What Will Virtual Reality Bring to the Qualification of Visual Walkability in Cities?

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Abstract: Walking as a daily activity has become increasingly popular in recent years. It is not only good for people's health, but it also helps reduce the air pollution and other nuisances associated with vehicle use. As such, we have witnessed the shift in urban design towards a pedestrian-friendly city. While walkability is a broad concept consisting of many different aspects, our work focuses on only one part of it, namely "visual walkability". While standard research on visual walkability tends to conduct field experiments to collect data, we present a novel method to qualify visual walkability, namely assessment in virtual reality with omnidirectional videos. We analyze the possible questions we would encounter and propose an experiment with answers for each question.

1 INTRODUCTION

People should walk every day, whether from home to work or just for leisure, as this is the easiest way to exercise with minimal side effects for physical and mental health (Morris and Hardman, 1997; White et al., 2019). It is recommended that a healthy adult should take about 7500 steps per day or at least 15000 steps of intense physical activity per week to stay healthy (Tudor-Locke et al., 2011).

Therefore, modern urban planning strategies tend to encourage people to walk more every day (Boarnet et al., 2008; Giles-Corti et al., 2013; Johansson et al., 2016). This led to the concept of a walkable environment or walkability. According to Dovey (Dovey and Pafka, 2020), walkability is a multi-disciplinary field connected with public health, climate change, economic productivity and social equity. Talen (Talen and Koschinsky, 2013) defined a "walkable neighborhood" as a safe and well-serviced neighborhood that is equipped with qualities that make walking a positive experience. This is also the concept of WalkScore® (Duncan et al., 2011), which assigns a score for walkability based on distance to a variety of nearby commercial and public, frequently visited amenities.

Usual walkability research has used field experiments to collect data such as Pak (Pak and Agukrikul, 2017) or Raswol (Raswol, 2020), which is time-consuming and difficult to reproduce, and always involves many experts who give professional scores like Ewing (Ewing and Handy, 2009) or Kim (Kim and Lee, 2022), who cannot be easily recruited on a large scale. Thus, the results may not be suitable for classic "non-expert" pedestrians.

Street view imagery (SVI) is becoming easily accessible via different providers (Google street View, Tencent, Baidu, etc.), datasets such as Place Pulse 2.0 (Dubey et al., 2016) have provided examples of evaluating qualitative perceptions by training Convolutional Neural Network (CNN) with Street View images. Also, vision is our predominant sense (Stokes and Biggs, 2014; Hutmacher, 2019), which makes visual information an important part of walkability, this research focuses on "Visual Walkability". As a first approach, and before developing the concept in the next section on the basis of a definition taken from the state of the art, we define "Visual Walkability" as perceived walkability that depends on criteria which can be recognized by sight in the urban space by pedestrians. The first impression influences our decision whether to take this path or the duration and pleasantness of a walk. Some of the qualitative aspects of walkability, such as cleanliness, density, even safety, etc., can be measured quantitatively through the visual perception of pedestrians.

The objective of this work is to find out which visual elements influence pedestrians' perception of walkability in the urban environment, with the help of virtual reality (VR). This leads to our research ques-

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tions:

RQ1: Can visual walkability in the real world be preserved in virtual reality?

RQ2: Which parameters influence visual walkability in virtual urban space during daytime?

The emphasis in these questions are on the words “Virtual Reality”, “visual”, “urban” and “daytime”. We will only examine the visual impact on pedestrians in an urban environment during the daytime without considering in this work the changes in perception that would be induced by night-time perception. By examining visual walkability in virtual reality, we assume that we will eventually be able to better understand how pedestrians perceive the environment and simplify the walkability evaluation procedure with VR.

2 STATE OF THE ART

Nowadays there are not many studies that deal with visual walkability. Zhou (Zhou et al., 2019) defined it as a subjective concept that describes the environmental qualities that influence an individual’s perception of the environment as a place to walk. Li (Li et al., 2020) divided the walkability of streets into physical and perceived walkability and further investigated it in terms of visual walkability (Li et al., 2022). We have found that there is too little work in the field of visual walkability, so we are pursuing a further study on this topic.

2.1 Visual Walkability

The term Walkability is a very general word, consisting of many different subjects. For example, 51 perceptual qualities associated with walkability were mentioned based on Ewing (Ewing and Handy, 2009), and nine of them are commonly used based on the importance assigned to them in the literature: imageability, enclosure, human scale, transparency, complexity, legibility, linkage, coherence, and tidiness. Thus, walkability is often defined in terms of multi-sensory perception.

Since we want to go further with visual walkability, the elements that visually influence our perception of walkability are important to us. In the Table 1, we summarize the indicators and the methods that some of the previous research has used to calculate visual walkability.

Most of the research has used pictures to represent the environment thanks to the development of SVI, little has applied videos as instrument. Kim (Kim and Lee, 2022) and Nakamura (Nakamura, 2021) have used panoramic videos, but they did not justify their choices for video duration. We have also seen several studies in Table 2 that applied VR, but few of them have added virtual locomotion, which is an important factor for immersive experience, especially when evaluating walkability.

Furthermore, a large part of the research studying visual walkability has simply counted pixels in images (Ma et al., 2021; Zhou et al., 2019; Xu et al., 2022), as we list in Table 1, the validity of the analysis of relationships between each visual element remains doubtful. Although Li (Li et al., 2022) has employed a machine learning algorithm to uncover hidden information in these elements, not all of them have been validated.

2.2 Virtual Experiences

With the development of technology, the use of virtual audits instead of on-site experience has recently become more popular in the study of urban design quality. In Table 2 we summarize the most recent studies on the use of VR technology in the field of walkability. As far as we could find, the oldest article on this topic is only from 2019.

2.2.1 Virtual Reality

There are two main types of VR used in the field of walkability, computer-generated VR (CGVR) and Cinematic VR (CVR) (Kim and Lee, 2022). CGVR uses 3D models in computer software such as the Unity or Unreal Engine, to generate a virtual environment (VE) for players so that people can move freely and without restrictions in the VE. This is ideal for studying walkability. However, depending on the quality of the model, CGVR can be less realistic and/or time-consuming for modeling.

On the other hand, the CVR uses a camera to record an omnidirectional (360°) video and then present it in a Head-Mounted Display (HMD). Although we cannot choose the route in the videos but only follow a predefined route, the realism of the scene and the time required to produce the content is an advantage.

Both CGVR and CVR are better than a field experiment in terms of reproducibility, variable controls and efficiency. We can present the same material to each participant to ensure that they can have an identical experience regardless of weather, traffic, etc., without having to wait for consistent field conditions.

Table 1: Chosen indicators in state of the art articles.

References	Items	Calculation
(Zhou et al., 2019)	Building, road, sideways, vehicle, pole, tree, street greenery, sideway crowdedness, enclosure, promotion of road and pavement	Pixel ratios
(Ma et al., 2021)	Bicyclist, building, car, fence, pavement, pedestrian, pole, road, road mark, sign symbol, sky, tree	Pixel ratios
(Li et al., 2022)	Vegetation, Sidewalk, terrain, road, people, bike, truck, sky, pole, fence	Pairwise MLR
(Xu et al., 2022)	Sky, tree, building, car, road, wall, plant, grass, fence, earth, person, sidewalk, signboard, truck, bicycle	Pixel ratios
(Zhang et al., 2022)	Skyview factor, green look ratio, building ratio, motorway proportion, walkway width	Not explained

Pixel ratio: The number of pixels of an object to the total number of pixels in the image
MLR: Multiple Linear Regression model

Table 2: Methods applied in articles.

Article	Image		Video		VE	HMD	Eye-tracking	Locomotion
	Classic	360	Classic	360				
(Zhou et al., 2019)	*							
(Nagata et al., 2020)	*							
(Birenboim et al., 2021)					*	*	*	*
(Nakamura, 2021)			*	*		*		
(Zhang and Zhang, 2021)		*				*	*	
(Hollander et al., 2022)	*						*	
(Kim and Lee, 2022)				*		*		
(Li et al., 2022)		*				*		
(Liao et al., 2022)				*	*	-		
(Silvennoinen et al., 2022)					*	*		
(Jeon and Woo, 2023)		*						

* : Applied - : Not mentioned
VE : Virtual Environment HMD : Head-Mounted Display Locomotion: Movement in VR

2.2.2 Eye Tracking

Eye tracking, as the name suggests, tracks pupil movements and then calculates the point of gaze for two eyes. We have seen applications in psychology, computer science and many other fields (Carter and Luke, 2020). There are well-known manufacturers such as Tobii[1], SR Research[2], etc. as well as some open-source webcam-based eye tracking solutions (Papoutsaki et al., 2017; Dalmaijer et al., 2014). These solutions can be divided into real-life eye tracking, on-screen eye tracking and VR eye tracking.

However, there are not many studies that apply eye tracking to walkability. Birenboim (Birenboim et al., 2021) used eye tracking to calculate participants' gaze duration on a parked car in VE, and Zhang (Zhang and Zhang, 2021) used it to study architectural cityscape elements.

2.2.3 Virtual Locomotion

Locomotion in a virtual environment influences users' immersive experience. According to Martinez (Martinez et al., 2022), there exists five categories of locomotion techniques in VR:

- Walking-based: we use real walk (either on a treadmill) / redirected walk[3] (Razzaque et al., 2001) or walk-related behaviors like swing arms or walk-in-place[4] (Boletsis, 2017) to simulate locomotion in VE.
- Steering-based: we use our body part (head, hand, etc.) or joystick / mouse to direct the locomotion.

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[1] Tobii© 2023, https://www.tobii.com (accessed in February 2024).

[2] SR Research Ltd.© 2024, https://www.sr-research.com (accessed in February 2024).

[3] Remapping between real world and virtual environment, change people's real walking direction without they noticing it.

[4] Participant performs step-like movement while remaining stationary

- Selection-based: we choose our desired location in VE, then go there by teleport or virtual movement.
- Manipulation-based: we can drag the camera or the world (either in miniature) directly by hand in VE.
- Automated: the VE controls our locomotion and movement.

Among these methods, walk-in-place is moderately explored and has a relatively high immersion capability compared to other techniques (Boletsis and Cedergren, 2019).

3 EXPERIMENTAL DESIGN QUESTIONS

The aim of this section is not to explain in detail the practical conditions for conducting the experiment (e.g. how to incentivize the participants), but rather to list all the methodological questions that arise in the preparation phase. Here are the twelve methodological questions (MQ) we have identified:

MQ.1 Should the experiment be carried out in static or dynamic form? That is, will we use a static or a dynamic medium for this experiment? Static images are easier to capture using cameras or Street View Image providers, whereas dynamic images can create a more realistic environment and show the influence of moving objects.

MQ.2 What motivation do we give to the participants? Different travel motivations can lead to different walkability perception and route choices. Therefore, we need to specify the situation for the participants, whether they were traveling for recreation or commuting.

MQ.3 How much freedom do we give the participants during the experiment? This question refers to whether the participants can move freely in the VR. A greater degree of freedom can increase the level of immersion and reduce the effects of cybersickness, but leads to a less controlled experimental environment.

MQ.4 What kind of road do we present to the participants? Should it be a straight road or a winding road? Because the sinuosity of the road can also influence the walkability (Salazar Miranda et al., 2021).

MQ.5 How should we control for uniformity in experiment? The question is therefore to know what degree of similarity we consider acceptable in order to be able to compare two walking experiences.

MQ.6 What kind of VR should we use? As described in the Section 2.2.1, both CGVR and CVR have their advantages and disadvantages. This choice also depends on the answers of other MQ and constraints of implementation.

MQ.7 How long should we expose participants to VR? We need to strike a balance between allowing enough time to assess visual walkability and avoiding too much strain, as former studies performed by Nakamura (Nakamura, 2021) or Liao (Liao et al., 2022) did not justify their choice for duration.

MQ.8 Which variables should we study in our experiment? One advantage of using VR is that we can control the environment and therefore the variables we want to analyze. However, we cannot evaluate all elements at the same time, but need to define some of the most important ones and their relationship in the environment, such as some commonly mentioned Green View Index (GVI) or Sky-view Factor (SVF).

MQ.9 How will participant interact with VR? To enhance the sense of presence in VR, we need a proper interaction with it, like locomotion, interaction with the environment, etc.

MQ.10 What should we measure, and how, during the experiment? Since we want to study the influence on human perception, we would need both objective and subjective data from our experiments. Thus participants' subconscious reaction can be helpful when analyzing results.

MQ.11 Which questionnaire should we use? Both for the evaluation of the VR experience and for walkability.

MQ.12 How do we deal with other sensory perceptions? Like the acoustic or tactile perception of the surroundings.

4 METHODOLOGY

4.1 Experimental Protocols

Since the word "Walkability" contains the term "Walk", which is a dynamic action, we think that a dynamic medium is more suitable for the evaluation of walkability (answer to MQ.1). After reviewing the literature and the questions we came up with above, we decided to implement our experiment with omnidirectional videos (MQ.6) to create a more realistic and immersive virtual environment and ask participants to rate the walkability. This assessment will be subject to conditions. The participant will not have to imagine themselves as a passerby in a drifting situation (a leisurely walk with no time or specific goal), but rather as a daily commuter, such as the journey between home and work (MQ.2).

Since the quality of the 3D model has a great impact on the sense of presence in VR, which requires detailed modeling, an omnidirectional video seems to be a better choice (MQ.6). Under these circumstances, we will not give participants the freedom to move around in VR, but make them follow the route we filmed (MQ.3), which consists of several straight streets in different urban environments (MQ.4). We will still conserve the environmental sound in the videos, only for creating an immersive environment, but we will not take into account acoustic influence, since our study concentrate on visual elements (MQ.12). With a focus on visual elements and the sense of sight, we will ensure that the sense of hearing is not prominently engaged (i.e., we will make sure that no sound signals emerge from the background noise of the city in our videos, contrary to what one might expect in such a location).

First, we define our experimental field. We have a considerable number of variables to control, which makes it difficult to find the locations. The seasonal and climatic variables can be controlled by filming at the same location at different times of the year. Different times of day for traffic, etc (MQ.5). The goal is to have as little variation as possible in two videos. It may be impossible to have only one changing element in the videos, so we may also need to consider a combination of analyzable factors.

Then, we will define a measuring method for each potential element and sort them out from our videos. We can begin with calculating pixel ratio for each element, and creating an evaluation table with two levels according to Stated Preference method (Huang et al., 2022) as Table 3 (MQ.8).

Table 3: Element Evaluation Table example.

Element	Video 1	Video 2	Video 3	...
Vegetation	Low	Low	High	
Pedestrian	High	High	Low	
Building	High	Low	High	
Sky	Low	High	Low	
...				

Next, we would have to design questionnaires for the participants. To meet ethical standards for human subject experiments and to compare the results with both objective and subjective data, the questionnaire would include feelings and satisfaction with the VR experience as well as walkability ratings, e.g. elements that increase or decrease walkability (MQ.11).

We will invite non-expert volunteers, balanced by gender and age, so that they are best suited for our purpose of evaluating the walkability of a common everyday path. We will first do a simple demonstration of our experiment and explain to them how the system works and what they will see. But we will not tell our participants what we are actually measuring. Then we will ask them to rate the walkability in real time with a joystick and then fill in our questionnaire. The number of participants depends on the number of variables we will measure, and we expect 20 to 30 participants per variable. Because we didn't find enough evidence to define video duration (MQ.7) and interaction method (MQ.9) in our literature review, we need to perform preliminary experiments to answer these questions in section 4.4.

During the experiment, we will be collecting the visual attention (eye-tracking) data and participants' real-time evaluation, as well as their blink rate and walking speed / step frequency (MQ.10).

After each experiment, we will analyze the result with all the data collected. First, we output a video with each participant's visual attention data. Then generate a heatmap of visual attention, along with a real-time evaluation slider on the side. Using deep learning image segmentation technology, we can automatically obtain the result of objective data (Chen and Biljecki, 2023).

When we will have completed the experiment, we can obtain our conclusion on elements that influence visual walkability in VR, and compare with the results provided by previous studies in Section 2 and in Table 1.

4.2 Data Collection

4.2.1 Questionnaire Survey

First, because this is a VR experiment, we need a standard VR questionnaire to determine the level of immersion (Makransky et al., 2017) and cybersickness (Kim et al., 2018) of the procedure. Then, as mentioned in the experimental protocol, we need to collect the data from walkability questionnaires. We will also practice a commented city walk (Thibaud, 2013) in VR to collect the real-time reaction of the participants (MQ.11).

4.2.2 Gaze Point

In addition to the questionnaires, the most important result of our experiment will be the data on the participants' visual attention. In the end, we would like to create a heat map of visual attention to analyze it. However, since we are using videos, the format of this heatmap may differ from the normal heatmaps on photos, which may require a new way of presentation.

4.2.3 Blink Rate

As mentioned by Batistatou (Batistatou et al., 2022), people's blink rate can reflect their level of mental stress, as the longer duration of gaze fixation can represent an interesting/meaningful/threatening element. They assume that blink rate will be lower in a mineral urban environment (made of concrete) than in a green environment (full of vegetation). This subconscious action can also provide us with information for analyzing walkability.

4.2.4 Walking Speed

According to Franek (Franěk, 2013), people's walking speed is linked to environmental factors. And Silvennoinen (Silvennoinen et al., 2022) believes that in more walkable areas, people are willing to walk at a slower pace. We will measure participants (mean) walking speed during the experiences as a factor for analyzing walkability.

4.2.5 Real-Time Evaluation

During the video, we will set a slider controlled by a joystick to allow participants to evaluate immediate walkability. We hypothesize that this method could reflect the influence of moving objects, such as the speed of vehicles and the movement of crowds. This is our contribution to walkability research, as we are the first to introduce this method. However, the accuracy of this method has yet to be tested, as holding a controller in your hand can affect the feeling of immersion. We will also test this method in our experiment, both for its validity and for its influence on immersion.

4.3 Equipment Setups

For video filming, we choose Insta360[5] Pro 2 to perform the task. It can take up to 8k (7680 × 7680) resolution HDR (High Dynamic Range) videos at 30 fps (frame per second), 6k videos at 60 fps, or 4k videos at 120 fps, all formats support stereoscopic output, which means that it could generate different contents for two eyes. This feature can provide depth information, creating a more realistic omnidirectional video. It also has four embedded microphones to record sound from every direction. In simple, this camera can film 3D 360 videos with high-quality sound.

As for the choice of HMD, we don't have many choices, because we need a HMD with eye tracker. We have tested Vive[6] Focus 3 with eye-tracker attachment. This HMD has a resolution of 2448×2448 per eye, 90 Hz refresh rate, and 120° of FOV (Field of View). The eye tracker has 120 Hz frequency, and $0.5^\circ \sim 1.1^\circ$ accuracy. But with the eye-tracker attachment, the FOV is visibly reduced, and its lens technology, Fresnel lens, makes it heavy and thick. We have also tested Meta[7] Quest Pro, which has a resolution of 1800×1920 per eye, 90 Hz refresh rate, and 106° of FOV. Even though the latter has a lower resolution, these two HMDs have a similar PPD (Pixel Per Degree). But Meta Quest Pro used "Pancake" lens technology, which makes it lighter, thinner, and also clearer. So we decide to use Meta Quest Pro for our experiment.

In order to retrieve eye-tracking data and apply interactions with our videos, we use Unity software as graphic engine to create our virtual environment.

4.4 Preliminary Experiments

We started our experiment with some preliminary tests to define the details of the experiment. We now have eight recordings that we can show in the Unity software with the basic user interface and interactions.

We showed these videos to seven participants who are experts and students in the field of urban design, and told them to stop playing each video when they felt it was sufficient for the walkability assessment to determine the duration of the videos in the formal experiments. We took the average duration of 60 seconds as the standard time for experiments (MQ.7).

Six of the seven participants did not report an obvious feeling of cybersickness while standing up for the tests. Only one participant had an uncomfortable sensation in the HMD while standing, and this sensation decreased when she was sitting. We decided to continue these experiments while standing using the walk-in-place method (MQ.9).

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[5] Insta360© 2024, https://www.insta360.com (accessed in February 2024).

[6] HTC Corporation© 2011-2024, https://www.vive.com (accessed in February 2024).

[7] Meta© 2024, https://www.meta.com (accessed in February 2024).

5 CONCLUSION

In this article, we present a novel method for investigating this rarely focused part of walkability, the Visual Walkability, by combining it with virtual reality. According to the two research questions that we proposed, we have raised twelve questions that we might encounter while conducting the experiment. For ten of these twelve questions, we have found answers in the state of the art, while for the last two, we had to carry out preliminary experiments to guide our choice of experiment design. We hope that after completing this work, we can obtain a new and efficient workflow for evaluating visual walkability and thus facilitate future urban design towards a more walkable city.

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