kelly et al. (2011), and Kim et al. (2011) found that pavement cleanliness, wider sidewalks, and good connectivities are generally preferred by individuals. Lusk et al. (2018) and Kasraian et al. (2020a, 2020b) found that, in addition, the presence of trees increases preference to walk. These studies show that a conjoint experiment is especially useful to get quantitative insight in the weighting of individual attributes in judgments of preference or perceived walkability. Furthermore, a conjoint experiment involves the experience of individuals and therefore could also be used to analyze the relationship between emotions and perceived walkability (walking through experience).

2.2. Virtual reality techniques in conjoint experiments

In a conjoint experiment, attributes of the alternatives are varied based on a statistical design such that the separate effects of the attributes can be determined by analyzing the choice or preference data. Normally, text is used to describe the attributes (Caulfield et al., 2012). For example, Brown et al. (2009) used textual representations in a stated preference survey to investigate walking preferences of older adults in the United States. However, textual representations cannot always adequately convey the essence and complexity of certain decision contexts (Verhoeven et al., 2017). To circumvent this problem, the use of visual representations such as photos and images to present hypothetical situations instead of textual representations has been proposed (Shr et al., 2019). For instance, Tilt (2010) presented photos in a conjoint experiment to investigate walking preferences. Although visual representation may help the respondent to create more vivid imaginations of a presented environment, it still only provides a static and often rudimentary impression of the environment the researcher intends to present (Shr et al., 2019). Since the behaviour of residents involves direct, dynamic interaction with the surrounding physical and social environment, Birenboim et al. (2019) pointed out that the incorporation of virtual reality (VR) techniques could result in greater external validity compared to traditional representation methods in choice experiments. The main merit of VR technology lies in its potential "*to address the long-standing trade-off problem between mundane realism and experimental control that is encountered in many experiments on human perceptions and behaviours*" (Birenboim et al., 2019).

Bishop et al. (2001) used VR techniques in a choice experiment to examine how respondents perceive a virtual landscape of a specific area. In the experiment, respondents were asked to use mouse actions to choose paths and watch viewpoints. Later, Bishop and Rohrmann (2003) improved their approach by using dynamic 3D videos simulating a real outdoor environment via VR techniques in a conjoint experiment. Similarly, Kort et al. (2003) simulated an indoor environment and invited respondents to watch the videos of virtual environment in their experiment. Perdomo et al. (2014) simulated a small real environment by representing 3D videos to investigate preferences of pedestrians. Rid et al. (2018) and van Vliet et al. (2021) constructed virtual alternatives by augmented-reality 3D rendering techniques and allowed respondents to watch and choose their virtual environment in an online survey. Similar to Perdomo et al. (2014), Kasraian et al. (2020a, 2020b) investigated pedestrians' perceptions of walkability by using a dynamic 3D representation (videos of virtual environments) of various hypothetical street designs in Toronto.

Furthermore, several studies focused on how to present immersive virtual reality of the built environment to respondents via new equipment. For example, VR glasses (virtual reality headset), which is a head-mounted device that provides immersive virtual reality for the wearer, allows one to dynamically display the built environment that enables a direct coupling between the respondents' motor actions and the simulation (Birenboim et al., 2019). Studying environmental preferences, Maffei et al. (2016), Higuera-Trujillo et al. (2017), Farooq et al. (2018), Abd-Alhamid et al. (2019), Atwa et al. (2019), Birenboim et al. (2019), Gao et al. (2019), and Zhu et al. (2020) have also applied VR glasses in conjoint experiments. Furthermore, Birenboim et al. (2019) and Zhu et al. (2020) compared the participants' stated preferences under immersive virtual reality and conventional representations. In their experiments, they asked respondents both to use a VR headset and to watch traditional representations (images) on a computer screen. Maffei et al. (2016), Higuera-Trujillo et al. (2017), Abd-Alhamid et al. (2019), and Gao et al. (2019) simulated real environments in the laboratory and used VR headsets to present them. Then they recorded preferences of respondents when environmental elements of the VR environments were changed.

To summarize, in the conjoint experiments, the reviewed studies include two techniques of representation of virtual reality environments: (1) videos of virtual environments (watching videos to feel the virtual environments), and (2) the immersive VR (using VR glasses to experience the virtual environments). These two techniques are based on 3D models (using software such as Unity, SketchUp, and Twinmotion) to simulate environments realistically, and then ask respondents to experience them using different techniques. Therefore, both methods rely on virtual reality technologies, but apply different techniques. In the immersive VR, respondents can access virtual reality environments immersively with VR glasses and create watching routes by themselves. But this method has as a downside that it limits the feasible sample size, as individuals have to come to the laboratory to experience the immersive virtual reality. Compared to the immersive VR, the video method fixes the watching route and cannot provide full immersive experience to respondents. On the other hand, the video-based method allows the use of a large sample size as it can be implemented in an online survey and does not require special equipment from the respondent to engage in the experiment. For example, Kasraian et al. (2020a, 2020b) collected data of 600 respondents via an online survey, which is a much larger sample than can be achieved in studies using the immersive VR to collect data in the laboratory (less than 100 participants regularly). Table 1 provides an overview of the virtual reality techniques in the conjoint experiments reviewed in this section.

It follows from this brief review that a conjoint experiment combined with VR technology to analyze perceived walkability has received only limited attention. Furthermore, a full-fledged experimental design would allow the identification of weights of individual attributes, but only a few reviewed studies considered an orthogonal design or a full factorial design in their experiment, as shown in Table 1. In the present study, the aim, therefore, is to combine a full-fledged experimental design (orthogonal design) with virtual environment displays in multiple scenarios to analyze perceived walkability in a more rigorous way. In this study, we use videos to present the virtual environments. Given our goal to identify groups that differ in these perceptions, we aim at a large sample and, therefore, use an online survey to collect data. A potential downside of using VR or, more generally, visual representations of alternatives in a conjoint experiment should also be mentioned, which is that arbitrary elements in a visualization may have an influence on how an alternative is perceived and evaluated. We tried to circumvent this potential problem in two ways: (1) we use street-block designs that are representative of the situation in the Netherlands in which the experiment is conducted, and (2) we use abstract representations and exclude as much as possible arbitrary details.

3. Methodology

In this section, we introduce the method to design a conjoint experiment using virtual reality environment in this study. We also introduce the approach used to collect and analyze the data.

3.1. Design of the experiment

The design process of our conjoint experiment using virtual reality environment includes three steps, as follows: (1) define attributes and attributes levels, (2) design the virtual reality environment, and (3) design the on-line questionnaire.

The first step is to define the attributes and attribute levels of the choice alternatives used in the experiment. Existing empirical research has already identified the neighbourhood characteristics that have an

Table 1
Virtual reality techniques in the conjoint experiments (chronological order).

Authors	Environments	Representation ways	Views	Tools/software	Experimental places	Choices/ scenarios	Statistic design	Sample sizes
Bishop et al. (2001)	River valley landscape	2D maps; 3D static images	Eye-level pedestrians	UNIX; IRIS	Laboratory	3 choices	/	25 participants
Bishop and Rohrmann (2003)	Suburban area	3D video	Oblique aerial view	Alias/Wavefront Advanced Visualizer	Real environment; Laboratory	2 scenarios	/	10 groups
Kort et al. (2003)	L-shape indoor space	3D navigation	Eye-level pedestrians	dvMockup	Laboratory	4 scenarios	/	101 participants
Perdomo et al. (2014)	Pedestrian zone	3D video	Oblique aerial view	PTV VISSIM	Online	2 scenarios	/	501 participants
Maffei et al. (2016)	Limited traffic zone	VR headset	Eye-level pedestrians	SketchUp pro; Worldviz Vizard v4.0	Laboratory	2 scenarios	/	32 participants
Higuera-Trujillo et al. (2017)	Shop indoor	Photos; VR headset	Eye-level pedestrians; Oblique aerial view	Unity; SketchUp 2015; Panoramic real photos	Laboratory	1 scenario	/	100 participants
Farooq et al. (2018)	Autonomous vehicles on urban roads	VR headset	Eye-level pedestrians	Unity	Laboratory	2 scenarios	/	42 participants
Rid et al. (2018)	Neighbourhood housing	3D video	Oblique aerial view	3D Studio Max; Dreamweaver 8.0	Online survey	18 choices	Full factorial design	402 participants
Abd-Alhamid et al. (2019)	Panoramic indoor	VR headset	Eye-level pedestrians	Panoramic real photos	Laboratory	2 scenarios	/	20 participants
Atwa et al. (2019)	Green business park	VR headset	Oblique aerial view	Auto CAD; SketchUp	Laboratory	3 scenarios	/	28 participants
Birenboim et al. (2019)	Cycling environment	VR headset	Eye-level cycling	3D Studio Max	Laboratory	8 scenarios	Full factorial design	86 participants
Gao et al. (2019)	Green parks	Photos; VR headset	Eye-level pedestrians	Panoramic real photos	Laboratory	9 scenarios	/	179 participants
Kasraian et al. (2020a, 2020b)	Street segments	3D video	Eye-level pedestrians	Unity	Online survey	3 scenarios	Full factorial design	600 participants
Zhu et al. (2020)	Real world street	VR headset	Eye-level pedestrians	Sketch Up pro; Unity	Laboratory	14 choices	Orthogonal design	48 participants
van Vliet et al. (2021)	Green parks	3D video	Eye-level pedestrians	Twinmotion	Online survey	16 alternatives	Orthogonal design	697 participants

influence on walking behaviour (Sallis, 2009). For the present experiment, we use the street-block as spatial scale level. Because a street block is part of a neighbourhood, street block characteristics are similar to neighbourhood characteristics regarding their effects on walking behaviour. Compared with the neighbourhood, the street block has a smaller size that is suitable to generate detailed 3D models in the VR environment and that allows respondents to perceive features of the built environment more directly within short walkable distances.

As for the selection of attributes, as reviewed in Section 2, land use mix-diversity, walking facilities, sidewalks, and trees are important factors influencing walking behaviour. Besides, in earlier work, we found that connectivity and open space are significantly associated with walking behaviour in the Netherlands (Liao et al., 2020b). Therefore, for the experiment we selected the above mentioned five characteristics of neighbourhoods as street block design attributes. To limit the size of the experimental design, we considered two levels for each attribute to create alternatives, as follows: (1) land use mix has the levels: only residential area and residential mixed with commercial area, (2) block connectivity has the levels: high and low connectivity (number of intersection points), (3) road size the levels: two lanes with narrow pedestrian zone and one lane with wide pedestrian zone, (4) open space the levels: does and does not have open space in the block, and (5) green has the levels: does have and does not have trees in the block. Table 2 shows an overview of the attributes and the levels of the attributes that were varied.

Given this specification, 32 (2^5) combinations of attributes are possible. However, it is possible to reduce the number of combinations and still avoid any correlations between attributes. The number of combinations is reduced by taking a fraction of a full-factorial design that has the known properties of preserving orthogonality and allows us to estimate the main effects of the attributes. Orthogonality is a

Table 2
Attributes and levels of the attributes.

Attributes	Levels
Land use mix	(1) Residential land-use (2) Mixed with commercial area
Block connectivity	(1) High connectivity (2) Low connectivity
Road size	(1) Two lanes with narrow pedestrian zone (2) One lane with wide pedestrian zone
Open space	(1) Has open space in the block (2) Does not have open space in the block
Green	(1) Has trees in the block (2) Does not have trees in the block

mathematical constraint requiring that all attributes are statistically independent of one another so that their effects can be identified through statistical analysis (Hensher et al., 2005). In this case, the full factorial design can be reduced to an orthogonal design consisting of eight attribute profiles (combinations of attribute levels). This orthogonal fraction of the full-factorial design allows us to identify the main effects of the attributes (and main effects only) and is shown in Table 3.

In the next step, the eight combinations were converted to eight virtual reality environments. We built a typical Dutch street block as a basic 3D model in SketchUp Pro 2019. In the street block, the experiment area is 300 m in length and 240 m in width. The eight 3D sketch models correspond to the attribute profiles of the orthogonal design, as shown in Fig. 1. Keeping the road width constant, we varied the type of road: (1) two lanes for cars with a narrow size of the pedestrian sidewalk, and (2) one lane for cars with wide space for pedestrians, as shown in Fig. 2. For the land use mix attribute, we created an all residential street block as the first level, and mixed with some commercial buildings

Table 3
An orthogonal design of eight attribute profiles.

		Combination 1	Combination 2	Combination 3	Combination 4	Combination 5	Combination 6	Combination 7	Combination 8
Land use mix	Residential land-use	*	*	*	*				
	Mixed with commercial area					*	*	*	*
Block connectivity	High connectivity	*	*			*	*		
	Low connectivity			*	*			*	*
Road size	Two lanes with narrow pedestrian zone	*	*					*	*
	One lane with wide pedestrian zone			*	*	*	*		
Open space	Has open space in the block	*		*		*		*	
	Does not have open space in the block		*		*		*		*
Green	Has trees in the block	*			*		*	*	
	Does not have trees in the block		*	*		*			*

* Note that the combination includes the attribute level.

(e.g. shops and supermarket) in the middle of the residential area to create the second level. For the connectivity attribute, we varied the number of intersection points in the street block. As for open space, we varied between presence and absence of open space. Regarding green, we varied the presence of street trees. Based on the 3D sketch models and different levels of the attributes, we generated eight virtual reality environments, which were then all eight imported to the Twinmotion 2019 (Epic Games, 2019) — a quick real 3D rendering software. In Twinmotion 2019, we added materials, trees, traffic, facilities, and people to all 3D sketch models, as shown in Table 4.

Next, we set a walking perspective and exported all virtual reality environments as movies. To keep consistency, all movies of the virtual reality environments had the same walking route, watching direction, geographical location, sunlight time, seasons, and weather. The length of each video is 1 min and 30 s. Additionally, to maintain consistency in the information conveyed, all scenarios utilize the same 3D objects (e.g., the same buildings, trees, and facilities) to represent characteristics, which means that participants see the same tree color, building style, and facility material in all scenarios. In this way it is ensured that participants evaluate the environments based on the attributes used to construct the environments, keeping all else equal.

The questionnaire is designed into two parts. The first part is about the individual's perception of his/her existing neighbourhood and personal characteristics, and the second part contains the virtual reality environment consisting of movies and related questions to retrieve perceptions of the virtual reality environments. The questionnaire in the virtual reality environments part is about how the participant experiences the virtual reality environments when he or she watches the video of the virtual environment. Participants are asked to rate the virtual environments based on the feelings each video evoked. Considering the length of the questionnaire, we randomly show 4 out of 8 dynamic 3D videos of the virtual reality environment to each respondent. We use two sections to ask participants about their perception of each virtual reality environment. The first section includes two questions about the quality of the environment, as follows: (1) “How satisfied are you with the overall quality of this virtual environment?”; and (2) “How satisfied are you with the walking friendliness of this virtual environment?”. Each question uses a 7-point Likert scale ranging from not at all satisfied to fully satisfied. We use the preference rating method from Birenboim et al. (2019). Using this method respondents can indicate the feelings they had during the virtual walk-through the environment. The questions of the second section are about the emotions the virtual environment evoked. Four dimensions of emotions were associated with the perceived walkability (walking through experience), as follows: happiness, comfort, annoyance, and security. Hereby, we ask participants to indicate to what extent they experienced each of these four emotions. The questions are framed as statements, namely “I felt happy/comfortable/annoyed/secure”, and for each item the respondent answered on a 7-point Likert scale ranging from completely disagree (1) to completely agree (7), as shown in Table 5. The second section includes questions concerning the benefits that are perceived from the virtual environment.

3.2. Data collection and analysis approach

Respondents are recruited from a national consumer panel in the Netherlands and through social media (Twitter, LinkedIn and Facebook). For the virtual reality environments, we introduced to respondents that scenarios are presented of a neighbourhood in virtual reality that represent a typical Dutch street block. Then we asked respondents to indicate the overall quality of virtual scenarios, the walking friendliness of virtual scenarios, and how they are feeling about the virtual scenarios when they watch the scenarios. In total 308 persons completed the on-line questionnaire, 272 from the consumer panel, and 36 from social media. To ensure sufficient data quality, respondents who provided the same answer to each question or took less than 8 min for the VR part were removed. After data cleaning, 295 respondents

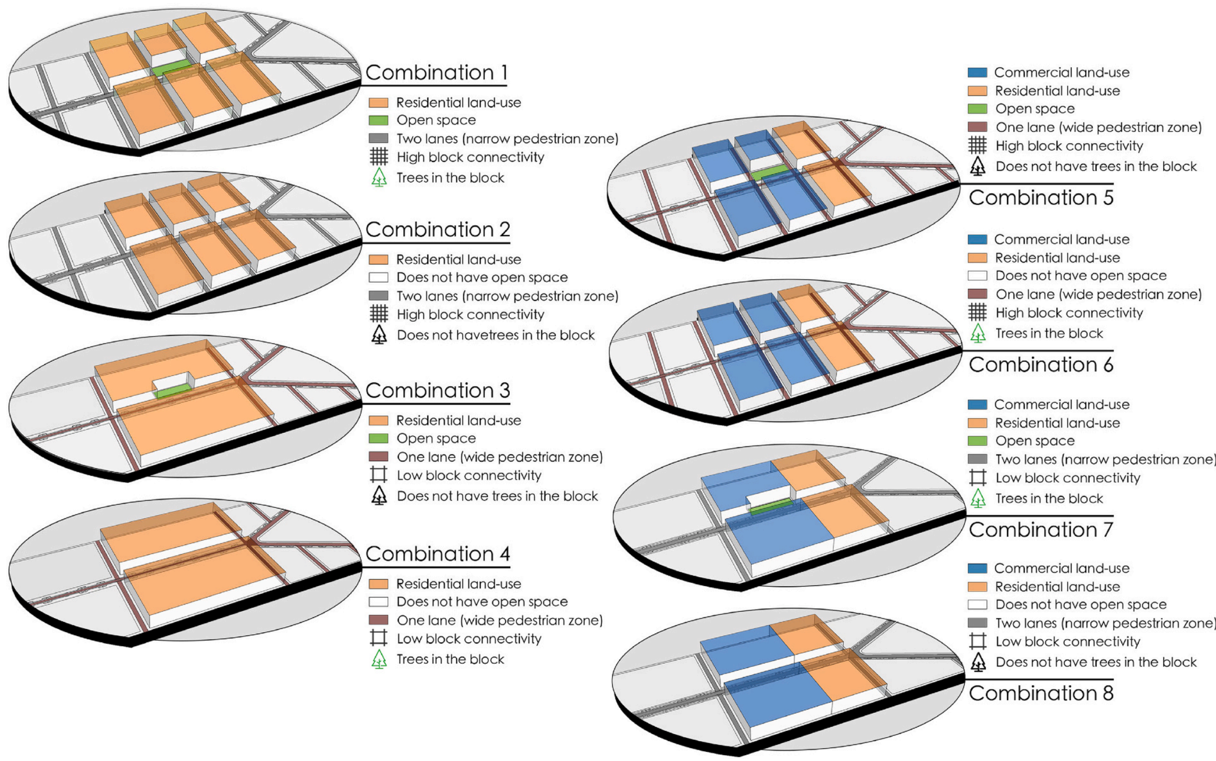

Fig. 1. The design combinations of street blocks.

remained in the sample. All respondents watched 4 videos (3D-videos) so that 1180 ratings on each item were recorded for the analysis. The socio-demographic characteristics of the sample are shown in Table 6.

In the final data set, we have observations for each respondent for 4 virtual walking trips. We use regression analysis as the basic method to analyze the data assuming that the dependent variable is approximately of interval level (7-point rating scales). We use the latent class regression model to take the panel structure of the data (repeated observation) into account and identify groups. Two regression analyses are performed: 1) regressing the perceived walkability on attributes of the environment and 2) regressing the perception of walkability on feelings (emotions) evoked by the environment. Measuring emotion using rating scales and analyzing the relationships between emotions and walkability have also been conducted in earlier studies (Birenboim, 2018; Ettema & Smajic, 2015; Paunović et al., 2009; Resch et al., 2020). Birenboim (2018), for example, used emotion variables as dependent variables in the data analysis, asking participants to rate their current sense of security, comfort level, satisfaction, and frustration level using one item for each of the dimensions. Therefore, in the second regression analysis, each emotion variable indicates one dimension of individuals' feelings separately. Therefore, these four emotion variables are manifest variables that are included as independent variables in the regression model. Application of the latent-class regression model offers class membership data. In a next step, the membership data are analyzed using a discrete choice model to identify the relationships between socio-demographic characteristics and class membership of individuals.

The latent class model assumes that individuals are implicitly sorted into a set of classes n and considers the finite mixture model with N classes of the form (Leisch, 2004):

$$h(y|x,\psi) = \sum_{n=1}^{N} \pi_n f(y|x,\theta_n) \quad (1)$$

$$\pi_n \geq 0, \sum_{n=1}^{N} \pi_n = 1$$

where y is a dependent variable with conditional density h, x is a vector of independent variables, π_n is the prior probability of class n, θ_n is the class-specific parameter vector for the density function f, and $\psi = (\pi_1, \ldots, \pi_N, \theta_1, \ldots, \theta_N)'$ is the vector of all parameters. In the model, f is a univariate normal density with class-specific mean $\beta_n{}'x$ and variance $\sigma_n{}^2$. Then, we have $\theta_n = (\beta_n{}', \sigma_n{}^2)'$ and Eq. (1) describes a latent class regression model (DeSarbo & Cron, 1988; Leisch, 2004). The posterior probability that observation (x,y) belongs to class j is given by (Leisch, 2004):

$$P(j|x,y,\psi) = \frac{\pi_j f(y|x,\theta_j)}{\sum_n \pi_n f(y|x,\theta_n)} \quad (2)$$

The latent class parameters are estimated by the maximum likelihood method, and the goodness of fit of the estimated model can be indicated by the McFadden's Rho-square ($\rho^2 = 1 - LLB/LLO$) (McFadden, 1973). The number of classes N is set by the user. To find the best number of classes, we run the model estimation several times for different values of N and use the Akaike information criterion ($AIC = -2(LLB - P)$) and Bayesian information criterion ($BIC = -LLB + [(P/2) * \ln(N)]$) to identify the optimal number of classes.

To analyze the relationships between socio-demographic characteristics and class membership, in the second step, we use the basic multinomial logit model. The posterior probabilities (Eq. (2)) are used to assign each individual to the class with maximum posterior probability (Leisch, 2004). Since there are two regression models (walking friendliness regressed on attributes and emotions, respectively), there are two class solutions for each individual that result from this analysis.

4. Results and discussion

4.1. Results of the relationship between the perceived walkability and attributes

In this section we discuss the results of the analysis concerning the regression of walkability on attributes varied in the experiment. Table 7

Fig. 2. The design road size of street blocks.

shows for the latent class regression model the statistics of different estimations under different settings of number of classes *N*. The results of the latent class regression model show that the AIC values decrease when the number of classes increases from 1 to 4 classes, while it increases when the number of classes increases to 5. Therefore, we identified the optimum number of classes as equal to 4 for the first regression model (walking friendliness regressed on attributes).

Regarding the effects of attributes on the perceived walkability, Table 8 shows the estimation results for the one class model and the model with four latent classes. The estimation results for the ordinary linear regression (one class) model are included for comparison. The value of the adjusted McFadden Rho square of the latent class model is considerably higher compared to the ordinary linear regression (one class) model indicating that there are strong differences between classes.

Looking at the estimation results in Table 8, the one-class model shows that residential land-use, wide pedestrian road, presence of open space and greenness are associated with walking friendliness. This result is in line with many empirical studies (Kasraian et al., 2020a, 2020b; Liao et al., 2020a, 2020b; Rosenberg et al., 2009; Sung & Lee, 2015). However, the one-class model does not fit the observations well as indicated by the low value of the adjusted McFadden Rho square (0.043). Compared with the one-class model, the four-class model shows an increase of the adjusted McFadden Rho square to 0.134. In the four-class model, the first class is labelled as *walking space oriented* (25.9%). This class considers more space for walking and presence of open spaces to be important for walkability. The second class is named *liveable space oriented* (47.8%). This group of individuals, in accordance to theories from empirical studies, considers a full range of attributes to be all relevant for walkability, i.e. residential land-use (not mixed with commercial), high connectivity, wide pedestrian road, presence of open space and greenness. The third class is labelled *open space oriented* (19.5%). The individuals in this class consider open space as the most important attribute for walkability followed by residential land-use. These findings are in line with many empirical studies which indicate

Table 4
The virtual design environments of street blocks.

Combination 1	Combination 2	Combination 3	Combination 4
			
• Residential land-use • High connectivity • Two lanes with narrow pedestrian zone • Has open space in the block • Has trees in the block	• Residential land-use • High connectivity • Two lanes with narrow pedestrian zone • Does not have open space in the block • Does not have trees in the block	• Residential land-use • Low connectivity • One lane with wide pedestrian • Has open space in the block • Does not have trees in the block	• Residential land-use • Low connectivity • One lane with wide pedestrian zone • Does not have open space in the block • Has trees in the block

Combination 5	Combination 6	Combination 7	Combination 8
			
• Mixed with commercial area • High connectivity • One lane with wide pedestrian zone • Has open space in the block • Does not have trees in the block	• Mixed with commercial area • High connectivity • One lane with wide pedestrian zone • Does not have open space in the block • Has trees in the block	• Mixed with commercial area • Low connectivity • Two lanes with narrow pedestrian zone • Has open space in the block • Has trees in the block	• Mixed with commercial area • Low connectivity • Two lanes with narrow pedestrian zone • Does not have open space in the block • Does not have trees in the block

Table 5
Questions and answers rating for the VR environment.

Questions	Likert scale (rat. 1–7)
Quality of the environment	
(1) How satisfied are you with the overall quality of this virtual environment?	Not at all satisfied (1)–fully satisfied (7)
(2) How satisfied are you with the walking friendliness of this virtual environment?	Not at all satisfied (1)–fully satisfied (7)
Emotions the virtual environments evoked	
(1) I felt happy	Completely disagree (1)–completely agree (7)
(2) I felt comfortable	Completely disagree (1)–completely agree (7)
(3) I felt annoyed	Completely disagree (1)–completely agree (7)
(4) I felt secure	Completely disagree (1)–completely agree (7)

Table 6
Socio-demographic characteristics of the respondents.

Variables	Levels	
Age (years)	/	43.64 (years)
Gender	Male	44.4%
	Female	55.6%
Education	Primary	2.70%
	Medium	45.1%
	High (BSc or higher)	52.2%
Work status	Full time work	39.7%
	Part-time work (high, 21–37 h)	22.7%
	Part time work (low, 1–21 h)	8.80%
	No paid work	28.8%
Travel time for work	Low commute time	46.8%
	Medium commute time	19.6%
	Long commute time	5.10%
	Others	28.5%
Gross income (per year)	Low income level	24.7%
	Middle income level	36.3%
	High income level	26.1%
	Others	12.9%
Ethnic background	Dutch	94.9%
	Non-Dutch	5.10%
Household type	Single	24.1%
	Couple without child(ren)	34.6%
	Parents	30.8%
	Others	10.5%
Dwelling type	Detached house	15.6%
	Semidetached or terraced house	54.3%
	Apartment	25.4%
	Others	4.70%
House owner situation	Own	66.8%
	Rent	33.2%
		***N* = 295 respondents**

that the perceived walkability was associated with residential density and open space (Bahrainy & Khosravi, 2013; Boakye-Dankwa et al., 2019; Hajna et al., 2015; Marquet & Miralles-Guasch, 2015). The fourth and last class is labelled *road size oriented* (6.8%). For this group, a wide pedestrian zone is important for walking friendliness. This finding is in line with Giles-Corti et al. (2005), Rastogi et al. (2011), and Yang et al. (2019), who found that wide pedestrian zone increased walking behaviour and walking time of people.

Table 9 shows the results of the estimation of the MNL model to predict class membership based on socio-demographic variables. The first class – Walking space oriented – is taken as the base category. Individuals of the *liveable space oriented* group are more likely to have high socioeconomic status because they are more likely to have middle or long commute time and high income, and they more often live in semi-detached or terraced houses and they are less likely to be immigration. The *open space oriented group* consists of individuals who are more likely to be female, more often have middle commute time, are more likely to live in semi-detached or terraced houses, and less likely to be parent. In addition, the *road size oriented* group has more wealthy people who more likely have high income and long commute time, and more likely live in detached, semi-detached or terraced houses. Since these three groups both include fewer middle income people and fewer homeowners, individuals of the *walking space oriented* group are more likely to be middle income people and homeowners. These findings are partly in line with Leslie et al. (2010) who pointed out that socioeconomic status was

Table 7
Statistics for latent class regression models (attributes). The significance of bold means the optimum number of classes with the lowest AIC and BIC values.

No. of class	Parameters	Log likelihood function	AIC	BIC
1	7	−2011.19	4036.37	4071.89
2	15	−1956.75	3943.49	4019.59
3	23	−1938.63	3923.25	4039.94
4	**31**	**−1931.31**	**3918.76**	**4076.89**
5	39	−1925.19	3928.38	4126.24

Note: AIC = Akaike information criterion; BIC = Bayesian information criterion.

associated with the perceived walkability.

4.2. Results of the relationship between the perceived walkability and emotions

In this section, we consider the results of the analysis regarding the relationship between perceived walkability and emotions evoked by the environment. Table 10 shows that the AIC and BIC values decrease when the number of classes increases from 1 to 3 classes and increase when the number of classes increases from 3 to 4 classes. Hence, the optimal number of classes is equal to 3 for this second regression model (walking friendliness regressed on emotions). In Table 11, the detailed estimation results of the three-class model. The table also shows the results of the one-class model for comparison. The one-class model indicates that all four emotions are significantly associated with walkability across all groups. The latent class model identifies three groups and shows an increase in adjusted McFadden Rho square from 0.204 to 0.271. The first class is labelled *happy feeling* (33.9%). This class associates walkability mainly with feelings of happiness. This finding is in line with Ettema and Smajic (2015) and Weijs-Perrée et al. (2020) who also found an association between sense of happiness and walking. Furthermore, feeling secure also plays a role in this group. The second class is labelled as *secure feeling* (44.3%). This group mainly associates walkability with feelings of security and secondly with comfort. The third class is named *comfortable feeling* (21.8%). This group associates walkability more strongly with feelings of comfort and less strongly with security. These findings are in line with Birenboim (2018) who found that the sense of security and comfort are significantly influenced by the walking environment. All in all, these results indicate that there is quite some heterogeneity on the level of affective experiences that individuals associate with walkability. Feeling secure and comfortable are common emotions shared by almost all groups. For a large segment of the people (approximately one-third) walkability in addition is related to feelings of happiness and reduces annoyance, whereas comfort does not play a role.

Table 12 shows the estimation results of the MNL model to predict class membership, the first class – *happy feeling* – is used as reference group in this model. Individuals of the *secure feeling* group are more likely to be high-earning workers due to the fact that they are more often highly educated, more likely to have middle and long commute time,

Table 9
Results of the MNL models (attributes).

	Liveable space oriented	Open space oriented	Road size oriented
	Coefficients	Coefficients	Coefficients
Age	0.021***		0.027**
Gender			
Female		0.337*	
Male (reference)			
Work status			
Part time work (low, 1–21 h)	−0.491**	−1.036***	
No paid work (reference)	/	/	/
Travel time for work			
Middle commute time	0.449**	0.563**	
Long commute time	0.875*		1.941***
Low commute time (reference)	/	/	/
Gross income (per year)			
Low income level	−0.705**		−2.226***
Middle income level	−1.032***	−1.137***	−2.800***
Others (I don't want to answer)	−0.867***	−1.415***	
High income level (reference)	/	/	/
Ethnic background			
Non-Dutch	−0.746**	−1.909***	
Dutch (reference)	/	/	/
Household type			
Parents		−0.722**	
Others (I don't want to answer)	0.705**		
Single (reference)	/	/	/
Dwelling type			
Detached house		−0.729**	1.880***
Semidetached or terraced house	0.636***	0.430*	2.263***
Others dwelling type	−1.160***	−0.951**	2.315***
Apartment (reference)	/	/	/
House owner situation			
Own house	−0.771***	−0.435*	−0.764**
Rent house (reference)	/		/

Note: ***, **, * ⟹ Significance at 1%, 5%, 10% level.

Table 10
Statistics for latent class regression models (emotions).

No. of class	Parameters	Log likelihood function	AIC	BIC
1	6	−2040.03	4084.06	4094.21
2	13	−1986.68	3983.37	4008.73
3	**20**	**−1962.88**	**3941.75**	**3982.34**
4	27	−1962.59	3947.19	4403.01

Note: AIC = Akaike information criterion; BIC = Bayesian information criterion.

Table 8
Results for latent class regression models (attributes).

	One-class model	Four latent classes model			
		Walking space oriented	Liveable space oriented	Open space oriented	Road size oriented
	Estimate	Estimate	Estimate	Estimate	Estimate
Residential land-use	0.466***	0.069	0.414***	0.182*	−0.125
High block connectivity	−0.103	0.104	0.233**	0.032	0.252
Two lanes with narrow pedestrian zone	−0.221**	−0.174**	−0.386***	−0.146	−0.566**
Has open space in the block	0.414***	0.171*	0.541***	0.549***	0.177
Has trees in the block	0.189**	0.084	0.259**	0.157	0.117
Share of the individuals	100%	25.9%	47.8%	19.5%	6.8%
McFadden's Rho-squared:	0.047	0.182			
Adjusted McFadden's Rho-squared	0.043	0.134			

Note: ***, **, * ⟹ Significance at 1%, 5%, 10% level.

Table 11
Results for latent class regression models (emotions).

	One-class model	Three latent classes model		
		Happy feeling	Secure feeling	Comfortable feeling
	Estimate	Estimate	Estimate	Estimate
I felt happy	0.075**	0.255***	−0.525	0.005
I felt comfortable	0.312***	0.079	0.271***	0.851***
I felt annoyed	−0.499***	−0.086***	−0.023	−0.002
I felt secure	0.358***	0.186**	0.567***	0.108***
Share of the individuals	100%	33.9%	44.3%	21.8%
McFadden's Rho-squared	0.207	0.281		
Adjusted McFadden's Rho-squared	0.204	0.271		

Note: ***, **, * ⟹ Significance at 1%, 5%, 10% level.

Table 12
Results of the MNL models (emotions).

	Secure feeling	Comfortable feeling
	Coefficients	Coefficients
Gender		
Female		0.692***
Male (reference)	/	/
Education		
High education	0.970**	
Primary education (reference)	/	/
Work status		
Full time work	−0.655***	−0.910***
No paid work (reference)	/	/
Travel time for work		
Middle commute time	0.731***	0.678***
Long commute time	0.996***	0.920***
Low commute time (reference)	/	/
Household type		
Couple without child(ren)		1.061***
Parents		0.762***
Others household type	−0.780***	1.203***
Single (reference)	/	/
Dwelling type		
Detached house	−1.126***	−1.304***
Semidetached or terraced house	−0.584***	−0.941***
Others dwelling type	−0.939***	−1.445***
Apartment (reference)	/	/
House owner situation		
Own house	0.359***	
Rent house (reference)	/	/

Note: ***, **, * ⟹ Significance at 1%, 5%, 10% level.

more likely to live in apartments, and more likely to own their dwelling. The *comfortable feeling* group individuals who are more likely to be female, more likely to have middle or long commute time, more likely to live in apartments, and less likely to be single. The *secure feeling* group and the *comfortable feeling* group are both more likely to have middle or long commute time workers, more likely to live in apartment, and less likely to be full time workers. This indicates that part-time workers, who spend more time in the commute and live in an apartment, more likely to associate walkability with feelings of security and comfort. We can derive, therefore, that individuals of the *happy feeling* group are more likely to be full-time workers, more likely to have low commute time, and less likely to live in an apartment.

All in all, differences in socio-demographic characteristics between emotion groups are very clear. The *happy feeling* group includes more full-time workers living close to their home. The *secure feeling* group contains more high-income workers with longer commute time and the *comfortable feeling* group includes more females and apartment residents.

5. Conclusion

In this study, we developed an experimental design (orthogonal design) with virtual reality environment to analyze how people perceive and experience walkability. In contrast to the traditional use of static presentations in a conjoint experiment, we used dynamic videos of virtual environments, which allowed respondents to virtually walk through and experience the hypothetical neighbourhoods with more spatial and social detail compared with traditional visualisations or texts. In the design of the experiment, we considered five attributes that are most commonly found to contribute to walking behaviour in previous studies. Our results confirmed findings from empirical studies that land use mix, connectivity, road size, open space, and green have an influence on individuals' perception of walkability. However, our findings also indicate substantial differences between groups. For approximately an equally sized group, walkability is determined by just the size of sidewalks and presence of open spaces, whereas land-use, connectivity and green are not considered relevant. The group differences are significantly related to socio-demographic characteristics. In other words, individuals with different socio-demographic characteristics perceive attributes differently for walkability. Therefore, it is useful and meaningful to provide different walkable designs for neighbourhoods with different socio-demographic compositions, at least in the Netherlands.

Regarding the relationship between perceived walkability and emotions the environment evokes, we find that perceived walkability is mainly associated with feelings of comfort and feelings of security. However, for a large segment of people walkability means more than just security and comfort. A large group also associates walkability with an increase in happiness and decrease of annoyance during walking. Also, on that level we find significant relationships between socio-demographic characteristics and group membership. So, individuals form different socio-demographic backgrounds experience different emotions in relation to walkability. For example, full-time workers working close to home are more likely to associate walkability with a happy feeling, whereas high-income workers working far from home associate it more often to a secure feeling. Across these dimensions women show a tendency to associate walkability more often to a comfortable feeling.

Although our study provides new insights into walkable neighbourhood design, it still has several limitations that could be addressed in future research. Firstly, our experiment used an online video representation, but immersive virtual reality technology (using the VR headset and equipment in the lab) could provide a more immersive and real environment for the respondents (van Vliet et al., 2021). Second, our video representation had a fixed route and viewing direction. A more realistic virtual environment would allow respondents to walk around and create a route by themselves. Therefore, to collect complementary data about perceptions and behaviour, it is interesting to repeat the experiment developed in this study using full-fledged VR equipment in the lab. This allows respondents to immerse themselves in the environment and walk more randomly and look around in the VR environment. Lastly, our experimental designs are based on the typical Dutch reality environments, and our respondents were also recruited from the Netherlands. Therefore, our findings are more useful and meaningful for the built environment under the Dutch context.

Despite these limitations, the present study has provided new insights and methods to interconnect theory and design practice and added to the growing experience in the use of VR in combination with conjoint experiment techniques to analyze spatial perceptions and behaviour. Our findings have provided insights into differences between groups in how people perceive the walking environment.

CRediT authorship contribution statement

Bojing Liao: Conceptualization, Methodology, Formal analysis, Writing – original draft. **Pauline E.W. van den Berg:**

Conceptualization, Methodology, Writing – review & editing, Supervision. **P.J.V. van Wesemael:** Writing – review & editing, Supervision. **Theo A. Arentze:** Conceptualization, Methodology, Writing – review & editing, Supervision.

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

Acknowledgements

This research was supported by the China Scholarship Council (China), grant number CSC 201807720070. We would like to thank the Chinese Scholarship Council for providing the funding for the Ph.D. study.

References

Abd-Alhamid, F., Kent, M., Bennett, C., Calautit, J., & Wu, Y. (2019). Developing an innovative method for visual perception evaluation in a physical-based virtual environment. *Building and Environment, 162*, Article 106278.

Adkins, A., Dill, J., Luhr, G., & Neal, M. (2012). Unpacking walkability: Testing the influence of urban design features on perceptions of walking environment attractiveness. *Journal of Urban Design, 17*(4), 499–510.

Atwa, S. M. H., Ibrahim, M. G., Saleh, A. M., & Murata, R. (2019). Development of sustainable landscape design guidelines for a green business park using virtual reality. *Sustainable Cities and Society, 48*, Article 101543.

Bahrainy, H., & Khosravi, H. (2013). The impact of urban design features and qualities on walkability and health in under-construction environments: The case of Hashtgerd New Town in Iran. *Cities, 31*, Article 101016. https://doi.org/10.1016/j.cities.2013.01.001

Birenboim, A. (2018). The influence of urban environments on our subjective momentary experiences. *Environment and Planning B: Urban Analytics and City Science, 45*(5), 915–932.

Birenboim, A., Dijst, M., Ettema, D., de Kruijf, J., de Leeuw, G., & Dogterom, N. (2019). The utilization of immersive virtual environments for the investigation of environmental preferences. *Landscape and Urban Planning, 189*(May), 129–138. https://doi.org/10.1016/j.landurbplan.2019.04.011

Bishop, I. D., Ye, W.-S., & Karadaglis, C. (2001). Experiential approaches to perception response in virtual worlds. *Landscape and Urban Planning, 54*(1–4), 117–125.

Bishop, I. D., & Rohrmann, B. (2003). Subjective responses to simulated and real environments: A comparison. *Landscape and Urban Planning, 65*(4), 261–277.

Boakye-Dankwa, E., Nathan, A., Barnett, A., Busija, L., Lee, R. S. Y., Pachana, N.Cerin, E., … (2019). Walking behaviour and patterns of perceived access to neighbourhood destinations in older adults from a low-density (Brisbane, Australia) and an ultra-dense city (Hong Kong, China). *Cities, 84*, 23–33.

Bochow, M., Taubenböck, H., Segl, K., & Kaufmann, H. (2010). An automated and adaptable approach for characterizing and partitioning cities into urban structure types. *International Geoscience and Remote Sensing Symposium, 2010*, 1796–1799. https://doi.org/10.1109/IGARSS.2010.5652972

Borst, H. C., Miedema, H. M. E., de Vries, S. I., Graham, J. M. A., & van Dongen, J. E. F. (2008). Relationships between street characteristics and perceived attractiveness for walking reported by elderly people. *Journal of Environmental Psychology, 28*(4), 353–361.

Brown, D. S., Finkelstein, E. A., Brown, D. R., Buchner, D. M., & Johnson, F. R. (2009). Estimating older adults' preferences for walking programs via conjoint analysis. *American Journal of Preventive Medicine, 36*(3), 201–207.e4. https://doi.org/10.1016/j.amepre.2008.10.014

Caulfield, B., Brick, E., & McCarthy, O. T. (2012). Determining bicycle infrastructure preferences–A case study of Dublin. *Transportation Research Part D: Transport and Environment, 17*(5), 413–417.

Cerin, E., Conway, T. L., Cain, K. L., Kerr, J., De Bourdeaudhuij, I., Owen, N.Sallis, J. F., … (2013). Sharing good NEWS across the world: Developing comparable scores across. *BMC Public Health, 13*, 309. https://doi.org/10.1186/1471-2458-13-309

Cerin, E., Macfarlane, D. J., Ko, H.-H., & Chan, K.-C. A. (2007). Measuring perceived neighbourhood walkability in Hong Kong. *Cities, 24*(3), 209–217.

Cerin, E., Saelens, B. E., Sallis, J. F., & Frank, L. D. (2006). Neighborhood environment walkability scale: Validity and development of a short form. *Medicine and Science in Sports and Exercise, 38*(9), 1682–1691. https://doi.org/10.1249/01.mss.0000227639.83607.4d

Cerin, E., Sit, C. H. P., Chin Cheung, M., Yin Ho, S., Lee, L., Chun, J., & Man Chan, W. (2010). Reliable and valid NEWS for Chinese seniors: Measuring perceived neighborhood attributes related to walking. *International Journal of Behavioral Nutrition and Physical Activity, 7*, 1–14. https://doi.org/10.1186/1479-5868-7-84

DeSarbo, W. S., & Cron, W. L. (1988). A maximum likelihood methodology for clusterwise linear regression. *Journal of Classification, 5*(2), 249–282.

Epic Games. (2019). *Unreal engine*.

Ettema, D., & Smajic, I. (2015). Walking, places and wellbeing. *The Geographical Journal, 181*(2), 102–109.

Farooq, B., Cherchi, E., & Sobhani, A. (2018). Virtual immersive reality for stated preference travel behavior experiments: A case study of autonomous vehicles on urban roads. *Transportation Research Record, 2672*(50), 35–45.

Foster, C., Hillsdon, M., & Thorogood, M. (2004). Environmental perceptions and walking in English adults. *Journal of Epidemiology & Community Health, 58*(11), 924–928.

Gao, T., Liang, H., Chen, Y., & Qiu, L. (2019). Comparisons of landscape preferences through three different perceptual approaches. *International Journal of Environmental Research and Public Health, 16*(23), 4754.

Giles-Corti, B., Broomhall, M. H., Knuiman, M., Collins, C., Douglas, K., Ng, K. Donovan, R. J., … (2005). Increasing walking: How important is distance to, attractiveness, and size of public open space? *American Journal of Preventive Medicine, 28*(2), 169–176.

Hagströmer, M., Oja, P., & Sjöström, M. (2006). The International Physical Activity Questionnaire (IPAQ): A study of concurrent and construct validity. *Public Health Nutrition, 9*(6), 755–762.

Hajna, S., Ross, N. A., Brazeau, A.-S., Bélisle, P., Joseph, L., & Dasgupta, K. (2015). Associations between neighbourhood walkability and daily steps in adults: A systematic review and meta-analysis. *BMC Public Health, 15*(768). https://doi.org/10.1186/s12889-015-2082-x (2015).

Harrison, R. A., Gemmell, I., & Heller, R. F. (2007). The population effect of crime and neighbourhood on physical activity: An analysis of 15 461 adults. *Journal of Epidemiology & Community Health, 61*(1), 34–39.

Hensher, D. A., Rose, J. M., & Greene, W. H. (2005). *Applied choice analysis: A primer*. Cambridge University Press.

Higuera-Trujillo, J. L., Maldonado, J. L.-T., & Millán, C. L. (2017). Psychological and physiological human responses to simulated and real environments: A comparison between Photographs, 360 Panoramas, and Virtual Reality. *Applied Ergonomics, 65*, 398–409.

Inoue, S., Murase, N., Shimomitsu, T., Ohya, Y., Odagiri, Y., Takamiya, T.Sallis, J. F., … (2009). Association of physical activity and neighborhood environment among Japanese adults. *Preventive Medicine, 48*(4), 321–325. https://doi.org/10.1016/j.ypmed.2009.01.014

Kaparias, I., Bell, M. G. H., Miri, A., Chan, C., & Mount, B. (2012). Analysing the perceptions of pedestrians and drivers to shared space. *Transportation Research Part F: Traffic Psychology and Behaviour, 15*(3), 297–310.

Kasraian, D., Adhikari, S., Kossowsky, D., Luubert, M., Hall, B.Hawkins, J., … (2020). Evaluating walkable streets with a 3D stated preference survey. In *99th Annual Meeting of the Transportation Research Board*.

Kasraian, D., Adhikari, S., Kossowsky, D., Luubert, M., Hall, B., Hawkins, J.Roorda, M. J., … (2020). Evaluating pedestrian perceptions of street design with a 3D stated preference survey. *Environment and Planning B: Urban Analytics and City Science, 48*(7), 1787–1805.

Kelly, C. E., Tight, M. R., Hodgson, F. C., & Page, M. W. (2011). A comparison of three methods for assessing the walkability of the pedestrian environment. *Journal of Transport Geography, 19*(6), 1500–1508.

Kim, S., Choi, J., & Kim, Y. (2011). Determining the sidewalk pavement width by using pedestrian discomfort levels and movement characteristics. *KSCE Journal of Civil Engineering, 15*(5), 883.

Kort, Y. A. W.d., Ijsselsteijn, W. A., Kooijman, J., & Schuurmans, Y. (2003). Virtual laboratories: Comparability of real and virtual environments for environmental psychology. *Presence: Teleoperators & Virtual Environments, 12*(4), 360–373.

Koschinsky, J., & Talen, E. (2015). Affordable housing and walkable neighborhoods: A national urban analysis. *Cityscape, 17*(2), 13–56.

Koschinsky, J., Talen, E., Alfonzo, M., & Lee, S. (2017). How walkable is Walker's paradise? *Environment and Planning B: Urban Analytics and City Science, 44*(2), 343–363.

Leisch, F. (2004). Flexmix: A general framework for finite mixture models and latent glass regression in R. *Journal of Statistical Software, 11*(8), 1–18. https://doi.org/10.18637/jss.v011.i08

Leslie, E., Cerin, E., & Kremer, P. (2010). Perceived neighborhood environment and park use as mediators of the effect of area socio-economic status on walking behaviors. *Journal of Physical Activity and Health, 7*(6), 802–810.

Liao, B., Berg, P. E. W.v.d., Wesemael, P. J. V.v., & Arentze, T. A. (2020). How does walkability change behavior? A comparison between different age groups in the Netherlands. *International Journal of Environmental Research and Public Health, 17*(2), 54. https://doi.org/10.3390/ijerph17020540, 2020.

Liao, B., van den Berg, P. E. W., van Wesemael, P. J. V., & Arentze, T. A. (2020b). Empirical analysis of walkability using data from the Netherlands. *Transportation Research Part D, 85*, Article 102390. https://doi.org/10.1016/j.trd.2020.102390

Lusk, A. C., da Silva Filho, D. F., & Dobbert, L. (2018). Pedestrian and cyclist preferences for tree locations by sidewalks and cycle tracks and associated benefits: Worldwide implications from a study in Boston, MA. *Cities, 106*, 1–9.

Maffei, L., Masullo, M., Pascale, A., Ruggiero, G., & Romero, V. P. (2016). Immersive virtual reality in community planning: Acoustic and visual congruence of simulated vs real world. *Sustainable Cities and Society, 27*, 338–345.

Marquet, O., & Miralles-Guasch, C. (2015). The walkable city and the importance of the proximity environments for Barcelona's everyday mobility. *Cities, 42*, 258–266.

McFadden, D. (1973). *Conditional logit analysis of qualitative choice behavior*.

Meusel, D., Ruiz, J. R., Ortega, F. B., Hägströmer, M., Bergman, P., & Sjöström, M. (2007). Assessing levels of physical activity in the European population–the ALPHA project. *Selección, 16*(1), 9–12.

Paunović, K., Jakovljević, B., & Belojević, G. (2009). Predictors of noise annoyance in noisy and quiet urban streets. *Science of the Total Environment, 407*(12), 3707–3711.

Perdomo, M., Rezaei, A., Patterson, Z., Saunier, N., & Miranda-Moreno, L. F. (2014). Pedestrian preferences with respect to roundabouts—A video-based stated preference survey. *Accident Analysis & Prevention, 70*, 84–91.
Rastogi, R., Thaniarasu, I., & Chandra, S. (2011). Design implications of walking speed for pedestrian facilities. *Journal of Transportation Engineering, 137*(10), 687–696.
Resch, B., Puetz, I., Bluemke, M., Kyriakou, K., & Miksch, J. (2020). An interdisciplinary mixed-methods approach to analyzing urban spaces: The case of urban walkability and bikeability. *International Journal of Environmental Research and Public Health, 17*(19), 6994.
Rid, W., Haider, W., Ryffel, A., & Beardmore, A. B. (2018). Visualisations in choice experiments: Comparing 3D film-sequences and still-images to analyse housing development alternatives. *Ecological Economics, 146*(October 2017), 203–217. https://doi.org/10.1016/j.ecolecon.2017.10.019
Rosenberg, D., Ding, D., Sallis, J. F., Kerr, J., Norman, G. J., Durant, N.Saelens, B. E., … (2009). Neighborhood Environment Walkability Scale for Youth (NEWS-Y): Reliability and relationship with physical activity. *Preventive Medicine, 49*(2–3), 213–218. https://doi.org/10.1016/j.ypmed.2009.07.011
Sallis, J. F. (2009). Measuring physical activity environments. A brief history. *American Journal of Preventive Medicine, 36*(4 SUPPL.). https://doi.org/10.1016/j.amepre.2009.01.002
Shr, Y. H.(. J.)., Ready, R., Orland, B., & Echols, S. (2019). How do visual representations influence survey responses? Evidence from a choice experiment on landscape attributes of green infrastructure. *Ecological Economics, 156*(February 2018), 375–386. https://doi.org/10.1016/j.ecolecon.2018.10.015
Spittaels, H., Foster, C., Oppert, J. M., Rutter, H., Oja, P., Sjöström, M., & De Bourdeaudhuij, I. (2009). Assessment of environmental correlates of physical activity: Development of a European questionnaire. *International Journal of Behavioral Nutrition and Physical Activity, 6*. https://doi.org/10.1186/1479-5868-6-39
Spittaels, H., Verloigne, M., Gidlow, C., Gloanec, J., Titze, S., Foster, C.De Bourdeaudhuij, I., … (2010). Measuring physical activity-related environmental factors: Reliability and predictive validity of the European environmental questionnaire ALPHA. *International Journal of Behavioral Nutrition and Physical Activity, 7*. https://doi.org/10.1186/1479-5868-7-48
Sung, H., & Lee, S. (2015). Residential built environment and walking activity: Empirical evidence of Jane Jacobs' urban vitality. *Transportation Research Part D: Transport and Environment, 41*, 318–329.
Talen, E., & Koschinsky, J. (2013). The walkable neighborhood: A literature review. *International Journal of Sustainable Land Use and Urban Planning, 1*, 42–63.
Tilt, J. H. (2010). Walking trips to parks: Exploring demographic, environmental factors, and preferences for adults with children in the household. *Preventive Medicine, 50* (SUPPL.), S69–S73. https://doi.org/10.1016/j.ypmed.2009.07.026
Ulrich, R. S., Simons, R. F., Losito, B. D., Fiorito, E., Miles, M. A., & Zelson, M. (1991). Stress recovery during exposure to natural and urban environments. *Journal of Environmental Psychology, 11*(3), 201–230.
van Vliet, E., Dane, G., Weijs-Perrée, M., van Leeuwen, E., van Dinter, M., van den Berg, P.Chamilothori, K., … (2021). The influence of urban park attributes on user preferences: Evaluation of virtual parks in an online stated-choice experiment. *International Journal of Environmental Research and Public Health, 18*(1), 212.
Verhoeven, H., Ghekiere, A., Van Cauwenberg, J., Van Dyck, D., De Bourdeaudhuij, I., Clarys, P., & Deforche, B. (2017). Which physical and social environmental factors are most important for adolescents' cycling for transport? An experimental study using manipulated photographs. *International Journal of Behavioral Nutrition and Physical Activity, 14*(1), 108.
Wallmann, B., Bucksch, J., & Froboese, I. (2012). The association between physical activity and perceived environment in German adults. *European Journal of Public Health, 22*(4), 502–508. https://doi.org/10.1093/eurpub/ckr069
Wang, H., & Yang, Y. (2019). Neighbourhood walkability: A review and bibliometric analysis. *Cities, 93*(April), 43–61. https://doi.org/10.1016/j.cities.2019.04.015
Weijs-Perrée, M., Dane, G., & van den Berg, P. (2020). Analyzing the relationships between citizens' emotions and their momentary satisfaction in urban public spaces. *Sustainability, 12*(19), 7921.
Yang, Y., He, D., Gou, Z., Wang, R., Liu, Y., & Lu, Y. (2019). Association between street greenery and walking behavior in older adults in Hong Kong. *Sustainable Cities and Society, 51*, Article 101747.
Zhu, W., Guo, S., & Zhao, J. (2020). Planning participants' preferential differences under immersive virtual reality and conventional representations: An experiment of street renewal. *Environment and Planning B: Urban Analytics and City Science, 48*(7), 1755–1769, 2399808320942776.