

## **Exploring Immersive Co-Design: Comparing Human Interaction in Real and Virtual Elevated Urban Spaces in London**

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## Article

# Exploring Immersive Co-Design: Comparing Human Interaction in Real and Virtual Elevated Urban Spaces in London

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**Abstract:** Virtual reality (VR) technology has the potential to revolutionize public engagement in the design of urban projects, leading to more sustainable and inclusive environments. This research scrutinizes this potential through a study of elevated urban spaces, specifically the Sky Garden and Crossrail Place in London. Comparing real and virtual interactions, the aim is to highlight their differences and similarities while underscoring the importance of design decision-making for sustainable public places. Through walk-along interviews with 33 visitors in each space and a VR experiment with a separate group of 33 participants, the study analyses the effectiveness of VR as a co-design tool. The outcomes demonstrate that VR positively influences user involvement and allows for the production and real-time testing of design alternatives. Significantly, the majority of participants, who had not physically visited the spaces, could identify design concerns and propose potential activities and features through the VR experiment. These findings were consistent with those expressed by actual users of the spaces. By comparing human activities, circulation, and design concerns in both physical and virtual environments, the research underscores the potential and limitations of VR as a co-design tool for creating sustainable public spaces.

**Keywords:** virtual reality; computational design; gamification; participatory design; elevated public spaces

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## 1. Introduction

The design of architecture and urban environments has long been a domain of specialized professionals, with limited involvement from the public [1–3]. However, notable successful examples, such as the Tempelhofer Feld in Berlin and the Superkilen urban park in Copenhagen, demonstrate the significant advantages of public involvement in the urban design process. These projects, enabled through collaborative efforts between the public, designers, and stakeholders, have resulted in innovative spaces that reflect the aspirations and needs of the communities they serve [4,5]. The growing recognition of the importance of creating such spaces has led to increased interest in involving the public in the design process [6,7]. This interest is rooted in the belief that such involvement can result in the creation of designs of higher quality and greater user satisfaction, leading to enhanced social and economic sustainability [8,9].

The integration of public participation in the design and implementation of architecture and urban projects has been widely acknowledged as a crucial factor in creating spaces that respond to the needs and desires of their users [3,10,11]. Public participation in urban design involves the active engagement of members of the public in the design process, giving them an opportunity to provide input, feedback, and ideas that are incorporated into the final design [12,13]. This approach has the potential to result in designs that are more representative of the needs and desires of the community, leading to higher levels of user satisfaction and greater utilization of public spaces [10,14].

Co-design is a collaborative approach in urban design that engages designers, stakeholders, and the general public in a collective process to develop solutions for diverse urban

challenges, including public spaces, infrastructure, transportation, and community developments [15,16]. This method aims to promote inclusivity and diversity by incorporating perspectives from the various parties involved, resulting in culturally and socially relevant, sustainable, and responsive spaces [17]. Co-design workshops, typically structured activities, facilitate a shared understanding of challenges and generate ideas for potential solutions [18,19]. Employed in various urban processes, co-design utilizes a range of tools and techniques, from manual methods to digital innovative tools, to enable active participation, creating participatory and interactive urban dialogues [10,20–22]. Essential for addressing social equity, co-design ensures that the needs and perspectives of marginalized groups are considered, fostering more diverse and inclusive spaces and, therefore, leading to better design outcomes [23].

Various tools and methods, such as visualization techniques, 3D modeling, augmented reality (AR), and virtual reality (VR), are utilized in co-design workshops to foster engagement and facilitate communication between designers and stakeholders [24–26]. Recently, an increasing trend in using human–computer interaction (HCI) for immersive computational design has emerged, employing advanced digital technologies to create interactive and responsive urban spaces that cater to community needs [24,27]. These technologies streamline communication and collaboration, yielding more effective and inclusive urban design outcomes. Despite recognizing the importance of public involvement in the design process, a gap remains in the academic literature regarding the most effective methods for incorporating public participation in urban design [28,29]. While some studies have explored the potential benefits of public involvement, further research is needed to better understand effective methods for public participation and evaluate its impact on design quality and user satisfaction [30–32].

VR technology has emerged as a promising solution to the issue of limited public involvement in the design process of architecture and urban projects. VR technology allows users to experience designs in a virtual environment and provides them with the opportunity to provide feedback in real-time [32,33]. This has the potential to significantly improve the quality of designs and increase user satisfaction by enabling users to test and provide feedback on designs before they are built [31,34]. Additionally, VR technology provides a unique opportunity for increasing public involvement in the design process by allowing users to co-design public spaces and provide input into the design process [30,33].

The utilization of VR technology in augmenting public engagement in the design process of architecture and urban projects has garnered interest due to its potential to significantly impact the quality of designs and user satisfaction [31,34,35]. While some studies have explored the use of VR technology in architecture and urban design, there remains, however, a dearth of academic literature that evaluates the effectiveness of VR technology as a tool for co-designing public spaces [30,33,36]. To address this gap, it is imperative to conduct further research that investigates the ways in which individuals interact and behave in virtual environments compared to real environments, assesses the validity of VR technology as a tool for co-designing public spaces, and evaluates its impact on the quality of designs and levels of user satisfaction [32,37]. The current lack of research in this area presents a valuable opportunity for academic inquiry, which can deepen our understanding of the potential of VR technology to enhance public participation in the design process and to create more efficient, sustainable, and equitable public spaces.

### *1.1. Research Background*

VR is a technological advancement that allows users to immerse themselves in computer-generated simulations within a three-dimensional environment, which can either resemble the real world or be entirely distinct [37]. VR systems typically employ headsets or multi-projected environments to produce authentic visuals and sounds, thereby enabling user immersion in a virtual realm [29,38]. Immersive virtual reality (ImVR) is an advanced form of VR that aims to provide users with a higher level of immersion by integrating additional sensory stimuli and creating a more seamless and convincing experience [27,32].

ImVR often employs advanced tracking technologies, haptic feedback systems, and more sophisticated graphics and sound, fostering a stronger sense of presence in the virtual environment [35,39]. This heightened immersion allows for more natural and intuitive interactions within the virtual world, ultimately leading to more meaningful engagement with the simulated environment [29,33].

In architectural and urban design settings, ImVR expands the notion of what is considered 'real', paving the way for the development of unprecedented simulations and sensations [37,40]. This approach enables project participants to assume an active role in previewing spaces, proposing modifications, and contributing to the formation of a habitable environment [34,41,42]. Although architecture, engineering, and construction (AEC) professionals may be familiar with ImVR, the technology remains a challenging novelty for the general public [43,44]. The integration of VR with building information modeling (BIM) and game engines within urban design projects offers considerable potential for enhancing end-user engagement and immersive, interactive design experiences [27,32,41]. Various VR plugins and game engines, such as Revit Live, Enscape, Unreal Engine, and Unity 3D, are available to architects and urban designers, facilitating the integration of VR into design and collaboration processes [41,45,46]. It is, however, crucial to recognize the inherent limitations associated with both BIM plugins and gamification methods within VR environments, including concerns about the validity and reliability of information obtained from VR simulations, potential biases, user comfort, accessibility, and potential discrepancies in individuals' behaviors and interactions in VR environments compared to real-life cognitive experiences [32,41,47]. These limitations underscore the need for comprehensive research on users' behaviors and interactions within VR environments as well as an evaluation of the most effective methods for ensuring legibility, flexibility, and user engagement.

The investigation of immersive virtual environments (ImVE) and their impact on design perception, physiological responses, and cognitive processes has yielded valuable insights that contribute to the enhancement of design patterns, creativity, and reasoning among users [35,39]. Empirical research suggests that ImVE can have positive effects on designers' cognitive functions, such as working memory, design information retrieval and access, spatial cognition, and attention allocation. Furthermore, ImVE has demonstrated favorable implications for users' perception and memory, leading to improved performance in problem identification and positively affecting both problem and solution spaces [27,30]. Collaboration within ImVE has also proven effective in fostering innovative problem-solving approaches among design collaborators. Nevertheless, some studies present contradictory findings indicating that heightened immersion could have adverse effects on recall, potentially due to cognitive limitations and mediated arousal [48–50]. This inconclusive evidence highlights the need for further research to thoroughly investigate the impact of immersive VR on participants' behavior and interaction within architectural and urban design contexts.

### *1.2. Elevated Urban Spaces*

Elevated urban spaces, comprising roof gardens, sky gardens, elevated parks, and skywalks, have gained prominence in high-density urban contexts, such as London [51–53]. These innovative spatial solutions contribute to the enhancement of urban environments by providing additional green and recreational areas that positively impact visitors' mental well-being [54,55]. The integration of such elevated spaces within the urban fabric is essential in addressing the growing need for accessible and health-promoting spaces in vertically expanding cities [56,57]. The emergence of elevated urban spaces in London can be traced back to the establishment of the world's first underground railway network in 1863, which marked the beginning of the city's multi-layered urban development [58,59]. London's transformation into a 'skyscraper city' has seen a trend toward the incorporation of elevated spaces in taller buildings [57,60]. The design and implementation of these spaces are influenced by a variety of factors, including accessibility, circulation, management, publicness, sustainability, and indoor environmental considerations [51,53,61,62]. Examples

of such spaces in London include the Sky Garden at 20 Fenchurch Street, The Garden at 120 Fenchurch Street, and Crossrail Place at Canary Wharf.

Despite the potential advantages of elevated urban spaces, they encounter numerous challenges, including regulatory constraints, accessibility issues, circulation and publicness considerations, limitations on activities, and design feature restrictions [51,52,54,63]. The COVID-19 pandemic further highlighted the vulnerabilities of certain indoor, elevated spaces, necessitating temporary closures during lockdowns. To address these challenges, it is crucial to adopt innovative co-design approaches that facilitate public participation in the design process. This underscores the need for further research, specifically within the scope of this paper, to explore the use of interactive virtual reality (VR) technology in developing a co-design approach that fosters user engagement in the design process of elevated urban spaces. By leveraging the capabilities of VR technology, designers and urban planners can gain a deeper understanding of users' diverse needs, ultimately contributing to the creation of elevated spaces that promote a more vibrant, sustainable, and equitable built environment.

### *1.3. Purpose*

The primary objective of this research paper is to explore the potential applications of virtual reality technology, with a specific emphasis on the utilization of gamification through Unreal Engine and building information modeling incorporating Revit and Enscape, to facilitate public engagement and co-design processes in the development of elevated urban spaces in London, exemplified by the Sky Garden and Crossrail Place. The research aims to systematically analyze the distinctions and commonalities between human interactions in physical and virtual environments. As such, it critically appraises the efficacy of implementing these two VR methods for establishing an interactive platform that fosters user involvement and inclusive design collaboration. It also assesses their implications for sustainable design quality and user satisfaction.

By addressing the existing knowledge gap in the academic literature concerning the most effective strategies for integrating public participation in urban design and leveraging VR technology as an instrument for co-designing public spaces, this research seeks to contribute to the creation of more vibrant, sustainable, and equitable built environments. Moreover, the study aims to elucidate the capabilities and constraints of these VR methods, thereby advancing the understanding of their potential impact on the urban design process and fostering a more informed and inclusive approach to the development of elevated urban spaces.

## **2. Case Studies**

In accordance with the research scope, aims, and purpose of this paper, which focuses on exploring the potential applications of VR technology in enhancing the design experience of elevated urban spaces, two distinct case studies in London were carefully chosen to facilitate a thorough evaluation of the proposed interactive model. The case studies were purposefully selected based on their unique characteristics and diverse spatial contexts, enabling the study to delve into various aspects of elevated urban spaces within the city.

The first case study, the Sky Garden, serves as a prime example of integrating green public spaces within high-rise buildings. It occupies the top three floors of the iconic 'Walkie Talkie' skyscraper at 20 Fenchurch Street, situated in the heart of London's financial district [64]. By investigating the Sky Garden, this research aims to comprehend the role and impact of elevated green spaces in densely populated and commercially driven areas, thereby scrutinizing the challenges and opportunities associated with incorporating nature into such environments (Figure 1).





**Figure 1.** London Sky Garden, 20 Fenchurch Street, London. Source: author.

In contrast, the second case study, the Crossrail Place roof garden, emphasizes the incorporation of green spaces within large-scale infrastructure projects. Located in North Dock, Canary Wharf, this 10,000 square meter, covered, elevated park is located above the Elizabeth Line, a crucial component of London's urban–suburban rail network [65]. The examination of the Crossrail Place roof garden seeks to provide insights into sustainable urban development and the potential benefits of embedding green spaces within transportation infrastructure (Figure 2).



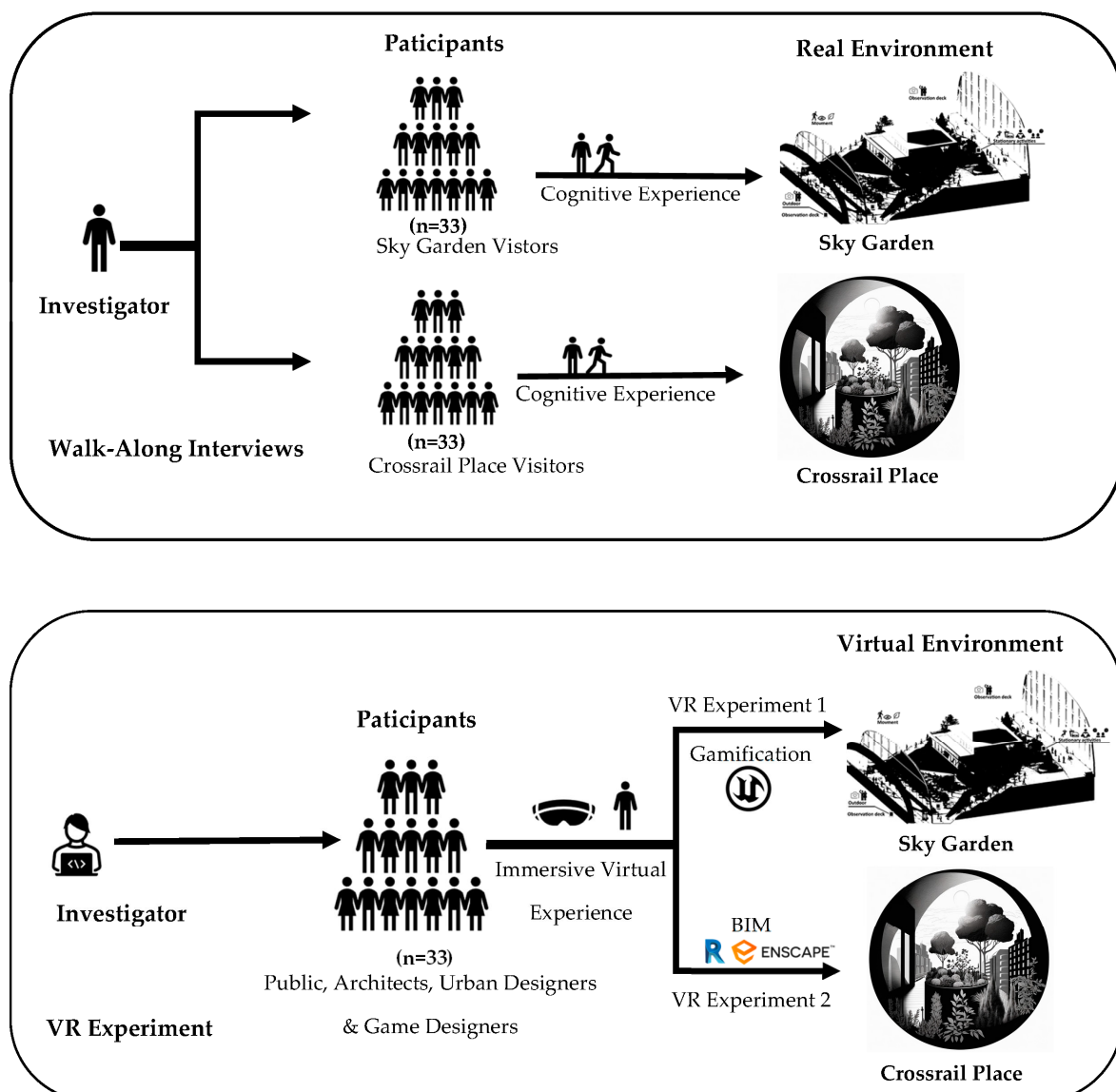
**Figure 2.** Crossrail Place roof garden, Canary Wharf, London. Source: author.

Through the analysis of the Sky Garden and the Crossrail Place roof garden, the study addresses the diverse ways in which elevated green public spaces can be integrated into the urban fabric as well as the challenges and opportunities unique to each context. Furthermore, the selection of these case studies allows the research to assess the differences and similarities in human interaction within both physical and virtual realms.

### 3. Methods

In order to comprehensively address the aims and objectives delineated within the scope of this study, a meticulously-crafted, qualitative, methodological framework was employed. A rigorous qualitative approach was implemented, encompassing two distinct

methods: walk-along interviews and a virtual reality (VR) exploratory experiment, followed by semi-structured interviews with the participants. The selection of these methods was carefully devised to yield in-depth insights into the efficacy of VR technology as a co-design approach in the development of elevated urban spaces, such as the Sky Garden and Crossrail Place (Figure 3). Moreover, the selected methods facilitated a thorough investigation of participants' behaviors, interactions, and activities, in addition to the design limitations in both real-world and virtual environments. This comprehensive approach enabled the researchers to examine potential divergences and convergences between the two modalities. Through this in-depth exploration, the research team was able to assess the opportunities and challenges presented by the integration of VR technology within the co-design process while also considering the potential necessity for new rules and regulations governing the use and design of such urban spaces.



**Figure 3.** Methodological framework to compare participant interactions in the cognitive and virtual environments. Source: author.

### 3.1. Walk-Along Interviews

The first method employed in this study, walk-along interviews, is a qualitative research technique wherein the investigator accompanies participants within the study

environment, specifically, the Sky Garden and Crossrail Place in London [66,67]. This approach, also known as ‘go-along interviews’, enables researchers to observe and discuss participants’ experiences and perceptions within the context of the studied environment. This facilitates a comprehensive understanding of user experiences and perceptions while concurrently identifying factors that shape the overall design experience [68].

Walk-along interviews are a well-established method in environmental psychology and urban design research, proven to be effective in various studies for exploring complex and multifaceted phenomena that are often challenging to measure quantitatively [67,69]. Through real-time engagement, spontaneous responses were captured and in-depth qualitative data was collected, allowing for the examination of human interaction and behavior within these elevated urban environments. Engaging in open-ended conversations with the participants, the researcher encouraged them to share their impressions, feelings, and opinions about the space, thereby facilitating the collection of rich, context-specific data that may not have been accessible through traditional interview techniques [69]. This method allows for a balance of structure and flexibility, addressing research concerns while permitting participants to express their unique perspectives and experiences freely.

A total of thirty-three ( $n = 33$ ) interviews were conducted and analyzed at each location, with each interview lasting approximately 30 min. Participants were recruited on-site and provided with a study overview, the expected duration of their involvement, and an ethics consent form to sign. The information gathered through these walk-along interviews allowed for deeper insight into the participants’ experiences, contributing to a more informed understanding of the factors that influence social interactions and activities within elevated urban spaces.

### Demographic Data Analysis

A total of 33 interviews were conducted at the Sky Garden in November 2021, with a gender distribution of 39.3% ( $n = 13$ ) males and 60.6% ( $n = 20$ ) females. The mean age of participants was 28.2 years. In terms of residency, approximately 36.6% ( $n = 12$ ) of the respondents resided in London, 39.4% ( $n = 13$ ) lived in other parts of the UK, and 24.2% ( $n = 8$ ) were international tourists visiting London. Similarly, 33 interviews were completed at Crossrail Place in December 2021. The gender distribution comprised 45.4% ( $n = 15$ ) males and 54.5% ( $n = 18$ ) females. The average age of participants was 30.3 years. Regarding their place of residence or work, approximately 60.6% ( $n = 20$ ) of the interviewees lived or worked in Canary Wharf, 24.2% ( $n = 8$ ) resided in other parts of London, and 15.1% ( $n = 5$ ) were short-term visitors to London, primarily tourists (Table 1).

**Table 1.** Demographic characteristics of participants at Sky Garden and Crossrail Place.

Demographic Information	Sky Garden	Crossrail Place
Interviews number	33	33
Gender		
Male	39.3% ( $n = 13$ )	45.4% ( $n = 15$ )
Female	60.6% ( $n = 20$ )	54.5% ( $n = 18$ )
Average age (years)	28.2	30.3
Residency/Work		
Living/Working in London	36.6% ( $n = 12$ )	60.6% ( $n = 20$ )
Living Elsewhere in the UK	39.4% ( $n = 13$ )	24.2% ( $n = 8$ )
International Tourists	24.2% ( $n = 8$ )	15.1% ( $n = 5$ )

### 3.2. VR Exploratory Experiment and Semi-Structured Interviews

The second method consisted of a VR exploratory experiment with a separate group of participants ( $n = 33$ ), immersing them in a virtual interactive environment of the Sky Garden and Crossrail Place. This approach enabled the researchers to examine the impact of VR technology on participants’ experiences and interactions within the study. The virtual reality (VR) experiment tests two different methods and tools for creating an interactive

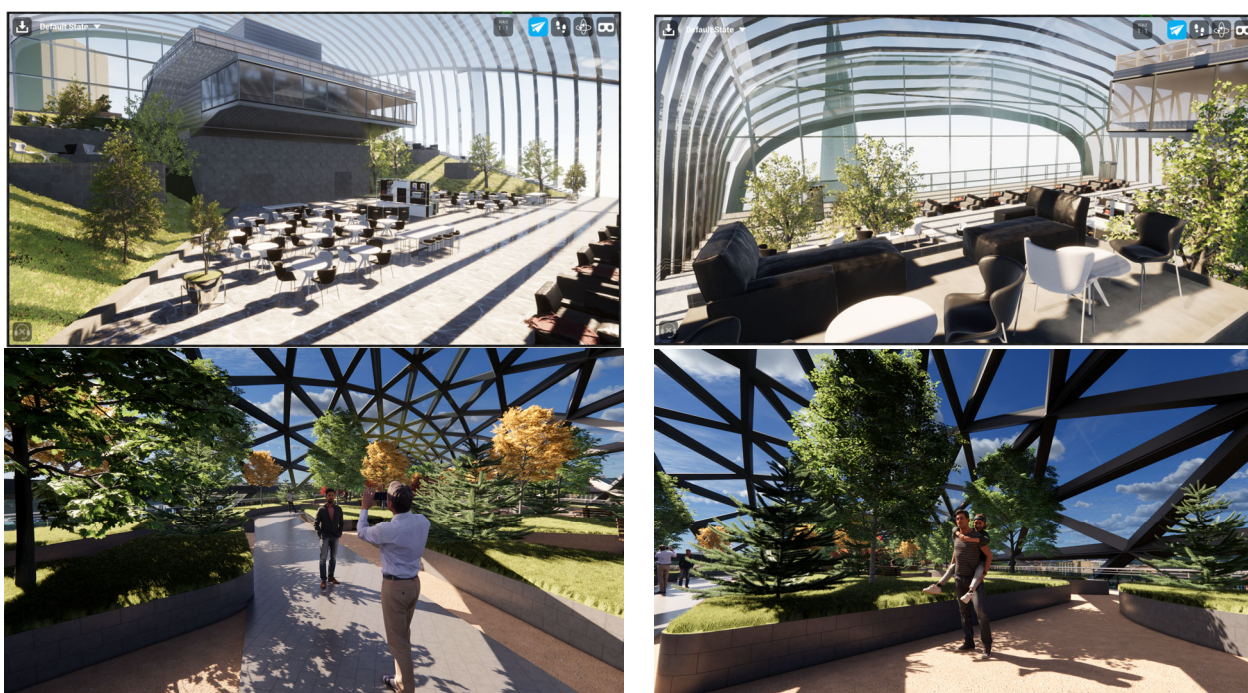


design model. One model is based on BIM ('Autodesk Revit' and 'Enscape' plugin) software and the other model is based on a game engine ('Unreal Engine'). These methods were specifically chosen due to their distinct abilities and capabilities in constructing an intuitive VR system and high-fidelity models. By offering diverse options and tools for design interactions, each method caters to unique aspects of the VR experience, ultimately providing a comprehensive and versatile platform for immersive and interactive virtual environments [41,45].

Following the VR experiment, qualitative semi-structured interviews were conducted to further discuss and analyze the experience of the participant's behavior in the experiment and their interaction with the designs. The interviews focused on participants' views on their virtual experience and behavior during the study. The duration of each interview was approximately 30 min. The conversations were recorded and transcribed, after which the recordings were deleted, to protect individuals, in accordance with the research ethics approval for the study.

### 3.2.1. VR Experimental Setup

In this study, the employment of virtual reality (VR) necessitated the utilization of both software and hardware tools. For the construction of the Sky Garden model, an initial design and modeling phase was undertaken using 3DS Max. Subsequently, the model was imported into Unreal Engine through the Data Smith exporter plugin, converting scene elements into compatible assets. To incorporate interactive features within the digital model, additional visual coding was executed using the 'blueprinting' method. Blueprint visual scripting, a fundamental component of Unreal Engine, represents an extensive gameplay scripting system that leverages a node-based interface to create dynamic gameplay elements (Figure 4). On the other hand, the Crossrail Place digital model was developed using building information modeling (BIM) techniques. Autodesk Revit 2022 software facilitated the model design process, eliminating the need for data exchange in the VR simulation. The Enscape plugin, compatible with Revit, enabled direct connectivity to the BIM model, providing real-time visualization in VR. This feature allows designers to implement real-time design modifications in VR as users engage with the model (Figure 4).



**Figure 4.** VR 3D models representing both the Sky Garden and Crossrail Place. Source: Author.

Regarding hardware, the study employed Oculus Quest 2, a standalone virtual reality headset developed by Facebook Technologies, a division of Meta. The device features four integrated cameras, ensuring user safety by tracking the real environment within the laboratory. The headset facilitates a full six degrees of movement tracking, allowing users to navigate the virtual environment. Additionally, a GoPro 360-degree camera recorded participants' motion within the laboratory setting. To mitigate the risk of VR-induced discomfort, safety precautions were implemented. The laboratory environment maintained adequate ventilation, and participants were offered the option to wear anti-nausea travel sickness wristbands during the VR experience. The laboratory was arranged to provide a safe space, free from obstructions in the user's immediate vicinity, prior to wearing the headset. The Oculus Guardian safety feature established room-scale mesh boundaries in VR, which appear when participants approach the edge of the designated experimental area, preventing collisions with walls or furniture. To gradually introduce the VR experience, user engagement was limited to 20 min, with intermittent breaks included. During these breaks, participants completed a personal comfort checklist, monitoring any symptoms experienced.

### 3.2.2. Participants

This study engaged 33 participants from diverse age groups and professional backgrounds, including architects, urban designers, interior designers, computer engineers, academics, and general public users. The recruitment process employed snowball sampling through various international networks. Participants were invited via email, which provided comprehensive information about the study. To maximize the generalizability of the results and ensure the findings were representative, targeted sampling methods were utilized: (i) the inclusion of participants from diverse architecture and urban design sectors, encompassing both large and small firms; (ii) the involvement of academics and experts in VR, design, and public engagement to share their perspectives; and (iii) representation from public participants, with consideration to age group and gender.

### 3.2.3. Procedures

This study utilized a VR laboratory experiment lasting approximately one hour to enable participants to interact with VR models of the Sky Garden and Crossrail Place. Participants were able to explore the virtual environments in real-time and make changes to the design features, including modifying materials, moving objects, adding or removing design features, and adjusting lighting and time of day. Participants gave informed consent and were given the option to withdraw at any time if they felt uncomfortable. The experiment was divided into three stages, including a short presentation and induction, participants completing an initial survey, and testing the VR models for 20 min (Table 2).

**Table 2.** Experiment procedures.

Activity	Duration
Induction (health and safety and consent)	15 min
Survey	10 min
Sickness Questionnaire	5 min
London Sky Garden (VR experiment)	10 min
Break (sickness questionnaire)	10 min
Crossrail Place Roof Garden (VR experiment)	10 min
Break (sickness questionnaire)	10 min
Semi-Structured Interview	30 min

During the Sky Garden experiment, participants were directed to follow a one-way circulation system, as required by COVID-19 regulations in the actual location, and were asked to interact with the space design by altering the materials of the floors, walls, and furniture to select their preferred design theme. They were then given access to X-ray

and virtual annotation options, enabling them to modify the design and organization of the space by moving or hiding objects or elements as well as to add highlights or write notes. Finally, participants were instructed to take two snapshot pictures of their newly designed space using the virtual camera, capturing the best views and areas they would like to photograph as if they were physically present in the Sky Garden.

In the Crossrail Place experiment, participants were advised to move freely in the space without following a fixed circulation. They were asked to add or remove design features and components to the roof garden and then test them in real-time, with the design components and features chosen by the participants added by the researcher using Autodesk Revit and edited by the participants. These included items such as public art, fountains, benches, flowers, and animals. To enhance the immersive realism of the VR model, sound effects were selectively introduced. These sound effects, such as crowd noise, birds tweeting, musical sounds emulating someone playing a guitar in the space, or the sound of a water feature, were added using Enscape if requested by a participant. The participants were encouraged to interact with the added features and elements, using the light simulation tool and virtual camera to render images.

### 3.2.4. Demographic Data Analysis

In this study, the 33 participants were systematically divided into distinct categories (Table 3). Group A consisted of 36% ( $n = 12$ ) of the participants who had previously visited London Sky Garden and Crossrail Place before engaging in the VR experiment, while the remaining 64% ( $n = 21$ ) were exposed to both gardens exclusively through VR during the investigation. Group B encompassed public users (55%;  $n = 18$ ) and experts (45%;  $n = 15$ ) from various fields, such as architecture, urban design, interior design, game design, and academia. Group C was composed of 52% ( $n = 17$ ) first-time VR users, 42% ( $n = 14$ ) occasional VR users, and a small fraction of regular VR users (6%;  $n = 2$ ). The subset of participants ( $n = 16$ ) with prior VR experience reported exposure to the technology across several domains, including gaming (the most dominant), social networking, mental health, architectural design, urban design, education, and product design.

**Table 3.** Demographic survey results for VR participants.

Group	Description	Percentage	Number of Participants
A	Visited gardens before VR experiment	36%	12
	Exposed to the gardens only through VR	64%	21
B	Public users	55%	18
	Experts	45%	15
C	First-time VR users	52%	17
	Occasional VR users	42%	14
	Regular VR users	6%	2

### 3.3. Qualitative Data Analysis

The investigator conducted a thematic analysis utilizing diverse qualitative data sets. Content analysis, an efficacious method for achieving descriptive objectives [70,71], guided the data examination through a summative approach. This analytical strategy facilitated the exploration of concepts comprising a number of themes, sub-themes, and their interconnections [72,73]. The final stage entailed investigating evidence of relationships between the overarching themes and discerning quotations that were initially challenging to categorize and incorporate into the themes and sub-themes. Subsequently, these sub-themes were integrated under the primary themes during the analysis stage of the research.

The comprehensive analysis of the study, derived from the collected data in both the physical and virtual environments, identified four predominant themes. These themes encompass: spatial circulation design, which focuses on the arrangement and organization

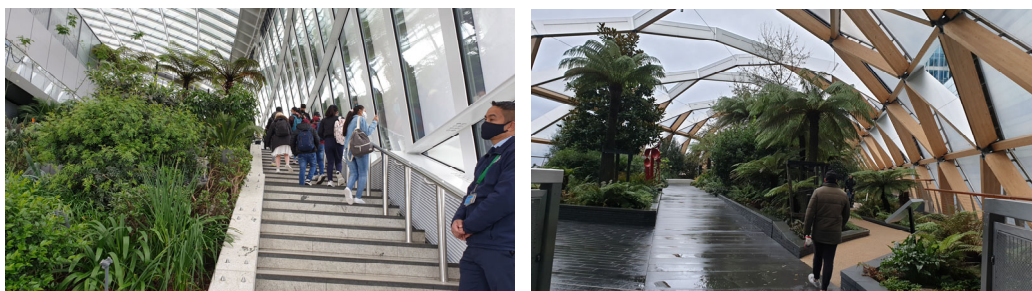


of spaces; design considerations, which address various concerns and factors influencing the design process; activities, highlighting the diverse range of actions and interactions occurring within the space; and finally, suggested design features and interactive design, which entail recommendations, proposals, and the integration of dynamic and engaging components in the design to enhance the overall user experience.

## 4. Results

### 4.1. Circulation

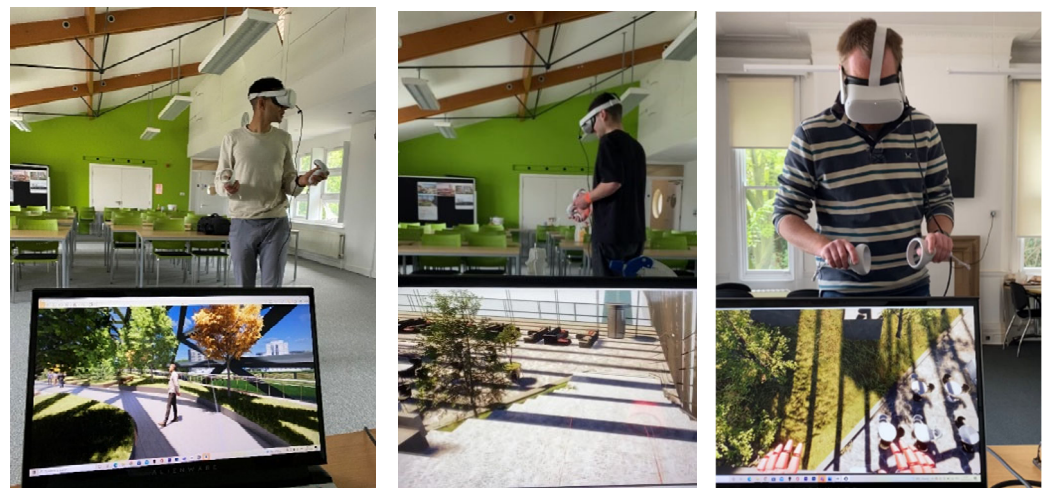
The analysis of the space circulation design theme in elevated urban spaces revealed a range of perspectives from participants in both the real-world walk-along interviews and the VR experiment. To gain a deeper understanding of the complexities of this design element, it is crucial to consider and compare the similarities and differences between the physical and virtual environments. The one-way circulation system in the Sky Garden, for instance, garnered mixed responses from participants in both environments (Figure 5). Some participants ( $n = 28$ ) acknowledged its necessity during pandemics and post-crisis, asserting that it facilitated a more focused and undisturbed appreciation of the views. One participant in the real environment remarked, “The one-way circulation was okay. I think it works really well as it makes you concentrate more on the views and you are less bothered by the people walking around you” (female, aged 33 years, living in London). Conversely, several participants ( $n = 38$ ) found the one-way circulation system restrictive, expressing frustration with having to traverse the entire path again if they missed a particular city view, as one participant stated that “if you pass something on the left and you want to see it again you must go around again. I guess that was a little bit annoying, so I went around a couple of times” (male, aged 27 years, living in London).



**Figure 5.** Participants’ circulation in the real environments of both the Sky Garden and Crossrail Place during the walk-along interviews. Source: author.

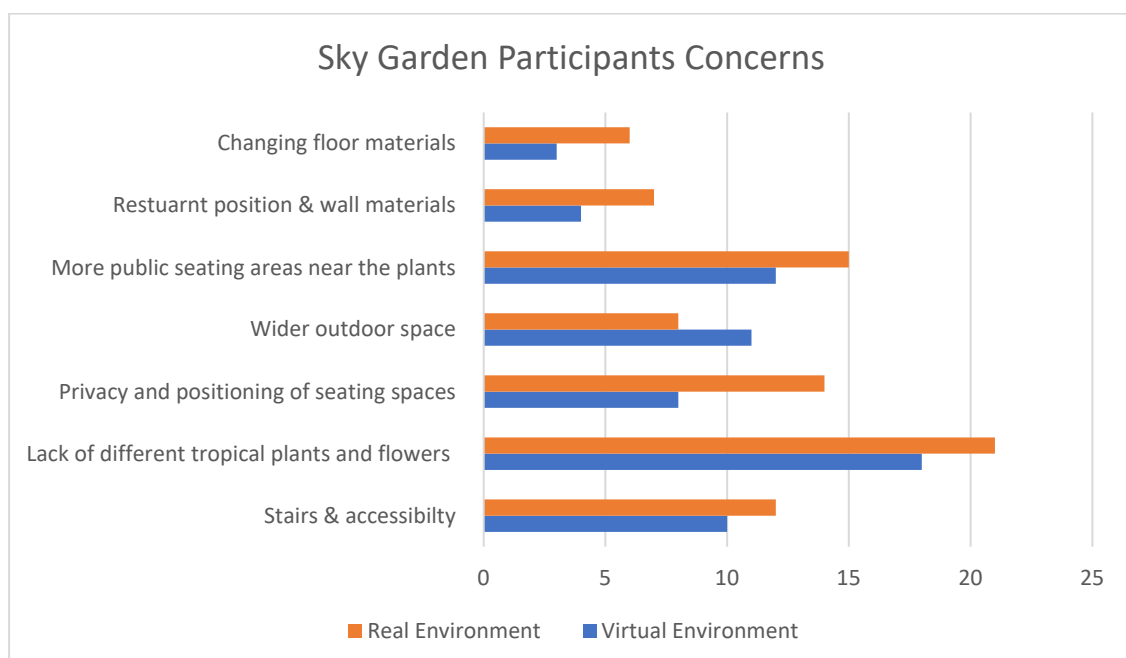
With respect to the different levels and accessibility in the Sky Garden, participants in both the real environment and the VR experiment enjoyed navigating between the varying heights (Figure 6). However, they concurrently expressed concerns regarding the limited accessibility for disabled and wheelchair users. In the VR experiment, participants ( $n = 21$ ) who had not previously visited the Sky Garden appreciated the experience of ascending the stairs virtually, with one stating, “I liked going up the stairs to different levels; it gave me the feeling of hiking or climbing a mountain and trying to experience different platforms” (a participant that had not previously visited the Sky Garden). However, they also suggested implementing accessible ramps or a stair platform lift as an alternative to accommodate wheelchair users: “Virtually, the space circulation is clear and easy to move around, but physically, because of the stairs in London Sky Garden, it might be a bit difficult for people with physical disabilities to move around” (landscape designer).



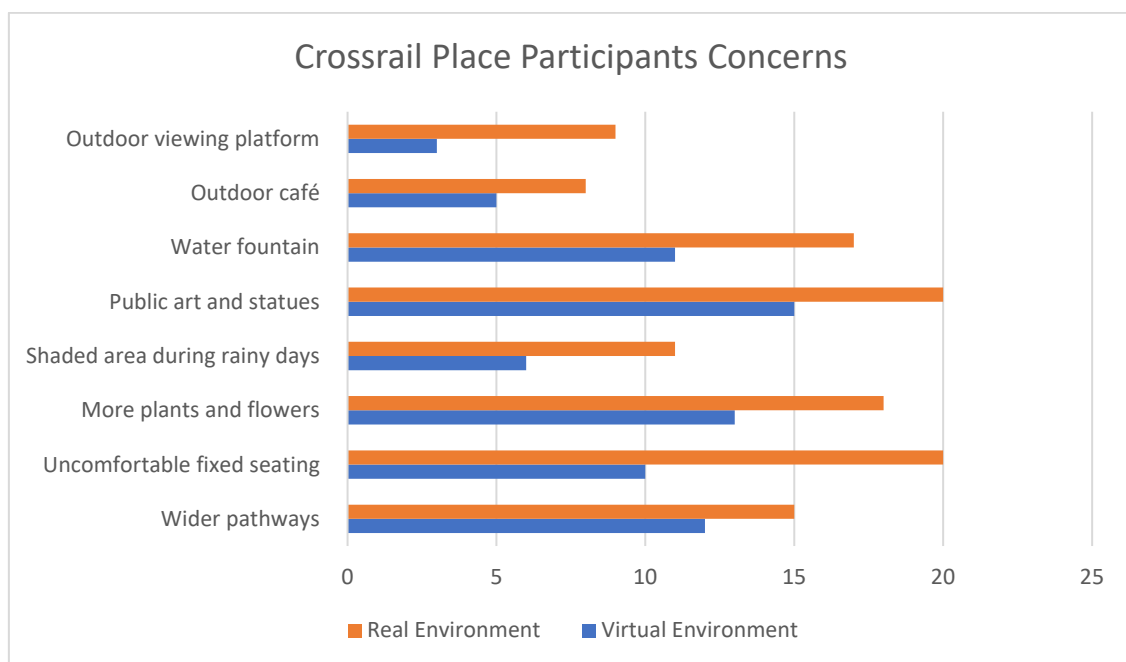


**Figure 6.** Participants' circulation in the virtual environments of both the Sky Garden and Crossrail Place during the VR experiment.

When exploring participants' preferences in the VR experiment, the responses diverged (Figures 7 and 8). A significant number of participants ( $n = 20$ ) expressed a preference for the Sky Garden's circulation due to its open floor plan, glass facade, and symmetrical layout. Conversely, a smaller group of participants ( $n = 13$ ) favored the Crossrail Place circulation, citing the curvy and multiple pathways as factors that contributed to a more natural and engaging park-like experience. One participant commented, "For Crossrail Place, it feels like you are walking and discovering space more like in a winter garden" (interior designer).



**Figure 7.** Bar chart illustrating the number of participants' concerns (out of a maximum of 33) in both the real and virtual environments of the Sky Garden.



**Figure 8.** Bar chart illustrating the number of participants' concerns (out of a maximum of 33) in both the real and virtual environments of Crossrail Place.

Lastly, the curved pathways in Crossrail Place were highlighted by participants in both the real environment and the VR experiment (Figures 5 and 6). These individuals appreciated the organic and intriguing feel of these pathways compared to more linear and symmetrical circulation systems. However, they also observed that the pathways were narrow, potentially confusing for first-time visitors, and lacked adequate privacy for those sitting on benches. In the VR experiment, participants suggested widening the pathways to address these concerns and to improve accessibility: "In Crossrail Place, I felt that the width of the pathways was too narrow for people to move. I really like the whole idea physically; the gardens and the landscape features were fantastic. Personally, I prefer the Crossrail Place circulation and I think the curves add a bit of adventure to the public space" (an urban designer that had not visited the Crossrail Place roof garden before).

#### 4.2. Design Considerations

Upon examining the design concerns derived from the participants in the real environment and the VR experiment, several critical insights surfaced, emphasizing the parallels and distinctions between the physical and virtual realms. Both participant groups pinpointed various design concerns and limitations in the Sky Garden and Crossrail Place. Most participants ( $n = 30$ ) in the VR experiment acknowledged the effectiveness of the virtual circulation method in simulating the physical environment. The method enabled them to gain a detailed overview of different design aspects, such as a sense of scale, lighting, materials, and furniture organization. Participants without a background in architecture or urban design were also able to express their views on the design limitations and to get involved in editing and testing their ideas in real-time, demonstrating the value of virtual reality as a tool for design evaluation.

Regarding the Sky Garden design, a significant number of VR participants ( $n = 26$ ) identified their limitations and concerns, which paralleled those of participants in the real environment (Table 4). These design limitations included providing more green areas and public seating spaces near plants and redesigning the organization of seating areas for more privacy, social distancing, and accessibility. There were also concerns about the design and materials in the restaurant and the outdoor viewing platform. In the physical experience of the Sky Garden, 85% of the participants ( $n = 28$ ) reported concerns about the design of

the space and suggested improvements for a better visiting experience. Common themes echoed those of the VR participants, including design concerns related to the privacy and positioning of seating spaces, the lack of different tropical plants and flowers, stair accessibility for disabled people, outdoor terrace design, and restaurant design (Figure 7).

**Table 4.** Comparative design concerns between physical and virtual participants in Sky Garden.

Design Concerns	Participants: Previously Interviewed at the Sky Garden in London	Participants: Not Been to the Sky Garden (Interviewed during the VR Experiment)
Public seating	<i>"It will be nice to provide more seating spaces for everyone and not only for people who are ordering food and drinks".</i>	<i>"I think having more public seating spaces like benches or stair seating near the plants could make people feel more comfortable sitting without feeling forced to order food or drinks".</i>
Seating areas organization	<i>"Despite the thing we are having right now because of COVID-19, I need more private seating areas. The seating spaces are comfortable but very close to each other. They need to be well designed and placed to maintain social distancing and privacy".</i>	<i>"I also think it will be awkward having to share the sofa with strangers. If I am physically in the space, I will choose to sit on one of the chairs near the plants".</i>
Plants and green spaces	<i>"I think with the name itself Sky Garden, I would like to see a different kinds of flowers and roses. If they can add more green features, it will differently encourage more people to come and visit, not only for the view".</i>	<i>"With the name 'garden', you are expecting to see more natural plants. It would be nice to add more green space and a bit more flowers".</i>
Outdoor terrace	<i>"The terrace was restricted with a certain number of people, so the garden might need a more open space for people".</i>	<i>"I think maybe an open space, so instead of being in an indoor environment all the time, it may be a bigger outdoor area".</i>
Restaurant design	<i>"I think that the restaurant in the middle is like blocking out most of the view; you have to go around it to see most of the city views and landmarks".</i>	<i>"I don't like the design and the position of the restaurant in the middle of the space I think it needs to be more open and the higher you go up the better view you would get; and for the restaurant design it would be better if it's all glass and transparent so even people inside could enjoy the view".</i>
Accessibility	<i>"I don't know how it would work if you were handicapped in any way, or if you have a disability. A lot of the garden experience is on the stairs so you wouldn't be able to see any of that if you are taking the elevator".</i>	<i>"I always care about people with wheelchairs or old people. I didn't see any ramps in the roof gardens. You could do a hybrid: blend ramps and stairs together, and it will be both statically and functionally so good".</i>

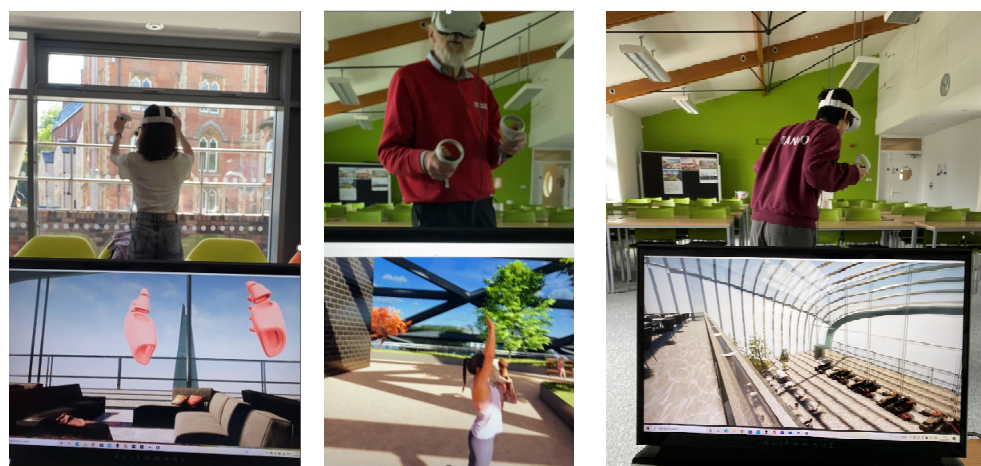
Many participants (n = 18) in the VR experiment preferred Crossrail Place due to its green, natural, and landscape features, describing it as "more public" than the Sky Garden. Participants in both the real environment and the VR experiment again expressed similar concerns, such as the need for comfortable and sociable seating areas, wider pathways for privacy and accessibility, and more plants and flowers. Data from the Crossrail Place real environment highlighted several concerns that were also identified by VR participants, such as the lack of shaded areas to protect visitors from inclement weather, narrow pathways, uncomfortable seating benches, poor visual accessibility, and a lack of social interaction. Many participants in the real environment also mentioned the absence of public toilets on the roof garden level, necessitating visitors to go to the ground floor (Figure 8).

In conclusion, participants in both the real environment and the VR experiment identified various design concerns and limitations in the Sky Garden and Crossrail Place, illustrating the similarities between the physical and virtual worlds. The virtual circulation method effectively simulated the real environment experience, enabling participants to provide valuable feedback for potential improvements.

#### 4.3. Activities and Participant Interaction

In the virtual Sky Garden, participants anticipated engaging in activities such as enjoying city views, having a drink, eating, meeting friends, and taking photographs. Meanwhile, at Crossrail Place, they expected more relaxation-oriented activities, including enjoying the plants and natural environment, reading, eating lunch, and taking photographs. Participants generally appreciated the virtual environment exploration in both spaces, with many recognizing its potential for additional virtual activities. They valued the ability to explore and test the space without physically being there and suggested offering free virtual tickets to attract more visitors to the physical locations. A substantial number of participants who had not visited either garden indicated that the VR experience made them more interested in visiting in person.

The majority of the participants ( $n = 31$ ) noted that the VR experience provided a sense of confidence and freedom to explore various physical and virtual activities, such as jumping, flying, dancing, running, and sitting on the floor. The VR environment stimulated their senses and encouraged interaction with the design features and objects, helping them understand their needs and preferences within the space. However, the absence of other sensory experiences, such as touch, air movement, and smell, was seen as a barrier to creating a fully immersive experience (Figure 9). One academic participant, for example, stated that: “I suppose that VR also affords magical possibilities: such as the fact that I could fly, I can go through the ground, stand on a sofa, can do things that I can’t do in the real world. So, if you put these various things together, you are not going behave in any form of regulated way”.



**Figure 9.** Participants’ interaction with the virtual environment.

Interestingly, many participants ( $n = 29$ ) expressed a sense of loneliness in the virtual space, preferring to share the experience with others, such as friends, family, or the public. They enjoyed observing static human models in Crossrail Place and suggested additional social activities, such as online gatherings, meetings, webinars, and using the space as a social platform (Figure 9). Participants also expressed interest in more interactive experiences, such as playing games or watching movies with others. Some participants, reflecting on their lockdown experiences, acknowledged the potential of VR as an online social platform for use in future pandemics. While they recognized that virtual socialization could not fully replace physical experiences, they believed it could positively impact the mental health of individuals living alone during pandemics. Indeed, a participant that had previously visited both places noted that:

*“From my point of view in terms of mental health, especially during the lockdown, it (VR experience) could make a big change, especially for people living alone. It will definitely be suggested, I think it’s an enjoyable element that can bring more happiness and change people’s mood if they use space to socialise with others.”*



#### 4.4. Suggested Design Features and Interactive Design

##### 4.4.1. Real Environment Insights: Design Features

The analysis of data gathered from participant interviews in real environments sheds light on their capacity to pinpoint design concerns and suggest new features and activities for both the Sky Garden and Crossrail Place. Despite this, participants encountered challenges in visualizing the implementation and functionality of these proposed elements within the space. Additionally, they had difficulty accurately describing the locations of design elements and essential design fixtures necessary for fostering vibrancy, safety, and social interaction.

For both spaces, participants suggested features and activities to improve the design quality of the space, encourage physical activity, and promote social interaction. Common suggestions included: adding electricity sockets; providing drinking fountains; playing soft background music; placing new relaxing seats and quiet areas near plants; and offering guided tours. To facilitate social interaction, participants also recommended organized events, live music events, interactive social seating areas, and educational features. Features encouraging physical activity included more plants and flowers, fitness equipment, yoga classes, table tennis tables, interactive night lighting pathways, and themed events.

##### 4.4.2. Virtual-Reality-Enabled Interactive Design Exploration

During the VR experiment, participants were able to identify most of their design concerns and suggest design features and activities that were similar to the real environment participants' needs and suggestions. However, the VR experiment enabled the participants to unleash their creativity, imagining and testing their design ideas in real-time using interactive design tools. The opportunity for interactive design was highlighted as a crucial and enjoyable aspect by the participants. All participants ( $n = 33$ ) concurred that the utilization of these innovative tools and features could substantially enhance their perception of the design quality in both case studies. A majority of the participants ( $n = 28$ ) posited that the incorporation of these tools in architectural design could effectively engage users, empowering them to envision and refine project details. This engagement would facilitate a deeper understanding of design challenges, allowing users to adapt the design and evaluate the space's utilization based on individual needs and activity preferences.

The interactive design process, as explored during the experiment, was divided into two subcategories: interactive design simulation and real-time design. Interactive design simulation provided participants with the ability to manipulate and assess various design scenarios for the space. Examples of these scenarios include light simulation, which allowed participants to examine lighting in real-time across different times of day and seasons; material modification of design objects, such as floors, walls, tables, and seating areas; the X-ray feature, which granted participants the capability to reposition and conceal different design objects within the space; virtual annotations that facilitated the outlining and illustration of participant-initiated changes and requirements in the space; and lastly, the virtual camera, which participants employed to capture rendered images and screenshots of their real-time alterations and refinements in the space (Figure 10).



**Figure 10.** Participants testing their design ideas in real-time using interactive design features.

The first experiment using the interactive gaming VR platform based on Unreal Engine demonstrated positive outcomes for the participants. The platform allowed them to manipulate the spatial design of the Sky Garden model, testing and capturing various design scenarios. Key themes that emerged included altering the spatial organization of the space by moving objects and design fixtures to create more areas for social interaction as well as spaces for relaxation and privacy. Participants also experimented with changing the materials of walls, floors, and restaurant spaces to make the Sky Garden more visually appealing and colorful. Furthermore, some participants, particularly designers, employed the VR annotation tool to emphasize their design concerns, offering ideas and suggestions such as incorporating more plants and water features.

In the second experiment, the integration of Revit BIM software with the Enscape plugin provided a real-time design experience in VR at Crossrail Place. This method required the investigator to actively respond to participants' needs and preferences, making real-time design changes based on their input. As participants virtually navigated the site, they were able to voice their design concerns and identify desired additions to the space, enabling them to test the feasibility of their ideas in real-time (Figure 10).

A significant number of participants ( $n = 21$ ) expressed the need for increased interaction in the Crossrail Place roof garden and proposed new design scenarios and activities to attract more visitors. These design ideas were then tested by the participants within the VR environment, allowing them to assess the impact of their suggestions on the overall space. Recurring design themes included water features (e.g., fountains or ponds), exercise spaces (e.g., calisthenics parks or cycling areas), public art, comfortable seating, more plants and flowers, open plazas for various events (e.g., musical concerts), gaming areas (e.g., pool tables and table tennis tables), outdoor cafés, and outdoor spaces for animals such as birds and butterflies. This real-time design exploration empowered participants to actively engage in the design process and fostered a deeper understanding of the implications of their ideas on the space's overall functionality and aesthetics.

## 5. Discussion

This study's findings build upon and extend the growing body of literature that emphasizes the potential of VR as a tool for public engagement in sustainable urban design practice [26,29,30]. The comparative analysis conducted between real and virtual environments demonstrated that participants in both settings could effectively identify design concerns and suggest improvements. In order to further elucidate the similarities and differences between real environments and VR 3D models, it is important to note that both mediums could provide participants with a rich understanding of the spatial configuration and aesthetic qualities of the gardens. However, certain aspects of the real environment, such as sensory experiences (smell, touch, wind, temperature, etc.) and nuanced details (weathering effects, plant growth, etc.), could not be fully replicated in the VR 3D model. This has some implications on how users perceive and interact with these spaces, influencing their observations and feedback. Nevertheless, the VR 3D model offered unique benefits that are not possible in a real environment. For example, it allows for the manipulation of design elements and easy visualization of alternative design scenarios, providing a dynamic tool for participatory design processes.

This is consistent with previous research on the utilization of immersive technologies in urban design [32,37] and other studies where VR has been employed for various applications, such as simulating pedestrian experiences in urban environments [33]. However, this study expands upon the existing literature by showcasing the effectiveness of VR in enabling real-time design modifications, fostering a more in-depth understanding of design challenges, and facilitating an interactive design process [34,35]. Previous studies have largely focused on using VR for visualization purposes, whereas the research presented in this paper focuses on the interactive aspect of VR, empowering users to actively engage with and modify the design of vertical green social spaces [31,40]. Highlighting the crucial implications for practice, the findings of our study indicate the transformative potential of VR for urban design, urban planning, and architecture design. By facilitating real-time modifications and providing an immersive understanding of design challenges, VR can serve as a powerful tool for designers and policymakers whilst playing a key role in the creation of more sustainable and inclusive cities.

The study's unique approach of incorporating both groups of participants—those who had physically visited the gardens and those who had not—also offers valuable insights into the potential of VR as a co-design tool for public spaces. This methodology, therefore, contributes to the broader discourse on inclusive and participatory urban design processes. By highlighting the capacity of VR to engage diverse stakeholders in the design process, regardless of their prior experience with the physical spaces, this study contributes to the ongoing exploration of innovative and sustainable solutions for our towns and cities.

The experimental study's results demonstrated significant potential in utilizing VR as a co-design approach for designing and refurbishing vertical green social spaces. As mentioned earlier, the majority of participants ( $n = 20$ ) who had not physically been to both gardens successfully identified design limitations and concerns through the VR experiment. This enabled participants to suggest various activities and design features, empowering them in the design process. Notably, the design issues and needs discussed by this group of participants closely aligned with the concerns and needs of actual space users who had previously been interviewed in both gardens. This finding suggests that the VR experiment effectively bridged the gap between the experiences of physical visitors and those who had not yet visited the spaces. Moreover, our study extends the application of VR beyond mere visualization to functioning as a co-design tool, fostering an inclusive, participatory design process. This suggests that VR can democratize urban design by empowering diverse stakeholders to actively contribute to the design of public spaces. Such inclusive design strategies are key to developing urban environments that are not only sustainable but also genuinely responsive to the diverse needs and preferences of all users, showcasing the potential of VR in fostering a more inclusive and participatory urban design process. Utilizing VR technology highlights the long-term significance of design

decisions, ultimately fostering the longevity and sustainability of public places by enabling stakeholders to efficiently address environmental, social, and economic considerations.

In constructing an immersive virtual environment for co-designing public spaces, several inherent limitations must be addressed. One significant challenge is providing sufficient physical space for participants to navigate freely within the virtual realm. Although the current study employed a standard ‘guardian’ area, respondents indicated that a larger, open space would enhance the sense of realism. Omnidirectional treadmills have been proposed as a potential solution; however, their high costs and required training render them unsuitable for widespread public use [74,75]. Additionally, some participants experienced VR sickness symptoms attributable to hardware factors (e.g., display type, mode, time delay), content factors (e.g., graphics, task-related features), and human factors (e.g., personal responses to VR). Reducing VR sickness in future research is essential to ensure participant comfort and optimize the overall VR experience [76,77].

Another limitation concerns social interaction within the virtual environment. Participants expressed a desire to share their virtual experiences with others, underscoring the need for an enhanced collaborative design experience. While VR social applications are currently available, they often provide limited design tools and inferior CGI model quality and lack direct links between architectural design software and social VR applications [32,43,78]. Addressing these concerns is vital for improving collaborative design experiences. For instance, integrating more advanced user interaction techniques, such as motion tracking technologies, could significantly enhance the VR experience by enabling more natural and intuitive interactions within the virtual environment [79].

In addition, recognizing users’ facial expressions, as suggested by research on active appearance models and neural networks, could make VR environments more interactive and responsive, leading to a more immersive user experience [80,81]. Haptic feedback remains a significant challenge in VR environments. Although existing VR systems deliver realistic visual and auditory feedback, haptic feedback is often lacking, limiting users’ ability to interact within free and constrained spaces. The development of multimodal haptic devices could ameliorate this limitation; however, cost and accessibility barriers persist [82,83].

The primary limitations of the main study relate to its small sample size, which may inadequately represent the broader population. To strengthen the study’s findings and enhance their generalizability, future research should incorporate a larger, more diverse pool of participants. Expanding the sample size would facilitate a more comprehensive understanding of VR’s potential as a co-design tool in urban design, particularly when designing and refurbishing vertical green social spaces. Another constraint involves the lack of knowledge and expertise among designers in creating interactive VR models as well as interoperability issues between 3D CAD software and VR platforms. Addressing these obstacles would render VR-based co-design more accessible to professionals. Furthermore, the time and financial requirements associated with designing realistic and interactive VR models may discourage professionals from adopting VR-based co-design methods, favoring traditional design approaches instead. Reducing these constraints is essential for promoting the use of VR in urban design.

As such, future research should focus on addressing the identified limitations by exploring larger sample sizes, improved VR experiences, and the role of artificial intelligence (AI) in augmenting users’ ability to describe and design schemes in real-time. Moreover, future studies could consider the incorporation of sensing devices for collecting more refined physiological features in the virtual environment, respecting participant privacy and ethical considerations. Furthermore, the development of architectural software to integrate VR into intuitive design systems would help eliminate the need for designers to learn new programming skills or export models to other game engines. Consequently, this would make VR-based co-design more accessible and practical for urban design professionals. Finally, the exploration of combined VR and AR technologies could pave the way for more immersive and effective co-design processes. In such a mixed-reality scenario, real-time



camera tracking would allow for seamless integration of real and virtual worlds, thus offering a more robust platform for co-design activities [84].

## 6. Conclusions

The present study has investigated the potential of virtual reality (VR) as a participatory design tool for public space design, specifically comparing the experiences and design feedback of participants in real-life and virtual environments. The findings demonstrated that VR-based design tools offer a valuable platform for participatory design and user engagement, enabling participants to actively explore, test, and suggest changes to the design of public spaces. This is essential if we are going to create public spaces that can meet peoples' needs and, therefore, achieve long-term social and economic sustainability.

In both the real-life and virtual environments, participants provided valuable insights into design concerns and suggested features to improve the design quality, encourage physical activity, and promote social interaction. However, VR-enabled interactive design exploration empowered participants to actively engage in the design process, unleashing their creativity and allowing them to test and visualize their ideas in real-time. This deeper engagement facilitated a better understanding of design challenges and helped participants adapt the design based on their individual needs and preferences. The study also revealed the potential of VR as a social online platform for future pandemics. While participants acknowledged that virtual socialization could not fully replace physical experiences, they recognized the positive impact of VR on mental health for individuals living alone during lockdowns or pandemics.

Overall, the research findings highlight the advantages of integrating VR into the participatory design process, demonstrating its potential to engage users, enhance design quality, and improve the overall functionality and longevity of the design and the aesthetics of public spaces. Future research should further explore the potential of VR in urban design and planning, investigating its application in various contexts and examining the long-term effects of VR-enhanced participatory design on public space utilization and satisfaction.

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