Urban Forestry & Urban Greening 76 (2022) 127712

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

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

Original article

Auditing an urban park deck with 3D geovisualization—A comparison of in-situ and VR walk-along interviews

Kaisa Jaalama[a,1,*], Toni Rantanen[a,2], Arttu Julin[a,3], Nora Fagerholm[b,4], Aino Keitaanniemi[a,5], Juho-Pekka Virtanen[c,d,6], Hannu Handolin[a,c], Matti Vaaja[a,7], Hannu Hyyppä[a,c,8]

[a] *Department of Built Environment, Aalto University School of Engineering, P.O. Box 14100, FI-00076 Aalto, Finland*
[b] *Department of Geography and Geology, University of Turku, 20014 Turku, Finland*
[c] *Finnish Geospatial Research Institute FGI, Geodeetinrinne 2, FI-02430 Masala, Finland*
[d] *Forum Virium Helsinki Oy, Unioninkatu 24, FI-00130 Helsinki, Finland*

A R T I C L E I N F O

Handling Editor: Tenley Conway

Keywords:
Green space
3D city model
Urban planning
Digital twin
Perception
Virtual reality

A B S T R A C T

Virtual reality-based urban audit methods are gaining increasing attention; however, most virtual urban audit studies have focused on panoramic views. The 3D city model-based geovisualizations have remained until now rather unexplored in user studies for urban audits and for communicative urban planning. We explored the feasibility of a 3D geovisualization-based urban audit in virtual reality (VR) for assessing the perceived quality of an urban park deck in Helsinki, Finland. For this purpose, we created a photorealistic and geometrically accurate 3D model (Bryga 3D) based on photogrammetric and laser scanning data. Bryga 3D was implemented on a game engine to be viewed with a head-mounted VR display. Bryga 3D's ability to convey information in a subjective urban audit, that is, subjectively perceived affordances of a park deck, was tested in a walk-along interview study comparing auditing in situ and via the VR method. A comparison of the results with in-situ (n = 13) and VR interviews (n = 21) show that the perception of several tangible elements, such as spatial division, landforms, paths, and chairs when using Bryga VR was similar to when performed in situ. Perception of vegetation was weaker in VR in terms of its detailed quality, which somewhat affected the presented development ideas and assessment of the seasonal context. Also, weaker perception of the surroundings and city context affected the results in VR. However, considering that Bryga 3D presents an example of a highly automated 3D city modeling process conducted with minimal manual work, its results are encouraging for future attempts to advance such realizations for the purposes of communicative urban planning. 3D geovisualization-based virtual audits could be used when urban green space audits are not possible or when they are demanding to implement in situ.

1. Introduction

1.1. 3D geovisualizations and assessment of urban green spaces

The potential of 3D geovisualizations for a variety of land use and planning assessments has been increasingly addressed in academic research (e.g., Willenborg et al., 2018, Onyimbi et al., 2018). While 3D geovisualization is a broad concept and includes a variety of three-dimensional geospatial data visualizations (Hildebrandt and Döllner 2010, Bleisch, 2012, Neuville, 2020), 3D city models aim to serve as public scalable multipurpose platforms (Döllner et al., 2006, Biljecki et al., 2015, Julin et al., 2018). 3D city models usually refer to

* Corresponding author.
E-mail address: kaisa.jaalama@aalto.fi (K. Jaalama).
[1] ORCID: https://orcid.org/0000-0002-0377-8497
[2] ORCID: https://orcid.org/0000-0002-3781-7204
[3] ORCID: https://orcid.org/0000-0001-9887-1573
[4] ORCID: https://orcid.org/0000-0001-5020-0746
[5] ORCID: https://orcid.org/0000-0002-1351-5906
[6] ORCID: https://orcid.org/0000-0003-0281-9717
[7] ORCID: https://orcid.org/0000-0001-9907-0516
[8] ORCID: https://orcid.org/0000-0003-2487-3159

https://doi.org/10.1016/j.ufug.2022.127712
Received 5 April 2022; Received in revised form 13 August 2022; Accepted 16 August 2022
Available online 23 August 2022

city-wide data sets (Kaden and Kolbe, 2013); nevertheless, some studies have applied 3D city models for spatial analyses at the local and neighborhood scale, such as in property assessment (Krüger and Kolbe, 2012, Palliwal et al., 2021) and analysis related to urban green infrastructure (Dissegna et al., 2019, Virtanen et al., 2021). 3D city models are also related to digital twins of the city, as 3D city models play a role in their development (Batty, 2018, Ketzler et al., 2020). Recently, 3D city models have been increasingly applied to game engines, which offer a multi-perspective and multimodal reconstruction of three-dimensional space and open up opportunities for virtual reality applications with geospatial datasets (Laksono and Aditya, 2019, Tschirschwitz et al., 2019, Keil et al., 2021).

One of the potential examples of how to utilize 3D geovisualizations in communicative planning is the assessment of urban green spaces. In recent years, the importance of easy-access and equally distributed local-scale urban ecosystem services have gained attention in urban green infrastructure (UGI) planning and research (Wolch et al., 2014, Tan and Samsudin, 2017). In addition to access to green spaces, several studies have posed concerns about the quality of green spaces, as the existence of green space in a locality does not always equate with quality of the environment (Lennon et al., 2019). Thus, the assessment of cultural ecosystem services in particular (i.e., the cultural nonmaterial benefits people obtain from ecosystems (see e.g., Chan et al., 2012)) is stated to benefit from human audits and participation (Faehnle et al., 2014, Rall et al., 2019) and the importance of inclusive urban green infrastructure governance has been actively debated (Møller et al., 2019).

1.2. Omnidirectional virtual urban audits

To gather perception-based data on the environment, urban field audits and walk-along interviews (or walking interviews) have been used as methods in which the participant is located in situ (also on foot or on-site) while observing the environment. Audits are either objective—that is, they are implemented by researchers or trained fieldworkers (usually with a detailed field manual)—or subjective audits, assessing perceived qualities and satisfaction, or a mix of these (Kim and Lee, 2022). A remarkable share of the field audit literature is designed to assess built environment characteristics that affect health-related behaviors, such as walkability audits (see e.g., Clifton et al., 2007, Aghaabbasi et al., 2018). Some of the field audit and walk-along studies are motivated by urban green space research, such as investigating how the size of a park affects the perception of green space (Macintyre et al., 2019), which park features influence visiting a park (Veitch et al., 2020), and how residents value green infrastructure within their neighborhood (van Vliet and Hammond, 2021).

During the last decade researchers have increasingly started to test alternative ways to conduct urban audits with digital omnidirectional data. The materials used in omnidirectional virtual audit studies can be roughly divided into two main categories: hypothetical 3D visualizations of the built environment (see e.g., Birenboim et al., 2019), and 3D geovisualizations, which are based on reference data from the real-life environment, usually representing a distinct place or area. Again, the latter can be further divided into two (Fig. 1). Firstly, there are several audit studies that advance panoramic view images, such Google Street Views (GSVs) as one or the main source material for the audit (e.g., Pliakas et al., 2017, Cleland et al., 2021). These emerged after 2007 when Google Street View debuted in American cities (Anguelov et al., 2010, Wilson et al., 2012, Charreire et al., 2014). A recent study compared street view images, 360-degree videos presented in a head-mounted display (HMD) and in-situ field audits, indicating that the advantage of a virtual audit is connected to a larger study area (Kim and Lee, 2022).

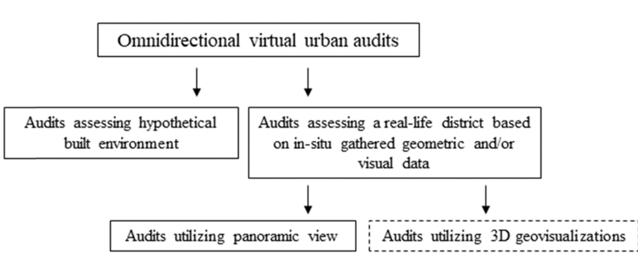

Fig. 1. Omnidirectional virtual urban audits in the academic literature.

Secondly, there are some audit-like studies, sometimes targeted at participatory planning, advancing geospatial 3D models, that is, 3D geovisualizations (e.g., Newell et al., 2017), including communicative planning with park areas (van Leeuwen et al., 2018). Sanchez et al. (2017) utilized a predetermined walk in a VR-based 3D geovisualization for comparing audio-visual designs of public spaces, and Pouke et al. (2019) investigated a VR-based 3D geovisualization for future urban planning scenarios. 3D geovisualizations are also applied in landscape preference studies (Manyoky et al., 2014), while some studies concentrate on perception-alternating factors of 3D geovisualizations. These include an examination of stimuli and experience-altering factors, such as immersiveness (e.g., Pouke et al., 2019), sense of place (Newell and Canessa, 2015, Jaalama et al., 2021a), and user performance (Lokka and Çöltekin 2019, Kubíček et al., 2019). The perception of 3D geovisualizations has also been studied through affordances (Jaalama et al., 2021a), that is, subjectively perceived opportunities of the environment (e.g., Kyttä 2004, Lennon et al., 2017).

Clearly, a user's perception and performance are of importance, because for designing effective virtual environments, it is necessary to understand how users perform within immersive simulations, that is, which virtual environments are more successful at stimulating and replicating real-world user behavior (Halik and Kent, 2021). However, apart from designing effective environments, the investigation motivated by communicative planning is also an important matter, that is, how 3D geovisualizations can stimulate participant discussion and information transfer for planning objectives (Hayek, 2011). Yet there are fewer studies that study 3D geovisualizations in terms of their feasibility for subjective urban audits for urban green space planning.

1.3. Study aim

Until now we have not been able to find a subjective urban audit or walk-along interview study that applies a photorealistic and geometrically accurate 3D geovisualization of urban green space perceived through an HMD. Thus, we demonstrate a general workflow for a 3D measurement-based and highly automated 3D city modeling process for game engines. The study aim is to assess to what extent the respective application can be utilized to convey information on affordances in reality-based VR audits, such as in walk-along interviews for the quality assessment of an urban park. To do this, we compare walk-along interview data conducted in situ on an urban park deck in Helsinki, and with a 3D geovisualization of the park deck on an HMD in VR (later Bryga 3D). Finally, the effects of embedded 360-degree panoramic views and participants' prior visit(s) to the park deck are analyzed. Our research questions are (1) how do the perceived affordances differ between VR and in-situ interviews, and (2) how do the distinct approaches of 3D geovisualization-based VR audits convey information on affordances for virtual audits?

2. Materials and methods

2.1. Study site

The study area was the Bryga park deck, located in the Kalasatama district (lit. Fish Harbour) of Helsinki, Finland (see Fig. 6, section c). Kalasatama is a former brownfield district with 5,000 inhabitants as of 2021. It is one of Helsinki's flagship renewal projects that is expected to become an urban district of 25,000 inhabitants and 10,000 workers by 2035. (City of Helsinki, 2021) Bryga park deck is a newly-built urban recreational outdoor area, spanning 0.7 ha and located on the roof of the shopping mall Redi. Bryga features mounds and rocks, stormwater structures, steel pergolas and a playground area, in addition to picnic areas with tables, chairs and sun loungers. Trails and smaller paths run between vegetation areas. Apart from lawn, there are some 50 species of vegetation, including conifers, perennials and different kinds of grasses. 35% of the park area is covered by vegetation, and another 18% by other permeable surfaces. A metro line and a highway connection to eastern Helsinki run under the construction complex of Bryga. (Landezine Media, 2022). The park deck is connected to four courtyards of nearby high-rise buildings that were still under construction when the 3D measurements for the Bryga 3D model and the in-situ walk-along interviews took place.

2.2. VR application development of Bryga 3D

To conduct VR-assisted interviews, a VR application was produced with the help of 3D measuring technology, highly automated 3D model processing, and game engines. The general workflow of the application development is described in Fig. 2.

2.2.1. Data acquisition and data preprocessing

The datasets for developing Bryga 3D were collected using terrestrial laser scanning and aerial imagery based on unmanned aerial vehicles (UAV). Laser-scanned data sets were collected using two Leica RTC360 scanners with on-field preregistration. UAV-based aerial image datasets were collected with a DJI Phantom 4 Pro+ drone for subsequent highly automated 3D modeling. A set of ground control points were measured to assist in combining the collected datasets by using a Leica GS18 GNSS RTK device. The detailed specifications and parameters of the scanners and UAV are listed in Appendix A.

2.2.2. Data preprocessing

Laser-scanned preregistered point cloud data was preprocessed with Leica Cyclone Register 360 (version 2020.1.0). The process included cleaning the data of erroneous and outlier points, for example points caused by reflections and dynamic objects, such as vehicles and people. All scanning stations were registered, and the point cloud was colorized. To improve the visual quality of the point cloud colorization and later 3D model texturing, the panoramic images for each scan were processed using the external image editing software Darktable (version 3.0.0). Aerial imagery was processed using Adobe Lightroom Classic (version 10.1.1). The tonal scales of the images were adjusted to recover lost details due to over- and underexposure. Blurred images were excluded from the image set to avoid problems during photogrammetric reconstruction.

2.2.3. Automated 3D modeling

The 3D model was produced as automatically as possible using the photogrammetric 3D reconstruction software RealityCapture (version 1.1). The laser-scanned point cloud data and the collected aerial images were used to produce the resulting textured 3D mesh model. The model was also georeferenced by registering it with the measured ground control points. The resulting final game engine-compatible model was simplified from the original full density model in order to run in a VR application.

2.2.4. VR application development

The final Bryga 3D application development was achieved in Unreal Engine 4 (version 4.26.2), a versatile commercial game engine. The application was built around the automatically processed 3D model of the Bryga park deck (Figs. 3a, 4a, 5a). In addition, two manually generated 3D model assets, namely high-rise buildings and untextured Helsinki 3D city model data (level of detail 2 (LoD2)) were added to the final VR scene to visualize the surroundings of the Bryga park deck (for untextured model, see Fig. 3a). Also, dynamic lighting (sun and clouds) was added to further increase the immersion of the VR application. Bryga 3D in VR was built lightly in terms of data so that it would run effortlessly in the game engine. Figs. 3, 4 and 5 show a comparison of the final Bryga 3D model with the photographs taken in situ.

In the final VR application, the users could move with the teleportation-based locomotion technique in a predefined area within the scene using VR controllers. The navigable area was defined to match the walking route of the walk-along interviews. In addition, a set of 17 interactive panoramic image spheres were added along the route, marked with green dots. These spheres utilized the panoramic photographs collected by the laser scanner to show a purely image-based view

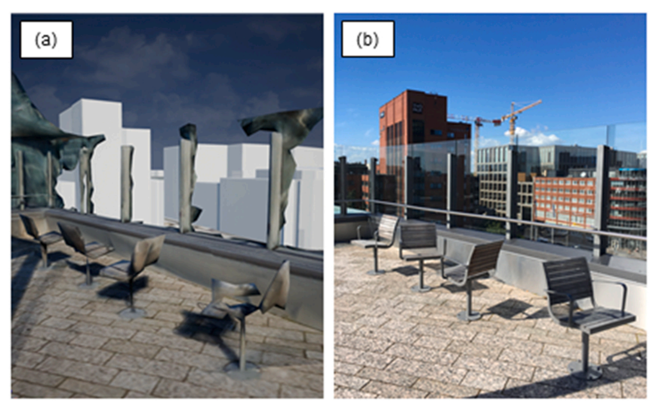

Fig. 3. Bryga 3D in VR (section a) and the respective view in situ as captured in photographs (section b).

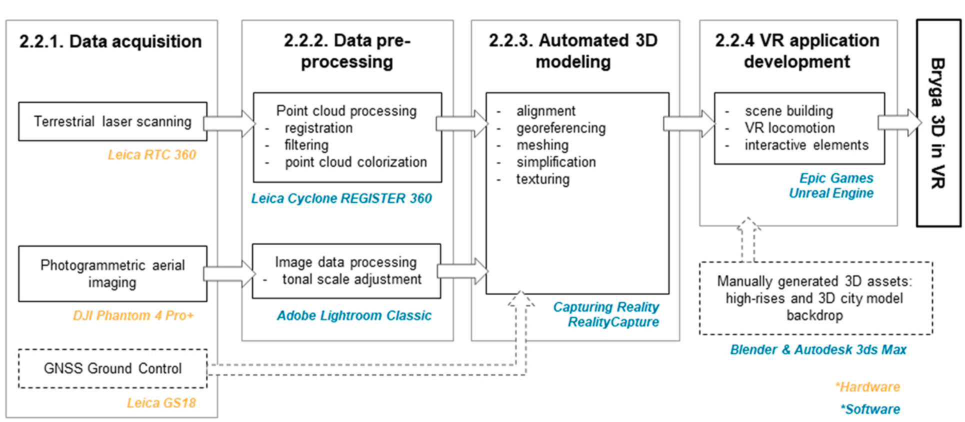

Fig. 2. General workflow of the Bryga park deck VR application development.

Fig. 4. Bryga 3D in VR (section a) and the respective view in situ as captured in photographs (section b).

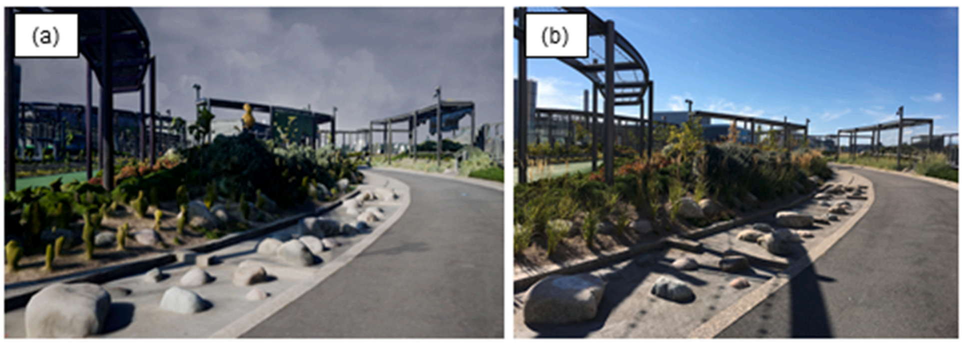

Fig. 5. Bryga 3D in VR (section a) and the respective view in situ as captured in photographs (section b).

in contrast to the 3D model-based view. The spheres with the panoramic images, perceivable through HMD, were distributed evenly along the route to illustrate the most focal points of the park; however, we wanted to avoid adding too many panoramic images to maintain the usability of the application. The panoramic images were activated only in the second interview round in Bryga 3D. The participant could see panoramic views by navigating to the dot and raising the hand-held controller. Other interactive elements included a map of the area with the walking route and arrows as guidance markers.

2.3. Interview study design

2.3.1. Recruitment of participants and presurvey

During the fall of 2020 we recruited 11 participants to the in-situ interviews, which took place on the Bryga park deck in September and October 2020. An additional two participants were recruited to the in-situ interviews in October 2021 to fulfill the data. In fall 2021, 21 participants were recruited to take part in the VR-assisted interviews at Oodi public library in Helsinki. VR interviews were the main interest in our study, and the in-situ interview data was collected to be used as reference. For this reason, the number of participants was higher in the VR interviews.

Recruitment was conducted via the study project's social media accounts, via the study staff members' networks, and via snowball sampling. The participants were laypersons and professionals interested in supporting our research or getting to know the Bryga park deck and/or the technology behind 3D geovisualizations better. In recruiting the participants, we aimed for a group representing diverse backgrounds; therefore, while marketing the interviews, we did not especially target professional green space planners, for example. In addition, remote sensing experts, researchers and students were excluded from the VR interviews to avoid biased perception towards 3D geovisualization. However, some of the interview participants were professionally involved with the topics of land use planning. These participants had occasional challenges in answering the interview questions, including affordances, from a personal user perspective. These challenges were considered when analyzing the interview data. Participants were aged 30–43, except for a single participant aged 59. The average age of the participants was 35, while the median age was 33. In both interview groups, the number of participants who had visited the park deck prior to the interviews was five; that is, 38% of the in-situ participants and 24% of the VR participants.

All the participants signed the informed consent document and replied to a presurvey that included information on the participants' age, prior familiarity with the Kalasatama area, and possible former visits to the Bryga park deck (Appendix B). Also, prior use of VR headsets and familiarity with 3D geovisualizations were asked about before the VR interview was conducted (Jaalama et al., 2021a, Newell and Canessa, 2018). The average length of the VR interviews was 24 min and that of in-situ interviews 19 min (interview length without instructions at the beginning). Some 24% (n = 5) of the VR participants and 38% (n = 5) of the in-situ participants had visited the Bryga park deck prior to the interview. The overall results of the presurvey on participants' background variables are presented in Appendix C.

2.3.2. Interview procedure

The same interview design was applied to the in-situ and the VR walk-along settings to compare the two methods. The walk-along interview design included a predetermined path that was followed in both interview settings (Fig. 6) to ensure the comparativeness of the two methods. After the VR interview, a brief additional round was performed with the participants using panoramic views in selected spots of Bryga (these were not included in the reported interview lengths). The field study process in the VR and in-situ interviews are presented in Fig. 7.

All the interviews were semi-structured in character, as we asked predetermined questions (Appendix D) but also let the participants point out and describe the attributes in the environment freely. In the VR interview, the participant could do this by using the virtual hands for pointing and by gazing at the objects while interviewer was observing the walk from a laptop screen (Fig. 8). In the in-situ interview, this was

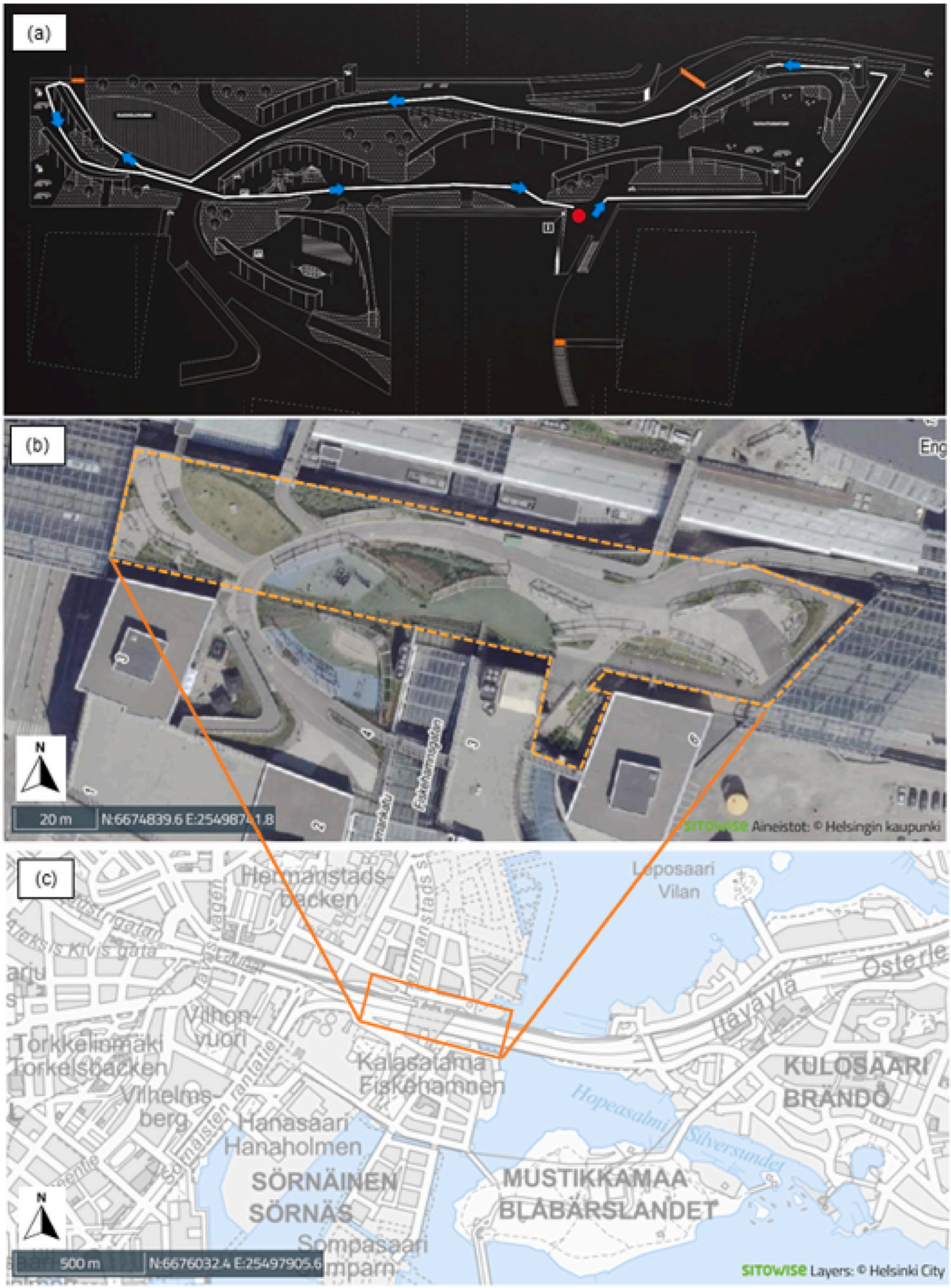

Fig. 6. Predetermined route for the walk-along interviews in VR and in situ (section a; an adaptation of original map on the Bryga park deck), the study site shown on orthophotograph (section b; city of Helsinki map service), and the study site's location in the Kalasatama district (section c; city of Helsinki map service).

done by observing the participant while walking along. All the interviews were initiated by giving the participant a general task for the course of the whole interview: "during the walk, describe in your own words what you see around you and what kind of a place Bryga is." Further questions were asked according to the plan (Appendix D). The idea was that the participants could describe the environment rather freely and intuitively; however, we ensured that all the topics of the affordances star were touched upon by the end of the interview. The interviewer could also ask further questions based on the responses and observations of the participants; nevertheless, we aimed to avoid leading the participants one way or another. It was not uncommon that the participant would come up with some of the topics of the affordances

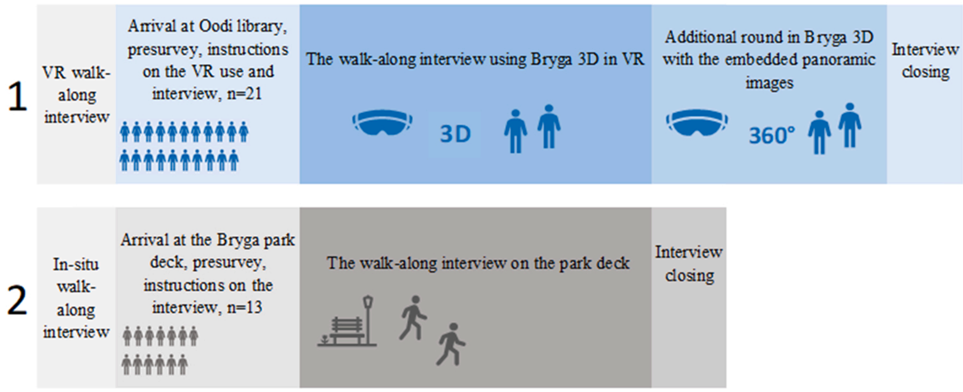

Fig. 7. The interview procedure in the VR (1) and in-situ (2) interviews.

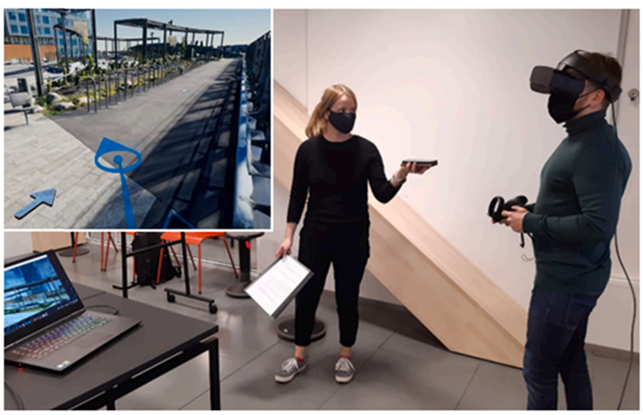

Fig. 8. VR interview at Oodi public library in Helsinki.

star intuitively by themselves. In such cases, the interview plan was adjusted to follow the discussion and the questions were modified accordingly (i.e., if not necessary, the same topics were not covered twice). As illustrated above, the questions were not strictly bound to specific points or exact moments along the walk. However, due to the interview plan, similar patterns emerged throughout all the interviews. For example, the question "how would you improve Bryga?" was asked as the final question in the majority of the interviews.

The interviews were conducted following the Aalto University's Research Ethics and Research Integrity guidelines and the Finnish Advisory Board on Research Integrity guidelines (Finnish National Board on Research Integrity, 2019). COVID-19 security measures were followed in the VR interviews and particular caution was shown toward the participant in terms of possible nausea caused by the VR system (see e.g., Hupont et al., 2015). In the in-situ interviews, we faced technical problems with the interview recording. For this reason, in two of the in-situ interviews we had to use interview notes as an additional data source—these were excluded from the summative analysis but used for the content analysis.

2.3.3. *Affordance star to capture green space quality*

To understand how the quality of green space could be determined through human audits, academic literature has suggested the affordances approach, which refers to the subjectively perceived opportunities of the environment. In the ecological approach to affordances (Gibson, 1979 cited in Lennon et al., 2019) the environmental attributes are dealt together with the context, that is, acknowledging the diversity of personal, social, and environmental conversion factors that advance or hinder the realization of needs and desires (Douglas et al., 2017; Withagen et al., 2012, Lennon et al., 2019).

To concretize the use of affordances for reviewing the qualities of a green space, Lennon et al. (2017) have provided an affordances star concept, through which the distinct environmental qualities perceived by a human subject can be articulated and structured. The affordances star has six dimensions that interact to produce opportunities and constraints. These are space (e.g., landforms); scale; time; objects (e.g., presence or absence of trees, benches); actions (e.g., jogging, bird watching); and the physical and psychological state of the person positioned in relation to these other dimensions. Further, these dimensions do not exist independently of the others in producing the experience of quality of the green space (Lennon et al., 2017).

The interview design was thus based on the affordances star (Lennon et al., 2017) that models the qualities of a green space that are important in green space planning and assessment from an individual, observable point of view, including tangible and intangible aspects of the green space. The affordances star was the test frame—not the primary study subject but a tool that enabled us to gather and compare observations central to the planning aspect. The topics of the affordances star were used to form the semi-structured interview topics (Appendix D). We applied a realist study perspective (Braun and Clarke, 2006) which has been shown to be convenient in interview settings dealing with perceived environmental attributes (see e.g., Macintyre et al., 2019). That is, we applied a larger interview sample size and analyzed participants' explicit descriptions instead of a more in-depth analysis with few individuals' experience, and a semantic rather than a latent approach.

2.3.4. *Data analysis*

Qualitative data was audio-recorded during the walk-along interviews and transcribed verbatim. The data was anonymized prior to reporting the results and analyzed using content analysis, coding, and regular expression search with the support of Atlas.ti (Version 9) (see phases 1–3 in Table 1). Both for in situ and walk-along interview data, the inductive coding of items was conducted. This was followed by deductive thematic content analysis (see e.g., Outermans et al., 2016), based on preliminary coding driven by the affordances star framework (Lennon et al., 2017). When possible and meaningful, we advanced a summative content analysis approach; that is, counting and comparisons followed by interpretation of the findings (Hsieh and Shannon, 2005, Veitch et al., 2020). The results of the two data sets were compared to gain insight into their differences (phase 4). The possible effect of a prior visit to the Bryga park deck was controlled in the VR interview data (phase 5). A brief content analysis was performed with the interview data with 17 panoramic images embedded in Bryga 3D. By doing this, we could identify the benefit of additional panoramic views for the use of 3D geovisualization in VR (phase 6). Finally, based on the previous analysis results, the distinct approaches of Bryga 3D in VR were compared subjectively (by N.N.) by assessing their abilities (low = 1, good = 2, or moderate ability = 3) to convey information on the central affordances, and by using in-situ interview data as reference.

Table 1
Analysis design.

Data		Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6
1	VR walk-along interview data	Coding of the interview data into items to identify recurring space descriptions and affordances	Coding of the items into the categories according to the affordances star	Regular expression search for summative analysis and content analysis where applicable	Comparison of the results and identification of differences between the groups	Analysis of the effect of prior visit in the VR interview data	Content analysis of interview data with the embedded panoramic images to identify the possible change in perception and additional benefit of embedded panoramic views in a 3D geovisualization
2	In-situ walk-along interview data	Coding of the interview data into items to identify recurring space descriptions and affordances	Coding of the items into the categories according to the affordances star	Regular expression search for summative analysis and content analysis where applicable	Comparison of the results and identification of differences between the groups		

A total of 80 items were identified from the VR and in-situ interview data and allocated under the six categories of the affordance star. One additional category was formed for constraints in perception. 74 items were included in the summative analysis; that is, the number of interviews in which the respective item occurred was investigated. Hence, six items were only investigated through content analysis, as these were not meaningful for validation via summative means but they did bring insight to the data via content analysis.

3. Results

3.1. Individual affordance categories as perceived in situ and in VR—results from summative and content analysis

3.1.1. Space (tangible and intangible)

The tangible and intangible descriptions of space occurred in the majority of the VR and in-situ interviews (see Appendix E). Both positive and negative intangible descriptions occurred in both data sets, sometimes within the same interview. In the VR interviews, positive characteristics included terms such as pleasant and good quality of space. Negative descriptions of space included terms such as run-down, dirty, and unwelcoming, and were to some extent different between the two groups. The VR participants were disturbed by the flaws in the model, resulting in space descriptions such as “unsafe, weird, and apocalyptical”.

In the VR interviews, the negative descriptions were often related to the hesitation caused by the feeling of unrealness or weirdness, as the majority of the participants found that there was something wrong in the environment or that the environment did not make sense, or they made a wrong interpretation caused by misleading visual information. Also, the impression that VR participants were alone in the virtual environment led to hesitation for some. Some VR participants described the place as private and empty or open and spacious. On the contrary, some of the in-situ participants described the place as “controlled” due to the comprehensive fencing, and that there were “cage-like” structures. These notions did not appear in the VR interview data, but a controlled feeling was reported due to the surveillance cameras in the VR group as well.

In both groups there were participants who would not refer to the Bryga park deck as a green area. This was connected to the identified purpose of the space; a good share of participants in both groups said that they would not come to visit the place for the nature but for some other recreational purpose. The divisions of space, such as play area, paths, and places for picnics were broadly identified and in line with each other in both groups.

3.1.2. Scale (surroundings, size, and connectivity to the surroundings)

Both groups were aware that the park is located above the streets, and in both groups an equal share of participants compared the Bryga park deck to another real-life place. Both groups found it difficult to assess the size of the park deck; however, the presented assessments and references were generally in line with each other. Instead, there were some differences between the groups in how the participants perceived the surroundings and linked them to the park use. In the in-situ interviews, more than half mentioned the remoteness of the Bryga park deck and its weak accessibility to the surroundings, while less than a quarter mentioned this in the VR interviews. This difference between the groups was accentuated if the VR participants with prior visits to the Bryga park deck were excluded.

In the in-situ interviews, the scenery was reported in more detail and the role of the surrounding city was present in the descriptions and was well elaborated. In the VR interviews the descriptions were much more linked to the park itself, and if the views were mentioned, the descriptions were more likely to be speculative and to include uncertainties. More than half of the VR participants mentioned the surrounding views, but for many it was challenging to identify the buildings or other premises in the scenery, and for some it was challenging to locate the park deck within the city district. Around half of the VR participants reported having issues in understanding the surroundings and the views or made wrong interpretations of the surrounding environment. Some in-situ participants found nice spots in terms of scenery, while others were somewhat disappointed with the views. VR participants saw potential in the scenery but could not tell for sure.

Apart from the content analysis, uncertainty with the surroundings was shown in summative analysis, as the shopping center under the park was mentioned in 47% of the VR interviews, and in 91% of the in-situ interviews (see Fig. 10). The big road under the park deck was mentioned by 33% of the VR participants and 64% of the in-situ participants. The majority (n = 20, 95%) of the VR participants mentioned the surrounding high-rises (these were the only objects with a modeled texture outside the park premises).

3.1.3. Time (temporal context and possibilities)

Both VR and in-situ participants included notions on the changing characteristics of space, such as that the area is still being built, it is newly built, and the vegetation is newly planted and has not grown yet. Generally, the potential seasons and day- and night-time possibilities were identified similarly in both groups. Sunny weather was reported by many in the VR interviews, but when the VR participants were asked to assess the current season, the responses varied from spring to summer and fall. Thus, VR participants had issues in identifying the relevant season.

3.1.4. Objects (materials, vegetation, and facilities)

According to the summative analysis, the objects were the most commonly occurring category in both interview data sets (see Appendix E). The participants in the VR and in-situ interviews identified the materials and facilities in a similar manner. Facilities were generally comprehensively identified by both groups, and the descriptions of them were given in detail. Bicycle stands, pergolas, and deck chairs, benches and tables, sunloungers and play area equipment were mentioned by at least 80% of all the participants in both interviews (see Fig. 9).

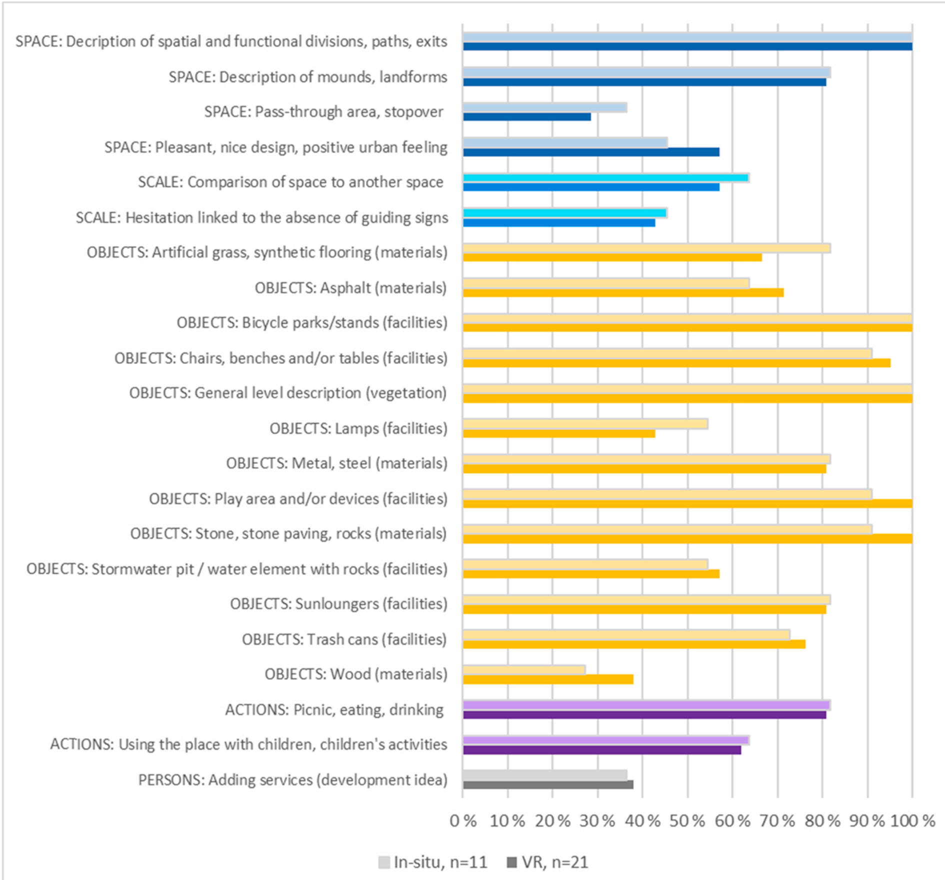

Fig. 9. Key similarities in perception between VR and in-situ interviews. Items mentioned by at least 35% of the participants in the VR or in-situ interviews, with 15 or fewer difference in percentage points between the occurrence rates. Darker color denotes VR interviews and lighter color denotes in-situ interviews.

However, from a quality point of view, VR participants occasionally expressed uncertainty with some of the materials and the facilities. For example, there were misunderstandings connected to the problematic geometry and texture of the playground equipment and the Bryga park deck fence (since the laser scanner was not able to capture the parts made of glass). Some of the VR participants considered the fence to be broken or a confusing design, or they could not tell what was wrong with it. Thus, the fence was mentioned more often in the VR data. Both VR and in-situ groups generally found the decks a dominating, sometimes even disturbing feature in the scene. Also, the amount of bicycle stands, as well as the convenience of their use on a high deck, was consistently questioned in both groups. As the bicycle stands were so numerous, some of the VR participants started to doubt their own perception (even if it was correct).

Identifying or naming the vegetation was challenging for VR participants. If the details and species were described, they were merely speculations or obviously wrong interpretations. On the contrary, if inquired, the in-situ participants could provide detailed description of the vegetation, that is, they could name or describe the vegetation type in detail. The in-situ participants also commented often on the lack or quality of the greenery and presented their personal opinions on the plantings.

While unable to name the species, many VR participants still identified the general type of the vegetation. More than half of the VR group reported trees, shrubs, and grass, and many were able to identify between low and high vegetation. The majority of the VR participants reported grass and more than half of the VR participants could also distinguish between the artificial grass and the real grass. They were also to some extent able to describe the color and color intensity, and some physical forms and the size of the vegetation, and some reported that the vegetation was recently planted. Many VR participants also noticed a variation in the spatial division of vegetation, as many reported preferring the western side of the park since the impression of vegetation was fuller and nicer there. The same spatial variations and preferences were reported in the in-situ group.

3.1.5. Actions

Both groups could name potential actions on the park deck. The differences in perceived actions were often linked to the differing ability to perceive surroundings between the VR and the in-situ settings. For example, when almost half of the VR participants suggested that it would be possible to come and look at the scenery, only one in-situ participant found it a possibility to consider (and that idea was linked to watching not the scenery itself, but a festival that is organized annually nearby). Most of the in-situ participants linked the park to a visit to the nearby shopping center or to visit while passing by. Less than one third of the VR participants mentioned this. This difference between the groups was accentuated if the VR participants with prior visits to the Bryga park deck were excluded from the analysis.

3.1.6. Persons (personal context, social aspects, and development ideas)

Finally, participants assessed their potential visits to the park deck in similar way. In both groups many considered the Bryga park deck too urban and less like nature in terms of their recreation preferences. However, in both groups many considered the park as a good option if passing by or if there were another reason to spend time somewhere nearby. For the in-situ participants, it was easier to describe and link their potential visit to the surrounding services, and to point out possible constraints for a park visit (such as the remoteness and perceived bad accessibility to the deck). Even if most of the VR participants ($n = 18$, 86%) understood that the Bryga park deck is a real place and located in the Kalasatama area, they could not always describe the exact location, and thus the context was given less weight in the VR interview data.

Participants in both groups felt that the park deck is meant mainly for young people or children, or for the residents of or workers in the nearby high-rises. The majority of the in-situ participants mentioned other park visitors currently visiting the park deck, and their actions were observed in terms of interpreting the meaning and affordances of the park deck, which was not possible in VR.

The presented development ideas were mostly shared between the VR and in-situ participants and included adding or changing physical properties or facilities (like changing the pergolas, and adding warm materials such as wood), adding services, such as commercial services and venue for concerts, for example. Unlike the VR participants, the majority of the in-situ participants presented the development idea of increasing greenery and vegetation on the park deck (see Fig. 10). In the VR interview data, some expressed concerns about the park's safety, as the fence and playground seemed to be broken and generally the place looked unwelcoming (these were connected to the flaws in the semi-automated model). These concerns did not occur in the in-situ interview data.

3.2. The effect of prior visits and embedded panoramic views

3.2.1. Results from participants with prior visits to the Bryga park deck

There were implications that context and surroundings were understood more comprehensively among the VR participants with prior visits to the Bryga park deck (and were more similar to the in-situ interviews). It is also notable that the participants who had visited the park deck before described their visit(s) during the interview.

Two out of five participants with prior visits mentioned that Bryga's location is remote in their opinion, while only three out of 16 mentioned the same thing among the VR participants with no prior visit. Three out of five mentioned that Bryga could be visited while at the shopping mall under the deck, while only three out of 16 of the VR participants with no prior visit mentioned the same thing. Nine out of 16 VR participants with no prior visit reported uncertainties in understanding the views and what is in the immediate surroundings, while only one out of five participants with prior visits reported these challenges. VR participants with prior visits found the park deck worth visiting "if I happened to be spending time nearby," or as a secondary destination, linking the visit to some other purpose for visiting the area (this was similar to the in-situ participants). Furthermore, there were implications that prior visits affected the perception of intangible space to some extent; out of the six VR participants who described the park deck as windy, three had visited the park deck before. While five VR participants presented a development idea including a covering shelter, as many as four of them had visited the park deck before. However, as there were only a few VR participants who had visited the park deck (n = 5/21), the stated comparisons are strongly qualitative and indicative.

3.2.2. Results with embedded panoramic views

The additional round in Bryga 3D with 17 embedded panoramic images resulted in enhanced perception for some of the items. These were: (1) Participants were now able to see and interpret the views, which helped some to comprehend their location in the city. This made some of the participants more critical as they now found that the views were not as nice as they had hoped, and the space seemed busier due to the traffic. (2) Some reported that they now can be sure of the materials and that the interpretation of details was now easier. (3) The participants were able to make more detailed comments on the vegetation and vegetation color, which resulted in mixed outcomes. Some found that the vegetation seemed smaller and the place less green, but some found that the vegetation seemed larger and/or generally nicer. Some said that their idea of the vegetation did not change significantly. (4) Further, participants reported to have received better information on the relevant season. (5) Some reported that after seeing the people, they got more information on the space and how and by whom it is used. Also, some mentioned that it is nice not to be alone on the park deck anymore. (6) Finally, the environment did not look "intimidating" anymore, as the fence and play devices were no longer "broken". For some, the clarifications were an improvement but for some they were a disappointment. When asked about the reason for this, one participant explained that the game-like model offered a more place-neutral or even exotic image of the space that probably led to replacing the shortcomings in the model with the ideal features.

Even if many considered that the panoramic views were successful in assisting them with their understanding of the park deck, there were also some difficulties. These were linked to (1) to the lack of depth, which some found to be hindering their perception. (2) The absence of degrees of freedom (i.e., that one could not move within panoramic views and that the view was locked) was considered disturbing after moving freely in the environment. (3) Panoramic images did not always offer clear visual information, as they, for example, included reflections of the glass fence that prevented the view through the fence. (4) Also, the changing weather nuances in the panoramic images gave an incoherent impression of the environment.

Generally, the perception linked to the purpose of the place, its

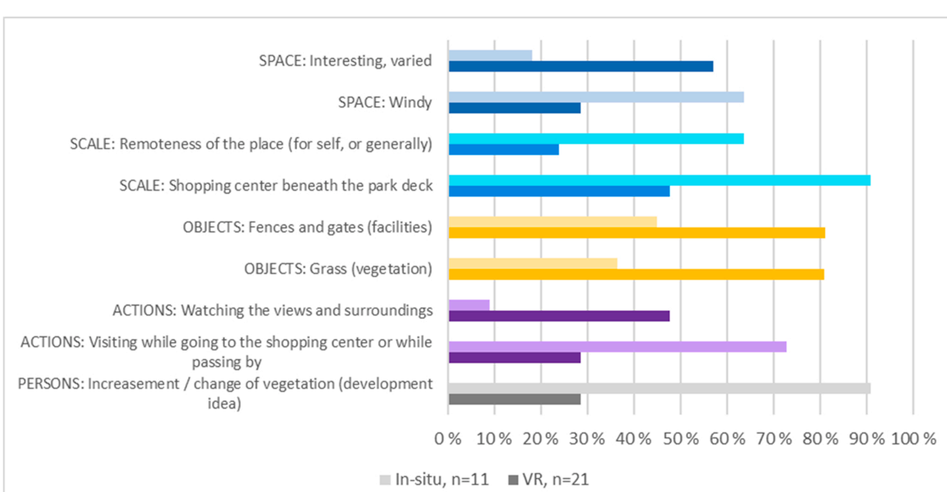

Fig. 10. Key differences in perception between VR and in-situ interviews. Items mentioned by at least 35% of the participants in the VR or in-situ interviews, with 35 or more difference in percentage points between the occurrence rates. Darker color denotes VR interviews and lighter color denotes in-situ interviews.

facilities, and possible actions remained the same with panoramic photographs. Only a few added or changed their earlier development ideas after the second round, unless the development ideas were linked to the flaws in the model (such as repairs to the fence). The effects on perception varied: Some said that only minor clarifications occurred in the second round and the park looked like they thought it would. For some, the difference was more remarkable, and they showed greater surprise when seeing panoramic photographs.

3.3. Distinct approaches of Bryga 3D in conveying information for the perception of affordances—indicative synthesis

An indicative synthesis shows that if the participant did not visit the green space prior to viewing it via a 3D geovisualization, the social aspects and contextual information are perceived less accurately. Panoramic images embedded in the 3D geovisualization can help in perceiving vegetation, materials and temporal context (further explications of valuing the distinct approaches of Bryga 3D are shown in Appendix F). The synthesis was made according to the qualitative and summative results by giving a value for how well the studied realizations were able to transmit information for the perception of affordances. The synthesis is based on three realizations; on Bryga 3D in VR when the participant had not visited the place before (blue line), when the participant had visited the park deck before (red line), and on Bryga 3D in VR combined with panoramic views (gray line) (Fig. 11).

4. Discussion

This paper presented a comparison of VR and in-situ walk-along interviews related to an urban park deck in Helsinki, Finland, in order to subjectively audit perceived affordances. We introduced three approaches for studying omnidirectional virtual urban audits: (1) The tested 3D geovisualization of the park deck is a geometrically accurate 3D model, as it was built utilizing laser scanning and photogrammetry. The tested 3D geovisualization was built with a highly automated workflow enabling a scalable modeling process. (2) The virtual reality application of Bryga 3D was built on a game engine enabling the use of an HMD. Finally, (3) the user study advanced a multidisciplinary approach as it applied a theoretical affordances star framework for testing the subjectively perceived qualities of an urban green space, and we were able to compare its results with those derived from in-situ data.

We can conclude that the study resulted in encouraging results for the future uses and development of omnidirectional virtual urban audits for the perception of affordances in urban green spaces and the

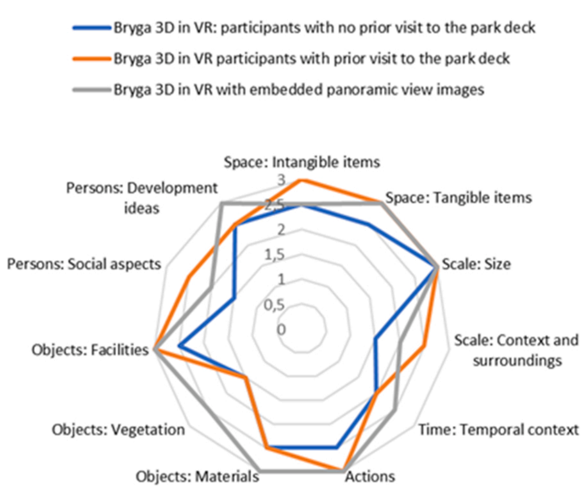

Fig. 11. Indicative synthesis of the distinct Bryga 3D approaches for the ability to convey information for perception of green space affordances. Three denotes good ability, two denotes moderate ability and one denotes low ability.

assessment of their quality. The comparison of in-situ and VR interviews resulted in more similarities than remarkable differences (Figs. 8–10). Hence, the different methods applied for walk-along interviews resulted in comparable outcomes. The perceived size, tangible and intangible elements, development ideas, and potential actions were mostly in line with each other in the VR and in-situ interview data. The differences between the VR and in-situ interviews were linked to perception of surroundings, vegetation, and the social and temporal context.

The weaknesses of Bryga 3D in VR were linked to the flaws in the modeling texture and geometry, which hindered the perception especially in terms of vegetation and, as a result, temporal context (season). Due to the technical restrictions of laser scanning and UAV photogrammetry-based highly automated modeling (e.g., Remondino et al., 2005, Soudarissanane et al., 2011, Julin et al., 2019) the flaws in visual quality appeared with dynamic (moving) items, with items of small-scale geometry (such as small vegetation), and with reflecting materials (such as glass fence). Hence, with the photogrammetry and laser scanning-based modeling techniques, the elements of urban green spaces are variably detectable (Jaalama et al., 2021b). The flaws could be improved by increasing the degree of manual modeling in the highly automated model, for example with vegetation modeling software such as Speedtree (Xiong and Huang, 2010). However, we chose not to do so as our task was to test to what extent highly automated and minimum-effort modeling is able to convey information for perception.

Also, the perception of surroundings resulted in being weaker in the VR walk-along interview, as the used data source for the park surroundings was a simplified LoD2 city silhouette without textures. The context of the park deck was perceived weakly in Byga 3D, and future studies need to solve how the links to the surroundings and urban context (i.e., how the park is situated in the city) can be illustrated as part of a virtual audit. This could be done by using a bird's-eye-view and a more detailed model of the surroundings of the targeted audit environment, for example. Having that said, with the use of game engines, it is recommendable to optimize the data volume to ensure the functionality of the application with lower computational power and with virtual reality systems. Hence, a combination 2D and 3D spatial data sets could be applied (Yin, 2017).

Furthermore, the social aspect of the VR application was addressed, as some of the VR participants disliked being alone on the deck or reported challenges in identifying the season or the purpose of the place when they found no reference to other park users. Future research could still address how to tackle the deficit in social interaction in the VR-based 3D geovisualizations. It also remains to be examined to what extent urban audits in green spaces need social reference, and how it shows in the results. Further, multimodality is addressed in previous VR studies for subjective perception (Maffei et al., 2016, Cranmer et al., 2020), and virtual urban audits could benefit from audio-visual information, as shown in Sanchez et al. (2017).

Previous research with 360-degree panoramic images has shown that omnidirectional virtual audits are particularly useful for auditing larger areas (Kim and Lee, 2022). With 3D geovisualizations, the same may not be true. While the Bryga 3D-like realization is easily scalable in terms of model construction, auditing was actually no faster in VR than in situ. This may also be due to the fact that in our study very few participants were experienced with HMDs, or that navigating in VR was new and exciting. On the other hand, compared to the panoramic view, navigable and geometrically accurate 3D geovisualizations in HMD enable the freedom of movement and unlocked perspective (Nebiker et al., 2010). Compared to panoramic views, this opens up possibilities (Pouke et al., 2019, Keil et al., 2021) for navigable simulation-like walk-along interviews and free exploration of the environment. In our study, we advanced a predetermined path to ensure the comparability of VR and in-situ results. In the future, similar studies could be conducted without a predetermined path by letting the participant lead the audit. As the tested audit concerned subjective perception and was explorative in terms of identified items, further testing could be conducted with objective and prestructured park audits (see e.g., Kaczynski et al., 2012). Automated auditing derived with computer vision (Koo et al., 2022) offer possibilities for objective audits and for audits mixing subjective and objective approaches.

The study also briefly explored the effect of prior visits to the location in the VR interviews. The importance of memory as a factor in strengthening understanding proved to be promising (Degen and Rose, 2012), as participants with prior visits used their knowledge to compile observations of the area. The importance of prior knowledge in environmental assessment has also been identified in previous studies related to the use of geovisualizations (Newell and Canessa, 2018, Jaalama et al., 2021a). As our results showed, because a prior visit to the park deck supported the perception in Bryga 3D, it may be that 3D geovisualizations with a semi-automated modeling process better suit those who are already familiar with the area, and conversely, extra effort with manual modeling should be used for audiences that are only exploring the relevant space for the first time. This notion should be verified in future studies.

The application of geospatial tools to advance the management and planning of urban green spaces is not a new approach. Studies with digital geospatial tools have presented distinct –although most often quantitative – approaches to measuring the quality of urban green space and ecosystem services, for example per capita green cover of the city (Anguluri and Narayanan, 2017), 3D urban green volume for ecological connectivity (Casalegno et al., 2017) and to advance air purification, carbon storage and cooling of the city (Derkzen et al., 2015). However, several studies have noted the importance of subjective approaches in ensuring the quality of urban green spaces. These assessments cannot always be derived from large-scale data with objective and quantitative means (Faehnle et al., 2014, Rall et al., 2019, Møller et al., 2019, Lennon et al., 2019). Visually appealing tools, such as urban digital modeling and twins, are developing rapidly, and their application in inclusive green space planning might become more tempting in the future.

We suggest that green space planning can benefit from human-scale digital approaches. However, due to the sensitive character of human-computer interaction (e.g., Osborne & Jones, 2022), their implementation also entails potential confrontations. While assessing the application of digital approaches instead of in-situ audits, it is advisable to consider the context: for instance, whether the use of 3D geovisualizations makes the green space assessment more accessible, or not, and whether the 3D geovisualization is able to foster the discussion on the various subjective meanings of the green space (Faehnle et al., 2014). When the 3D geovisualizations are used alongside the in-situ approaches, attention should be paid to whether the VR application distorts, for example, the perception of social affordances that might bias the results.

Also, the use of 3D geovisualizations in human audits requires the planners to acknowledge the effects of distinct design choices, such as the use of dynamic instead of stationary elements (e.g., Newell et al., 2017), the level of interactivity of the application (e.g., Herman et al., 2018), and the use of non-realistic visualization elements (such as low-detailed city modeling assets) (e.g., Döllner and Buchholz, 2005). The use of gamification in 3D geovisualizations could benefit the audits that are designed for more task-oriented participatory and collaborative planning processes (e.g., Ampatzidou et al., 2018, Hassan and Hamari, 2020). In our application, apart from the sun and clouds, we did not apply animated elements. When carefully designed and applied, the use animated elements in geovisualization has been shown to support the representation of spatial information, for example of spatiotemporal information (Harrower and Fabrikant, 2008, Mayr and Windhager, 2018).

In future audits, apart from the built infrastructure in urban green spaces (Veitch et al., 2020) it would be advisable to pay attention to the modeling quality of vegetation, as vegetation has a central role in green space assessment (Veitch et al., 2020, van Vliet and Hammond, 2021), and as we show, problems with it could lead to misinformed perception, and to delusively optimistic or pessimistic assessments. Vegetation has been shown to be a determining factor in VR-based assessments of the pleasantness of urban designs (Sanchez et al., 2017), and the importance of vegetation modeling might thus be even greater in the audit studies motivated by green space planning. Future studies on subjective audits for urban green space assessment could be applied in real-life planning processes to support their further critical examination in practice.

5. Conclusions

While technical advancements with 3D city models and digital twins of the cities are developing quickly, assessing the quality of urban green space through such a VR application represents interesting potential, not only from a technical but also communicative and methodological point of view. In the future, omnidirectional virtual urban audits could benefit from VR-based 3D geovisualizations that are built in a photorealistic and highly automated modeling process, especially when audits are not possible or are demanding to implement in situ. Our walk-along interview study showed encouraging results, especially for the assessment of green space quality with affordances linked to the perceived actions and tangible objects of a park. Key items in the park, such as fencing, materials and vegetation, should preferably be of decent quality in the automated model as part of the audit, especially if the participants do not have any previous experience of the targeted green space and are exploring it for the first time. Additional panoramic photographs could be embedded in the 3D model to further enhance the perception and conveyance of information. As our study comprises a qualitative assessment with an explorative study aim, more research is needed to further examine the prospects and constraints of VR-based 3D geovisualizations, and further to critically discuss the advances in distinct virtual geospatial realizations for the purposes of communicative green space planning.

Funding

This work was supported by the Academy of Finland [grant numbers 326246, 323783, 321555]; the Helsinki Innovation Fund; the Aalto Doctoral Programme in Engineering; the Helsinki-Uusimaa Regional Council [grant number UKKE029]; the European Social Fund [grant number S21997]; and the European Regional Development Fund [grant number A77489].

CRediT authorship contribution statement

Conceptualization: K.J, Writing – original draft: K.J, Methodology: K.J., H.H., N.F, Formal Analysis: K.J, Investigation: K.J., T.R., N.F, Resources: A.J., T.R., A.K., H.Ha, K.J, Writing – Review & editing: K.J., T.R., A.J., N.F., A.K., J.-P.V., M.V., H.H, Visualization: T.R., H.Ha, A.J., K.J, Supervision: N.F., H.H, Project Administration: K.J, Funding Acquisition: H.H., M.V., N.F.

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.

Data Availability

The authors do not have permission to share data.

Appendices A–F. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2022.127712.

References

Aghaabbasi, M., Moeinaddini, M., Shah, M.Z., Asadi-Shekari, Z., Kermani, M.A., 2018. Evaluating the capability of walkability audit tools for assessing sidewalks. Sustain. Cities Soc. 37, 475–484.
Ampatzidou, C., Constantinescu, T., Berger, M., Jauschneg, M., Gugerell, K., Devisch, O., 2018. All work and no play? Facilitating serious games and gamified applications in participatory urban planning and governance. Urban Plan. 3 (1), 34–46.
Anguelov, D., Dulong, C., Filip, D., Frueh, C., Lafon, S., Lyon, R., Ogale, A., Vincent, L., Weaver, J., 2010. Google street view: capturing the world at street level. Computer 43 (6), 32–38.
Anguluri, R., Narayanan, P., 2017. Role of green space in urban planning: outlook towards smart cities. Urban For. Urban Green. 25, 58–65.
Batty, M., 2018. Digital twins. Environment and Planning B: Urban Analytics and City Science 45 (5), 817–820.
Biljecki, F., Stoter, J., Ledoux, H., Zlatanova, S., Çöltekin, A., 2015. Applications of 3D city models: state of the art review. ISPRS Int. J. Geo Inf. 4 (4), 2842–2889.
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. Landsc. Urban Plan. 189, 129–138.
Bleisch, S., 2012. 3D Geovisualization-Definition and Structures for the Assessment of Usefulness. ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences 2, 129–134.
Braun, V., Clarke, V., 2006. Using thematic analysis in psychology. Qual. Res. Psychol. 3 (2), 77–101.
Casalegno, S., Anderson, K., Cox, D.T., Hancock, S., Gaston, K.J., 2017. Ecological connectivity in the three-dimensional urban green volume using waveform airborne lidar. Sci. Rep. 7 (1), 1–8.
Chan, K.M., Guerry, A.D., Balvanera, P., Klain, S., Satterfield, T., Basurto, X., Woodside, U., 2012. Where are cultural and social in ecosystem services? A framework for constructive engagement. BioScience 62 (8), 744–756.
Charreire, H., Mackenbach, J.D., Ouasti, M., Lakerveld, J., Compernolle, S., Ben-Rebah, M., Oppert, J.M., 2014. Using remote sensing to define environmental characteristics related to physical activity and dietary behaviours: a systematic review (the SPOTLIGHT project). Health Place 25, 1–9.
City of Helsinki. 2021. Kalasatama. Available: ⟨https://www.uuttahelsinkia.fi/en/kalasatama⟩.
Cleland, C.L., Ferguson, S., Kee, F., Kelly, P., Williams, A.J., Nightingale, G., Hunter, R.F., 2021. Adaptation and testing of a microscale audit tool to assess liveability using google street view: MAPS-liveability. J. Transp. Health 22, 101226.
Clifton, K.J., Smith, A.D.L., Rodriguez, D., 2007. The development and testing of an audit for the pedestrian environment. Landsc. Urban Plan. 80 (1–2), 95–110.
Cranmer, A., Ericson, J.D., Broughel, A.E., Bernard, B., Robicheaux, E., Podolski, M., 2020. Worth a thousand words: Presenting wind turbines in virtual reality reveals new opportunities for social acceptance and visualization research. Energy Res. Soc. Sci. 67, 101507.
Degen, M.M., Rose, G., 2012. The sensory experiencing of urban design: the role of walking and perceptual memory. Urban Stud. 49 (15), 3271–3287.
Derkzen, M.L., van Teeffelen, A.J., Verburg, P.H., 2015. Quantifying urban ecosystem services based on high-resolution data of urban green space: an assessment for Rotterdam, the Netherlands. J. Appl. Ecol. 52 (4), 1020–1032.
Dissegna, M.A., Yin, T., Wei, S., Richards, D., Grêt-Regamey, A., 2019. 3-D reconstruction of an urban landscape to assess the influence of vegetation in the radiative budget. Forests 10 (8), 700.
Döllner, J., Buchholz, H., 2005. Non-photorealism in 3D geovirtual environments. Proc. Autocar 1–14.
Döllner, J., Kolbe, T.H., Liecke, F., Sgouros, T., & Teichmann, K., 2006. The virtual 3d city model of berlin-managing, integrating, and communicating complex urban information. In Proceedings of the 25th international symposium on urban data management UDMS 2006 in Aalborg, Denmark, 15–17 May 2006.
Douglas, O., Lennon, M., Scott, M., 2017. Green space benefits for health and well-being: a life-course approach for urban planning, design and management. Cities 66, 53–62.
Faehnle, M., Bäcklund, P., Tyrväinen, L., Niemelä, J., Yli-Pelkonen, V., 2014. How can residents' experiences inform planning of urban green infrastructure? Case Finland. Landsc. Urban Plan. 130, 171–183.
Finnish National Board on Research Integrity. 2019. The ethical principles of research with human participants and ethical review in the human sciences in Finland. Finnish National Board on Research Integrity guidelines, 3/2019.
Halik, Ł., Kent, A.J., 2021. Measuring user preferences and behaviour in a topographic immersive virtual environment (TopoIVE) of 2D and 3D urban topographic data. Int. J. Digit. Earth 14 (12), 1835–1867.
Harrower, M., Fabrikant, S., 2008. The role of map animation in geographic visualization. In: Dodge, M. (Ed.), Geographic Visualization: Concepts, Tools and Applications. Wiley, Chichester, UK, pp. 49–65.
Hassan, L., Hamari, J., 2020. Gameful civic engagement: a review of the literature on gamification of e-participation. Gov. Inf. Q. 37 (3), 101461.
Hayek, U.W., 2011. Which is the appropriate 3D visualization type for participatory landscape planning workshops? A portfolio of their effectiveness. Environ. Plan. B Plan. Des. 38 (5), 921–939.
Herman, L., Juřík, V., Stachoň, Z., Vrbík, D., Russnák, J., Řezník, T., 2018. Evaluation of user performance in interactive and static 3D maps. ISPRS Int. J. Geo Inf. 7 (11), 415.
Hildebrandt, D., Döllner, J., 2010. Service-oriented, standards-based 3D geovisualization: potential and challenges. Comput. Environ. Urban Syst. 34 (6), 484–495.
Hsieh, H.F., Shannon, S.E., 2005. Three approaches to qualitative content analysis. Qual. Health Res. 15 (9), 1277–1288.
Gibson, J.J., 1979. The Ecological Approach to Visual Perception. Houghton Mifflin, Boston.
Hupont, I., Gracia, J., Sanagustin, L., Gracia, M.A., 2015. How do new visual immersive systems influence gaming QoE? A use case of serious gaming with Oculus Rift. IEEE, pp. 1–6.
Jaalama, K., Fagerholm, N., Julin, A., Virtanen, J.P., Maksimainen, M., Hyyppä, H., 2021a. Sense of presence and sense of place in perceiving a 3D geovisualization for communication in urban planning–Differences introduced by prior familiarity with the place. Landsc. Urban Plan. 207, 103996.
Jaalama, K., Kauhanen, H., Keitaanniemi, A., Rantanen, T., Virtanen, J.P., Julin, A., Hyyppä, H., 2021b. 3D point cloud data in conveying information for local green factor assessment. ISPRS Int. J. Geo Inf. 10 (11), 762.
Julin, A., Jaalama, K., Virtanen, J.P., Pouke, M., Ylipulli, J., Vaaja, M., Hyyppä, J., Hyyppä, H., 2018. Characterizing 3D city modeling projects: towards a harmonized interoperable system. ISPRS Int. J. Geo Inf. 7 (2), 55.
Julin, A., Jaalama, K., Virtanen, J.P., Maksimainen, M., Kurkela, M., Hyyppä, J., Hyyppä, H., 2019. Automated multi-sensor 3D reconstruction for the web. ISPRS Int. J. Geo Inf. 8 (5), 221.
Kaczynski, A.T., Stanis, S.A.W., Besenyi, G.M., 2012. Development and testing of a community stakeholder park audit tool. Am. J. Prev. Med. 42 (3), 242–249.
Kaden, R., Kolbe, T.H., 2013. City-wide total energy demand estimation of buildings using semantic 3D city models and statistical data. In Proc. of the 8th International 3D GeoInfo Conference.
Keil, J., Edler, D., Schmitt, T., Dickmann, F., 2021. Creating immersive virtual environments based on open geospatial data and game engines. KN J. Cartogr. Geogr. Inf. 71 (1), 53–65.
Ketzler, B., Naserentin, V., Latino, F., Zangelidis, C., Thuvander, L., Logg, A., 2020. Digital twins for cities: a state of the art review. Built Environ. 46 (4), 547–573.
Kim, S.N., Lee, H., 2022. Capturing reality: validation of omnidirectional video-based immersive virtual reality as a streetscape quality auditing method. Landsc. Urban Plan. 218, 104290.
Koo, B.W., Guhathakurta, S., Botchwey, N., 2022. Development and validation of automated microscale walkability audit method. Health Place 73, 102733.
Krüger, A., Kolbe, T.H., 2012. Building Analysis for urban energy planning using key indicators on virtual 3D city models-The energy atlas of Berlin. ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial. Inf. Sci. 39, 145–150.
Kubíček, P., Šašinka, Č., Stachoň, Z., Herman, L., Juřík, V., Urbánek, T., Chmelík, J., 2019. Identification of altitude profiles in 3D geovisualizations: the role of interaction and spatial abilities. Int. J. Digit. Earth 12 (2), 156–172.
Kyttä, M., 2004. The extent of children's independent mobility and the number of actualized affordances as criteria for child-friendly environments. J. Environ. Psychol. 24 (2), 179–198.
Laksono, D., Aditya, T., 2019. Utilizing a game engine for interactive 3D topographic data visualization. ISPRS Int. J. Geo Inf. 8 (8), 361.
Landezine Media. 2022. Bryga – Public rooftop park. Available: ⟨https://landezine-award.com/bryga-public-rooftop-park/⟩.
Lennon, M., Douglas, O., Scott, M., 2017. Urban green space for health and well-being: developing an 'affordances' framework for planning and design. J. Urban Des. 22 (6), 778–795.
Lennon, M., Douglas, O., Scott, M., 2019. Responsive environments: an outline of a method for determining context sensitive planning interventions to enhance health and wellbeing. Land Use Policy 80, 68–78.
Lokka, I.E., Çöltekin, A., 2019. Toward optimizing the design of virtual environments for route learning: Empirically assessing the effects of changing levels of realism on memory. Int. J. Digit. Earth 12 (2), 137–155.
Macintyre, V.G., Cotterill, S., Anderson, J., Phillipson, C., Benton, J.S., French, D.P., 2019. "I would never come here because i've got my own garden": older adults' perceptions of small urban green spaces. Int. J. Environ. Res. Public Health 16 (11), 1994.
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. Sustain. Cities Soc. 27, 338–345.
Manyoky, M., Wissen Hayek, U., Heutschi, K., Pieren, R., Grêt-Regamey, A., 2014. Developing a GIS-based visual-acoustic 3D simulation for wind farm assessment. ISPRS Int. J. Geo Inf. 3 (1), 29–48.
Mayr, E., Windhager, F., 2018. Once upon a spacetime: visual storytelling in cognitive and geotemporal information spaces. ISPRS Int. J. Geo Inf. 7 (3), 96.
Møller, M.S., Olafsson, A.S., Vierikko, K., Sehested, K., Elands, B., Buijs, A., van den Bosch, C.K., 2019. Participation through place-based e-tools: a valuable resource for urban green infrastructure governance? Urban For. Urban Green. 40, 245–253.
Nebiker, S., Bleisch, S., Christen, M., 2010. Rich point clouds in virtual globes–A new paradigm in city modeling? Comput., Environ. Urban Syst. 34 (6), 508–517.
Neuville, R., 2020. 3D Geovisualization: Identification of the Best 3D Viewpoint within Building Models (Doctoral dissertation). Université de Liège, Liège, Belgique.
Newell, R., Canessa, R., 2015. Seeing, Believing, and Feeling: The Relationship between Sense of Place and Geovisualization Research. Spaces Flows: Int. J. Urban Extra Urban Stud. 6 (4).
Newell, R., Canessa, R., 2018. From sense of place to visualization of place: examining people-place relationships for insight on developing geovisualizations. Heliyon 4 (2), e00547.
Newell, R., Canessa, R., Sharma, T., 2017. Visualizing our options for coastal places: Exploring realistic immersive geovisualizations as tools for inclusive approaches to coastal planning and management. Front. Mar. Sci. 4, 290.
Onyimbi, J.R., Koeva, M., Flacke, J., 2018. Public participation using 3D web-based city models: opportunities for e-participation in Kisumu, Kenya. ISPRS Int. J. Geo Inf. 7 (12), 454.

Osborne, T., Jones, P., 2022. Embodied virtual geographies: linkages between bodies, spaces, and digital environments. Geogr. Compass 12648.

Outermans, J., Pool, J., van de Port, I., Bakers, J., Wittink, H., 2016. What's keeping people after stroke from walking outdoors to become physically active? A qualitative study, using an integrated biomedical and behavioral theory of functioning and disability. BMC Neurol. 16 (1), 1–10.

Palliwal, A., Song, S., Tan, H.T.W., Biljecki, F., 2021. 3D city models for urban farming site identification in buildings. Comput., Environ. Urban Syst. 86, 101584.

Pliakas, T., Hawkesworth, S., Silverwood, R.J., Nanchahal, K., Grundy, C., Armstrong, B., Lock, K., 2017. Optimising measurement of health-related characteristics of the built environment: comparing data collected by foot-based street audits, virtual street audits and routine secondary data sources. Health Place 43, 75–84.

Pouke, M., Ylipulli, J., Rantala, S., Alavesa, P., Alatalo, T., Ojala, T., 2019. A qualitative study on the effects of real-world stimuli and place familiarity on presence. IEEE, pp. 1–6.

Rall, E., Hansen, R., Pauleit, S., 2019. The added value of public participation GIS (PPGIS) for urban green infrastructure planning. Urban For. Urban Green. 40, 264–274.

Remondino, F., Guarnieri, A., Vettore, A., 2005. 3D modeling of close-range objects: photogrammetry or laser scanning? Videometrics VIII. SPIE, pp. 216–225.

Sanchez, G.M.E., Van Renterghem, T., Sun, K., De Coensel, B., Botteldooren, D., 2017. Using Virtual Reality for assessing the role of noise in the audio-visual design of an urban public space. Landsc. Urban Plan. 167, 98–107.

Soudarissanane, S., Lindenbergh, R., Menenti, M., Teunissen, P., 2011. Scanning geometry: influencing factor on the quality of terrestrial laser scanning points. ISPRS J. Photogramm. Remote Sens. 66 (4), 389–399.

Tan, P.Y., Samsudin, R., 2017. Effects of spatial scale on assessment of spatial equity of urban park provision. Landsc. Urban Plan. 158, 139–154.

Tschirschwitz, F., Richerzhagen, C., Przybilla, H.J., Kersten, T.P., 2019. Duisburg 1566: transferring a historic 3d city model from google earth into a virtual reality application. PFG–Journal of Photogrammetry, Remote Sensing and Geoinformation. Science 87 (1), 47–56.

van Leeuwen, J.P., Hermans, K., Jylhä, A., Quanjer, A.J., & Nijman, H. 2018. Effectiveness of virtual reality in participatory urban planning: A case study. In Proceedings of the 4th Media Architecture Biennale Conference (pp. 128–136).

van Vliet, K., Hammond, C., 2021. Residents' perceptions of green infrastructure in the contemporary residential context: a study of Kingswood, Kingston-upon-Hull, England. J. Environ. Plan. Manag. 64 (1), 145–163.

Veitch, J., Flowers, E., Ball, K., Deforche, B., Timperio, A., 2020. Designing parks for older adults: a qualitative study using walk-along interviews. Urban For. Urban Green. 54, 126768.

Virtanen, J.P., Jaalama, K., Puustinen, T., Julin, A., Hyyppä, J., Hyyppä, H., 2021. Near real-time semantic view analysis of 3D city models in web browser. ISPRS Int. J. Geo Inf. 10 (3), 138.

Willenborg, B., Sindram, M., Kolbe, T.H., 2018. Applications of 3D city models for a better understanding of the built environment. Trends Spat. Anal. Model. 167–191.

Wilson, J.S., Kelly, C.M., Schootman, M., Baker, E.A., Banerjee, A., Clennin, M., Miller, D. K., 2012. Assessing the built environment using omnidirectional imagery. Am. J. Prev. Med. 42 (2), 193–199.

Withagen, R., de Poel, H.J., Araújo, D., Pepping, G.-J., 2012. Affordances can invite behavior: reconsidering the relationship between affordances and agency. New Ideas Psychol. 30 (2), 250–258.

Wolch, J.R., Byrne, J., Newell, J.P., 2014. Urban green space, public health, and environmental justice: the challenge of making cities 'just green enough'. Landsc. Urban Plan. 125, 234–244.

Xiong, Q., & Huang, X.Y. 2010. Speed Tree-Based Forest Simulation System. In 2010 International Conference on Electrical and Control Engineering (pp. 3033–3036). IEEE.

Yin, L., 2017. Street level urban design qualities for walkability: combining 2D and 3D GIS measures. Comput. Environ. Urban Syst. 64, 288–296.