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Immersive Urban Planning: Evaluating Park Safety Perception with Digital Twins and Metaverse Simulation

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Abstract

The objective of this study is to explore the use of emerging technologies such as the Metaverse and Digital Twin to highlight how these can be used to analyse and improve the perception of security in urban parks. Through the proposed methodological approach, which combines real data collection, 3D modelling, immersive simulations, and user feedback, a virtual environment representative of the Quartieri Spagnoli Park in Naples, chosen as a case study, was developed and tested. The experimentation involved a heterogeneous group of users and consisted of two phases of questionnaire administration, one in person and one in a virtual environment, to compare the individual and collective perceptions of users in relation to issues such as disorientation, lighting, and maintenance. The results obtained made it possible to identify a correspondence between the data collected in the two environments, and to highlight any critical issues that emerged. Undoubtedly, the virtual experience proved to be useful, accessible, and immersive, demonstrating the potential of these tools not only in identifying issues but especially in supporting participatory design and urban planning with a view to a smart city. In urban design, as in many other fields, being able to intervene and test changes in a virtual environment before actually implementing them is a valuable opportunity, as it allows the feasibility to be assessed without compromising the real space. It is precisely this aspect that makes this type of approach extremely interesting and important. The distinctive feature of the proposed approach lies in the implementation of digital twins in the metaverse, which can perform a dual function: simulation and verification. In the first case, simulations within the virtual environment allow project planning to be tested in order to predict the outcome; in the second case, it is possible to investigate the state of affairs, thus assessing whether the planning put in place has achieved the desired results.

Keywords: metaverse; digital twin; 3D modelling; urban planning

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1. Introduction

1.1. Traditional Risk Analysis

Safety in urban parks in metropolitan areas is an important aspect in determining people's quality of life. These places offer numerous benefits to the community, including recreation and opportunities for social interaction and physical activity. However, the perception of safety within these places can significantly influence their use by citizens. The issue of safety in urban parks fits perfectly into a broader framework, which is urban planning: the aim is to organise and regulate land use, infrastructure development, and

city [1] growth to promote sustainable development and improve the quality of life of residents. The perception of safety may depend on several factors, which can be identified, analysed, and then, if necessary, modified to make parks safer and more welcoming. Among the many factors, the design of the park is certainly of fundamental importance, as well-structured environments with wide views and no 'dark zones' help to reduce the risk of unlawful behaviour. Similarly, the choice of an adequate and effective lighting system is also essential: well-lit areas discourage criminal acts and convey a greater sense of security, especially in the evening hours [2–4].

The constant maintenance of the structures and greenery is another important aspect not only because it keeps the park's appearance pleasant, but above all because it reflects care and attention to the environment, reinforcing the idea of a protected and enhanced space [5,6].

Although the literature on urban safety has already made use of digital tools, few studies integrate these tools with sentiment analysis and user–virtual environment interaction, such as the Metaverse, with the aim of assessing and improving the perception of safety in urban parks. To achieve the goal of security, the physical layout and design of the urban park should follow the principle of crime prevention through environmental design (CPTED), which includes natural surveillance, access control, and spatial reinforcement.

The concept of security in an environment has two dimensions: the objective dimension, based on actual and recorded events, and the subjective dimension, based on emotionally perceived security. The subjective dimension implies that a person may have the perception that a place is not safe, when in fact it is, and vice versa. In general, people tend to act according to their perception of safety rather than actual safety, meaning that the use of outdoor environments is also influenced by perceived safety rather than objective safety [7]. This gives rise to the need to investigate how personal safety can be perceived within a public space. Knowing what potential and actual dangers a user experiences in an urban park is crucial in order to moderate and shape the design of greenery and architectural appearance, so as to limit and prevent criminal activities.

1.2. New Technology for Risk Analysis

Digital technologies, which are increasingly integrated into our daily activities, are also assuming a central role in the field of urban planning [8]. Tools such as data collection systems, artificial intelligence, environmental sensing, and digital participation platforms are radically transforming the way we plan, manage, and experience urban spaces [9]. These innovations enable greater dynamism and awareness of the environment, making cities more efficient, sustainable, and responsive to the needs of their citizens. The ability to monitor traffic, air quality, or the use of public spaces in real time, for example, allows public decision-makers to intervene in a timely and targeted manner, improving the quality of urban life and promoting more active community participation in decision-making processes [10,11]. Among the innovative concepts and tools that have emerged in recent years are undoubtedly smart cities, the Metaverse, the Internet of Things (IoT), and Digital Twins (DTs), which, besides shaping the future of contemporary society, have opened up new possibilities for improving security in urban parks [12,13].

The concept of the city has evolved over time in light of the fact that urban settlements are not merely the sum of their physical structures, but rather a set of complex relationships between the various elements that comprise them. Cities, therefore, can be defined as a dynamic system in which material and immaterial elements constantly interact, generating meanings and functions that go far beyond the mere sum of the components [14]. The ways in which cities are represented have also evolved over time: for decades, two-dimensional representations were used, on the one hand, to interpret the transformations of a territory,

and, on the other, to store data. Today, as the amount of data to be collected is becoming ever greater, the use of three-dimensional models is resorted to, which, with the support of technologies such as the IoT, DTs, and Metaverse, make it possible to represent even better realities as complex as urban ones [12,15].

In this regard, the concept of DTs, which originates as a digital replica of a physical object, process, or system, can also be applied to the context of urban and spatial planning. By digitally replicating the real city through the integration of data from sensors, 3D models, GIS, simulations, and real-time sources, a DT can be obtained that makes it possible to analyse scenarios, predict impacts, and test urban policies or infrastructure projects before actually implementing them, thereby improving the quality of decisions and reducing risks and waste. It must be said, however, that although DTs and the smart city are two closely related concepts, they are not synonymous [16,17]. A smart city is a broader approach, involving the adoption of digital technologies to improve urban services, environmental sustainability, mobility, civic participation, and quality of life for citizens [18–20]. In other words, a DT may be one of the foundations of a smart city, but it is not sufficient on its own to define it. The value of a DT lies in its ability to provide an integrated and predictive view of the city, facilitating the transition from reactive planning to proactive management, based on data and simulations [21].

In the context of urban planning, DTs can have interesting implications in the Metaverse: the development of construction projects, the planning of urban areas, and the optimisation of resource management are just some of the many uses of DTs in the Metaverse [22]. The emerging Metaverse concept describes a shared and interconnected virtual universe where people can interact in real time through digital avatars. This virtual space represents a fusion of augmented reality (AR), virtual reality (VR), and the Internet, creating an immersive environment where people can work, play, socialise, and shop [23].

The objective of this study is to exploit the implementation of DTs in the Metaverse to obtain data from a sentiment analysis, the results of which will be used to improve the security of a park, which will be taken as a case study [24]. The implementation in the Metaverse is chosen not only to take advantage of the existing space in a virtual manner, but above all because of the possibility of simulating different alternatives on the basis of the collected data and, thus, user preferences. Furthermore, the decision to consider urban parks is a very targeted choice [25]. In recent years, many researchers and practitioners of the built environment have considered the importance of eliminating crime within parks, through planning and design, recognising it as a real problem in our cities [26,27]. A park is a built space that was created as a place for recreation, for sporting or leisure activities and for social gatherings, and it should therefore be free of crime or crime incidents. When this is not the case, the reduced sense of security for users diminishes its value as a place of enjoyment and tranquillity [28,29].

The main objective of this study was to understand and validate the perception of safety within urban parks, comparing experiences in the real and virtual worlds. The study was applied to the Parco dei Quartieri Spagnoli in the city of Naples, and the results obtained highlighted both points of contact and significant differences between the two environments, offering new perspectives for assessing urban safety through innovative and digital approaches.

To obtain the results illustrated below, the Metaverse and Digital Twin were used as innovative tools to analyse and improve the perception of safety in urban parks, through immersive simulations based on real data and user feedback. The same feedback can also be used to make improvements to the spaces analysed, first in a virtual environment and then, only if deemed appropriate, in reality.

2. Related Studies

This paragraph is organised into three thematic strands: frameworks and instruments for urban park safety perception (CPTED); digital twin applications in planning related to safety—scenario testing, wayfinding/lighting, and maintenance/image proxies; and immersive Metaverse/VR studies in urban planning and participatory evaluation. This structure compares methodologies, strengths, and limitations, and validation practices. The continuous technological progress and the development of different ways of modelling, designing, and understanding a city has caused the very concept of the city to change, taking into account its complexity [14]. On account of this continuous evolution, over the years new tools have been added to interpret what surrounds us and what we use. One such tool is the IoT, which can be described as a network of sensors, software, and other integrated technologies that aim to connect and exchange data with other devices via the Internet. Another tool for more sustainable and quality-of-life-conscious urban planning, as well as energy consumption, is DTs. These are computerised representations of processes that define the functions that determine the functioning of a physical system and, in this sense, are strongly coupled with the original system, allowing information to be shared between the system and its twin [30]. The latter extensors also explore the definition of the city not only in its superficial physical form, but also in the series of activities functioning through urban processes, where the figure of the planner, the one who manipulates the DTs to understand the real system and improve the design with appropriate predictions, is fundamental.

DTs and the IoT are undoubtedly the current driving forces in the field of the built environment; they represent two different concepts, which, taken individually, represent a city that evolves and changes, but, when superimposed and linked together, make it possible to achieve efficient, sustainable urban planning that is capable of providing tools for monitoring and strategic environmental assessment [31]. Smart cities arise precisely from the integration of the IoT and DT and can be further implemented in the Metaverse, giving rise to intelligent strategic planning, as one will have access to real-time data embedded in a virtual environment [32]. Although the Metaverse is currently mainly used in the gaming sector by large corporations, its potential extends to numerous other areas, including marketing, education, smart cities, psychotherapy, tourism, and entertainment. Thanks to its digitisation tools and ability to foster social interaction between citizens [33], the Metaverse can be integrated into applications dedicated to smart cities, which make use of data to monitor various aspects of urban life, with the aim of increasing efficiency and improving quality of life. In the context of the DTs and the Metaverse, data represent a fundamental resource: they not only support these systems but also convey and concretise information and knowledge [22]. The DT constitutes a theoretical scenario applicable to the Metaverse, providing real data to its components and thus creating a direct correspondence between the physical and virtual worlds. In this way, the DTs of cities are becoming increasingly faithful to their real counterparts, as their digital elements are increasingly integrated into the processes that govern the dynamics of the real urban system [30].

Starting from the concept of the Metaverse and DTs, in [34] a platform is proposed that is developed on various management levels, each with a specific task. The minimum levels to combine DTs and the Metaverse are outlined, such as: a network infrastructure that guarantees reliable and high-speed connectivity; data management, which is essential to collect, process, and utilise information; a DT, intended as a digital replica of physical systems to facilitate understanding; and finally, the Metaverse, i.e., an immersive virtual environment in which people can interact with each other and with digital objects.

In [33], on the other hand, the authors analyse the potential applications of the Metaverse to smart cities: administration and citizen services, entertainment and quality of life,

education and universities, healthcare, tourism, transport, infrastructure and networks, public authorities, economics, and urban planning. With reference to the latter, the application of the Metaverse in a smart city opens up new horizons to the use of planning and simulation tools capable of providing a digital representation of the real urban environment, as data from the real world are integrated, favouring joint decision-making between administrations and planning offices. This interconnection allows for a risk assessment, as well as impact assessment, of all proposed changes to infrastructure and the environment. Some current applications of the Metaverse for smart cities, proposed in the article, include, for instance, in Seoul, Republic of Korea, where, by exploiting the Metaverse Seoul platform, digital administration services and virtual city tours have been implemented; in Spain, through the CatVers platform, social meeting places have been created; in London, through the partial use of the Metaverse, virtual city tours have been realised with the presentation of its cultural assets, but above all, intelligent urban planning has been achieved; in New York and Dubai, the Metaverse was used to provide real-time traffic data, and the visualisation of transport status and utilisation; and finally, in Singapore, through the partial use of the Metaverse and DT, risk planning, environmental monitoring, resource utilisation management and tracking, and consumption optimisation were implemented.

The convergence between DTs and the Metaverse opens up the possibility of sharing three-dimensional virtual environments through the Internet. This aspect could also have concrete applications in improving security in public parks, enabling more effective management and timely response in the event of emergencies [35]. However, this area of research is still at an exploratory stage: the perception of security, in fact, despite having shared aspects, remains a subjective experience. Investigations of environmental safety in Geoparks, for example, are still limited, especially when analysed through the principles of CPTED (Crime Prevention Through Environmental Design) [36]. This approach aims to reduce crime and improve quality of life through the conscious design of built spaces. Contemporary CPTED is based on six basic principles: territoriality, natural surveillance, access control, activity support, image care, and target reinforcement [35]. Furthermore, some studies have explored the link between physical elements, electronic surveillance technologies, and crime in urban tourism contexts. For example, physical barriers such as walls or hedges can limit the escape routes of potential victims, increasing the feeling of insecurity. From this perspective, it becomes crucial to carefully design fences and roadways to ensure privacy, security, and adequate evacuation routes for visitors.

A distinct trade-off exists between ecological realism (field studies) and experimental control (VR/DT) across these domains. DT papers frequently lack user engagement; VR papers are abundant in perceptual insights yet deficient in validation; park studies seldom examine counterfactuals. There is a lack of evidence regarding the transferability of safety perceptions from a physical park to its immersive digital twin, as well as on which Crime Prevention Through Environmental Design dimensions transfer consistently. Consequently, we delineate the following expectations: (i) lighting and wayfinding/disorientation must exhibit significant cross-environment consistency; and (ii) maintenance/image will be undervalued in VR due to insufficient decay cues. This disparity directly informs our design. Informed by previous research, we (a) utilise identical items in both contexts; (b) analyse spatial patterns to compare distributions across environments; and (c) document moderators identified in immersive studies (device heterogeneity and group presence). The DT is a testbed for evaluating interventions before implementation, while field data are the ecological benchmark. As summarised in in Table A1, prior work spans field surveys, planning-oriented Digital Twins, and immersive VR studies, each with distinct trade-offs in realism, control, and CPTED coverage.

In addition to urban safety, related fields like cultural heritage and education have aligned on best practices for immersive studies, encompassing detailed reporting of UX constructs, consideration of interoperability among devices and engines, and implementing layered architectures to organise content and interaction. These cross-domain lessons are independent of specific domains and guide our methodology.

By contemporary trends in XR research, we delineate the specific metrics our protocol assesses (CPTED-related safety items) and those it excludes (e.g., presence, cybersickness, general usability), while also addressing interoperability factors within our framework to facilitate replication across devices.

Previous research reveals multiple deficiencies regarding the specific issue of evaluating urban park safety perception through Digital Twins and Metaverse environments. Cross-setting validation of on-site versus virtual findings is infrequent, and virtual reality studies often inadequately represent maintenance and decay cues, which are fundamental to the CPTED 'image'. Digital Twin research frequently emphasises system functionalities and proxy key performance indicators rather than perceptual outcomes, and rarely employs the digital twin itself as a stimulus for evaluating safety perception. Samples are often limited in size and based on convenience; device heterogeneity is inadequately reported; and standardised UX constructs are measured inconsistently. Scenario-based testing of CPTED dimensions, such as lighting and wayfinding, is fragmented, lacking comprehensive spatially explicit comparisons across different environments. The table in Appendix A summarises the identified gaps that inform our design: we integrate in-situ mapping with an immersive digital twin of the same park to evaluate transferability, anticipating greater convergence for lighting and wayfinding, and diminished efficacy for maintenance and imagery. The subsequent section delineates these expectations as our research enquiries. As far as we can ascertain from the reviewed literature, very few studies jointly integrate a site-specific digital twin with an immersive Metaverse environment to evaluate subjective safety perception in public parks, using identical on-site and VR items and spatially explicit cross-environment comparisons. Based on the existing literature, we investigate the degree to which on-site safety perceptions are conveyed to an immersive digital twin of the same park. We explicitly compare CPTED dimensions anticipated to transfer effectively (lighting, wayfinding/disorientation) with those likely undervalued in VR (maintenance/image). This results in two research questions: **RQ1:** Do on-site safety perceptions transfer to an immersive digital twin of the same park? **RQ2:** Which CPTED dimensions transfer better (lighting, wayfinding/disorientation) and which are underestimated (maintenance/image) in VR?

3. Methods and Material

The assessment of the perception of security within a public park can be addressed through an integrated methodological approach that considers multiple aspects and exploits the advanced technologies offered by the Metaverse. This collective, shared, and persistent virtual environment stems from the fusion of the physical and digital worlds, enhanced by immersive and interactive tools. Through the Metaverse, realistic scenarios can be simulated, virtual environments can be modelled based on real data collected through IoT sensors and monitoring systems, and user behaviour can be analysed in response to different environmental conditions, such as lighting, spatial layout, or the presence of physical barriers. These digital environments thus allow for a dynamic exploration of how architectural, technological, and psychological factors influence the perception of security. The integration of technologies such as VR, urban DTs, and real-time data analysis engines allows us not only to observe and collect data on user experience, but also to test design

solutions before their physical implementation, thus contributing to safer, more inclusive and people-centred urban planning.

This study addresses the gap by integrating in-situ mapping with an immersive digital twin of the park and applying identical safety measures across both environments. This facilitates a direct assessment of transferability across CPTED dimensions and a spatially coherent comparison between on-site and virtual conditions. The distinctive feature of the proposed approach lies in the implementation of Digital Twins in the Metaverse, which can serve a dual function: simulation and verification. In the first case, planning is tested on the basis of simulations within the virtual environment, thus making it possible to foresee the outcome of the project to be implemented; in the second case, the possibility offered is that of investigating the state of affairs, thus making it possible to assess whether the planning carried out up to that point has achieved the pre-set objectives and whether the desired outcomes have been met.

The proposed methodology (Figure 1) aims to improve the smart city planning experience by taking into account different parameters that come into effect in urban and territorial planning thanks to the integration of traditional techniques with techniques from ICT. The study design, instruments, and analysis pipeline are described here; sample and site-specific details are reported in the case study section (Section 4).

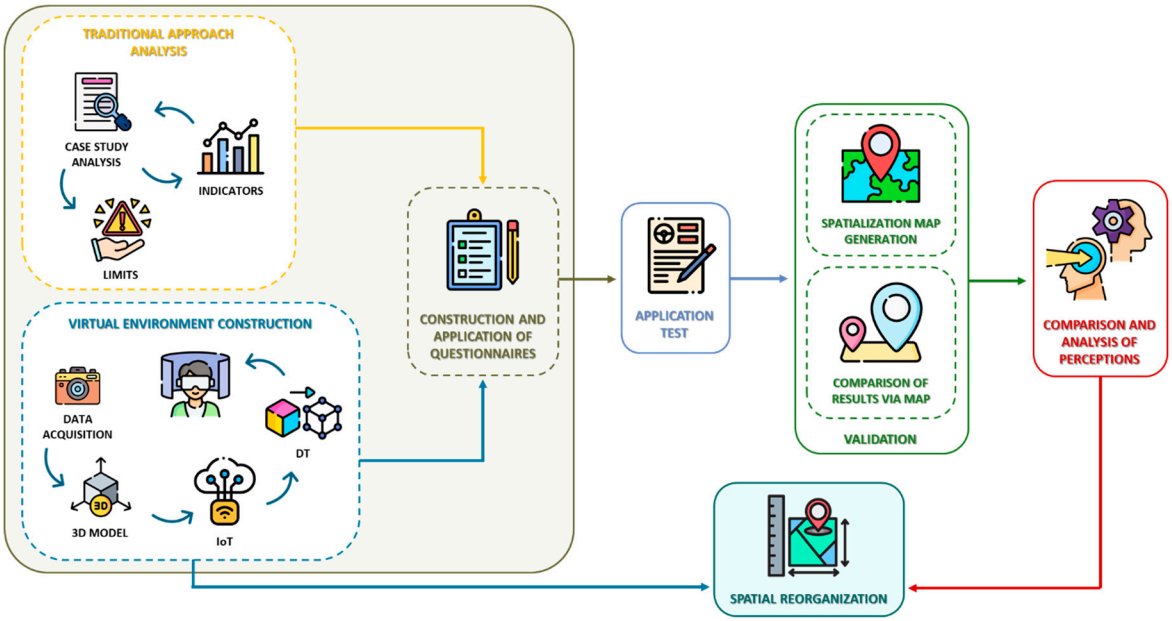


Figure 1. Proposed methodology.

1. The first step is data acquisition, a fundamental process that requires accuracy and systematicity since the basis for the choice of method is the specific objectives of the project, the resources available, and the nature of the data required. In the following work, data acquisition has been divided into two areas: one relates to the retrieval of graphics and/or photos, the other to reference data on the perception of safety. The latter can be gathered manually through the observation of phenomena, behaviour or places, or through interviews, questionnaires or surveys, thus directly involving people to gather detailed information on specific topics. Sensors are also a tool that enables the reception of data: wearable sensors, such as smartwatches, can monitor heartbeat, blood oxygenation, respiration, body position and temperature, which can be linked to the perception of the danger of a place; environmental sensors, on the other hand, by managing and processing parameters such as temperature, humidity, air quality, light, noise, gas and vibration, enable the acquisition of real data that,

when implemented, contribute to forming and improving smart cities. In the case in question, a questionnaire was provided, drawn up on the basis of CTED principles, and administered to a sample of 50 students from the Faculty of Architecture at the University of Naples.

2. After data acquisition, it is fundamental to carry out a comparison with indicators and safety estimation criteria. The former are selected on the basis of a comprehensive analysis of the factors influencing the safety of urban parks; the criteria can then be associated with specific CPTED strategies and socio-economic contexts. Specifically, there are several methodologies and approaches for identifying and selecting these indicators and criteria, including risk analysis, which involves identifying all potential hazards that may affect safety, assessing the likelihood of each hazard occurring, the impact it would have, and prioritising risks according to their likelihood and impact. At this stage, the results of the questionnaires were compared with the principles of CTED, selecting some of the latter to apply to the DT.
3. Subsequently, the construction of a three-dimensional model is proposed, which not only allows for a realistic and detailed visualisation of the projects or the reality to be represented, facilitating the understanding and communication of ideas, but also allows for the identification and resolution of project problems during the various phases, reducing costs and development time, improving accuracy and, in addition, facilitating the simulation and analysis of various scenarios, optimising design solutions. There are several ways to proceed with three-dimensional modelling. The easiest to understand, namely polygonal modelling, is a method that uses polygons to construct the surfaces of a 3D model, whose vertices allow the shape to be manipulated. By combining this technique with surface subdivision, it is also possible to model characters or objects in detail. There are also devices that physically scan a real object to create a complete and accurate model of its shape, namely, 3D scanners, which, when integrated with photogrammetry, reconstruct not only the shape and geometry of the object, but also its characteristic texture. Once the concept has been outlined and the general layout planned, the 3D model is constructed and the elements of the virtual world, such as buildings, landscapes, and objects, are positioned. Textures, lights, and sounds are then added to make the environment more realistic and immersive. Several software programmes are available today for developing 3D models. Among the most commonly used are: Sketchup, Blender, Revit, Rhino, Solid Works, and Autocad 3D (Version 2024).
4. The next stage is the creation of a virtual environment, which initially involves the outlining of the concept and planning of the general layout. Then, based on the drafted 3D model, we proceed to the positioning of elements in the virtual world, such as buildings, landscapes, and objects, with the possibility of adding textures, lights, and sounds to make the environment even more realistic and immersive. The virtual environment thus obtained allows us to have a simulated space where new ideas and solutions can be tested without risk to the real system and, in addition, to recreate specific conditions to be analysed. In addition, it guarantees interaction between users, be it visual, audio, or textual, thus also enabling remote collaboration. At this stage, an online platform was used to develop the three-dimensional model with the addition of elements and textures, such as spatial.io.
5. Finally, new data are acquired from the real and/or virtual experience, which may cover several aspects of the same case study, and from these, it is possible to create new environments or make changes based on impressions, evaluations, and critical points identified by the users, allowing them to simulate the appropriate context according to the feedback obtained. Once the data had been collected from the virtual environment,

they were used both to validate its creation and correspondence with the real twin, and to obtain feedback to be used in the design process.

Everything goes back to urban planning, which can be aimed at both safety and the development of design ideas. In the latter case, the application within the virtual environment of the design proposals, obtained from feedback and perceptions, allows for a concrete vision of the objectives that the project proposes to achieve. Specifically, the possibility of obtaining simulations of the various proposed ideas leads to savings in both economic and sustainability terms.

4. Application of the Methodology: Case Study

The process described above in the methodology section was applied to a case study of an urban park located in Naples, in the heart of the Quartieri Spagnoli, from which it takes its name. Within the park is the SS Trinità delle Monache complex, also known as the former Military Hospital, which is one of the largest abbey complexes in Naples. The entire structure covers a total area of about 25,000 square metres, of which about 16,000 square metres are occupied by gardens, internal courtyards, and other open spaces. It now presents itself as a heterogeneous whole characterised by both historical buildings and more recent constructions, which in some cases have altered and damaged the original layout (see Figure 2).



Figure 2. Photo of Quartieri Spagnoli Park, chosen as a case study.

The Local Action Plan, with respect to the park under study, envisages a series of integrated actions, in the short, medium, and long term, up to ten years, to make the park a public space for civic use, in which citizens can play a leading role in proposing and implementing projects and activities. For this reason, the Quartieri Spagnoli Park proves to be an excellent case for studying safety in urban parks, with the aim of promoting a more serene and frequent use of these vital spaces for society.

4.1. Data Collection Through Questionnaires

A two-cohort case study was conducted at Quartieri Spagnoli Park in Naples. Fifty on-site participants traversed a designated route and subsequently addressed the safety items, while a distinct group of twenty individuals engaged with an immersive digital twin of the same park and responded to the identical items following the virtual experience. The inclusion criteria required participants to be aged 18 or older and to possess normal or corrected-to-normal vision. All participants provided their informed consent, no compensation was offered, and demographic data collection was minimal (the mean age was approximately 27 years). The on-site route corresponded with the points of interest depicted in VR, facilitating spatially coherent comparisons between environments.

The immersive setup utilised a Meta Quest 2 headset linked to a PC with an Intel Core i7 (13th generation), NVIDIA RTX 4090 (NVIDIA Corporation, Santa Clara, CA, USA), and 32 GB of RAM. The headset operated at its standard refresh rate, aiming for a frame rate of 72 Hz. The digital twin was created in Unity, with delivery and support provided through 3DVista Pro (Version 2024.0), while 3D assets were developed in Blender and geodata were processed using QGIS (Version 2024.0). The foundational layers comprised municipal CAD (Version 2024.0) footprints and orthophotos; textures were exported at 2048 pixels, and performance was maintained through levels of detail and other standard optimisations. The night lighting in the downtown area was adjusted by aligning luminaire placements and the nominal output recorded on site, while wayfinding components (signage/landmarks) adhered to field notes. Participants utilised smooth locomotion at approximately 1.4 m/s, executing 30° snap turns, while the camera height was maintained at 1.65 m. A practice phase lasting approximately 15 min preceded the task. We exhibited both diurnal and nocturnal scenes by the field survey.

We implemented identical safety items across various settings using a five-point Likert scale that assessed disorientation/wayfinding, nighttime lighting, maintenance/image, and overall perceived safety; items were uniformly coded to ensure that higher scores reflected greater perceived safety. All items were measured on five-point Likert scales; wording, coding, and reverse-coding rules are provided in Appendix C. The complete item wording and summary results are presented in Appendix A. Data were evaluated for completeness; paired comparisons between on-site and VR scores were conducted for each dimension (paired *t*-test when normality was satisfied, otherwise Wilcoxon); and effect sizes were documented. Spatial patterns were aggregated on a uniform grid, and cross-environment similarity was evaluated through rank correlations, with multiple comparisons adjusted ($\alpha = 0.05$). For the first analysis and data collection phase, two survey days were organised on the perception of safety within the Quartieri Spagnoli Park. During the first day, the users involved were able to make an inspection of the park in order to closely analyse the facilities and contexts of interest, including the green spaces that characterise the park. At the end of the visit, they were given a questionnaire divided into eight sections, each of which explores a specific aspect of the users' experience. It starts with a section on demographic data, where information such as age, gender, level of education, employment status, and the frequency with which people visit the park is collected. This is followed by a section focusing on the liveability of the surrounding area, which analyses the ease with which the park can be reached, both on foot and by vehicle, also investigating the presence of parking spaces for cars and bicycles and the presence of daily services and cultural, health, and educational facilities in the surrounding area. The third section deals with the physical accessibility of the park. Here, the number and location of entrances, the location of the park within the urban fabric, and the presence of useful elements such as lifts, ramps, and parking spaces are considered. Accessibility for people with disabilities is also assessed. This is followed by a section on services and facilities within the park.

Aspects surveyed include opening hours, the presence of fences, fountains, public toilets, dog areas, playgrounds, refreshment areas, Wi-Fi coverage, signage, and recycling bins. The fifth section investigates perceived safety, assessing lighting and any dark areas, the presence of video surveillance and surveillance, or the presence of crime and social unease. Spatial aspects such as the shape of the park, the presence of architectural backdrops, and the so-called 'ballet of the park', i.e., the uses and types of visitors, are also considered in this phase. The sixth section focuses on the quality of greenery, through eight indicators: the visibility of spaces, the coherence and organisation of the scenery, the arrangement and maintenance of vegetation, spatial variety, lateral visibility, aesthetic complexity, the state of maintenance of green areas, and finally urban decorum, also assessed in relation to the furnishings and buildings present. Next, the liveability of the public space is analysed under three main dimensions: morphology (percentage of pedestrian areas, openness to the sky); attractiveness (type and variety of activities present, quantity of greenery); and comfort, understood in terms of thermal and acoustic level, as well as in terms of water quality. Finally, the last section is reserved for comments and suggestions from users. Here, users are asked to indicate any elements to be improved, such as park design, play or sports areas, lighting, signage, paving, seating, parking, public transport, green maintenance, cleanliness, opening hours and, of course, safety aspects.

First Results

The results show a general perception of safety within the park, but also highlight the need for more maintenance, both for the green areas and for the historical buildings present. The park is accessible on foot and well connected by public transport, although it lacks dedicated parking spaces; it is fenced off and has only one active access point; it also has a ramp for people with disabilities. In terms of security, the park benefits from the presence of nearby police stations and some video cameras, but night lighting is limited to a few spotlights. However, dark areas are limited and easily avoided and users therefore perceive the environment as generally safe. Suggestions collected from users include a request for better care of the greenery and buildings, the addition of water points, better signposting, and a map at the entrance to better orientate themselves in the park.

4.2. Comparison with Safety Indicators

Once the data had been acquired, it was appropriate to compare the results obtained from the questionnaires with a number of indicators identified through a methodology for evaluating the security of urban public parks (SEMUPP), which assesses and classifies the security levels of urban public parks [18]. This methodology integrates the principles of CPTED (Crime Prevention through Environmental Design) with socio-economic aspects. It evaluates parks based on 11 groups of safety factors and 17 measurable criteria, such as surveillance, lighting, maintenance, crime, and so on. Each criterion has a weight and contributes to the calculation of a safety score.

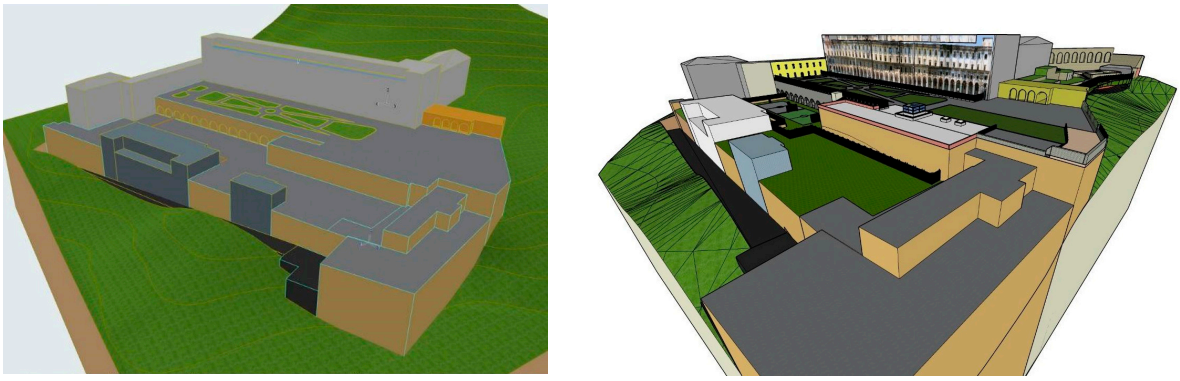
Analysing the data from the questionnaire and SEMUPP, it turns out that the Quartieri Spagnoli Park in Naples, when compared to other parks assessed through SEMUPP, is the least safe.

4.3. Virtual Environment Construction

Parallel to data acquisition using the traditional approach, the virtual environment, a replica of the park in the Spanish Quarter, was constructed. The construction of the virtual environment involved several phases: conceptualisation and planning; design and modelling; technical development; testing and iteration; implementation; and maintenance. The first fundamental phase consisted of an on-site inspection, which made it possible to integrate the information present in the plan, which was graphically elaborated in dwg,

with reference to the actual state. The different heights of the buildings and trees were also identified, in order to create a volumetric proportionality preparatory to the replication of the users' final perception.

For the actual modelling, first the Archicad software (Version 2024) was used (Figure 3), which, since the object of study consists of several height levels that are triggered together like terraces, allowed work to be carried out simultaneously, both in plan and in 3D modelling. Then, for even faster and more flexible modelling, SketchUp software (Version 2024) was used (Figure 3), which allowed the models to be further enriched by adding realistic textures, thus making them even more similar to the real thing. Finally, for the tree component, the study carried out previously on the greenery was reproduced, faithfully reproducing the types of trees present in the park.



(**a**) (**b**)

Figure 3. (**a**) Step 1, Modelling in Archicad; (**b**) Step 2, Modelling in SketchUp.

Once the complete model was obtained with all its details, it was exported from SketchUp in .obj format and imported into Blender. Blender is an open-source 3D modelling, animation, rendering, and compositing software, used in various fields such as design, architecture, film, and video games.

The final export, in .glb format, was then uploaded to Spatial.io, a platform that deals with virtual environments and augmented reality and is specifically designed to create collaborative virtual spaces (Figure 4).

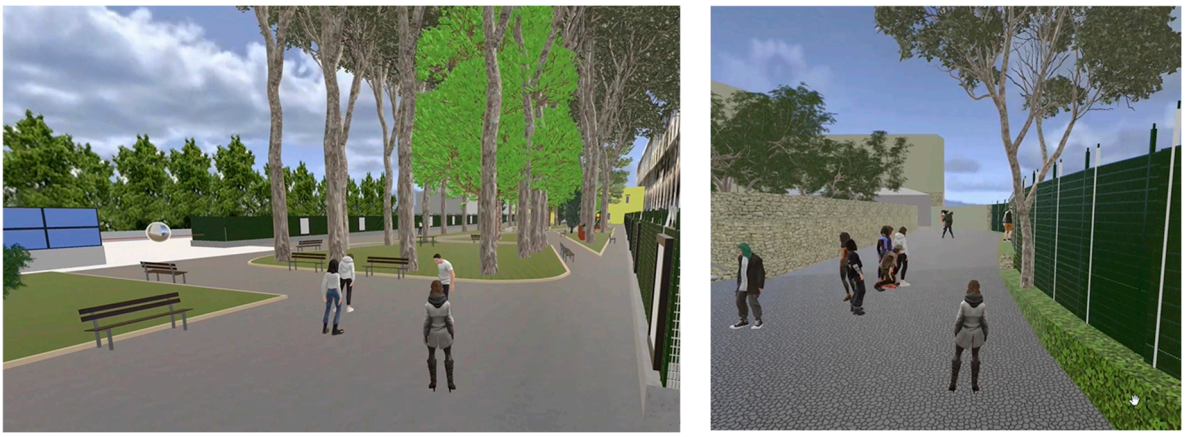


Figure 4. Virtual environment created in Spatial.io.

4.4. Acquisition of New Data

At this point, a second day of visiting the Spanish Quarter Park was organised, but this time the visit took place through virtual and augmented reality. In this case, users had

the opportunity to enter the virtual environment to interact with the elements of the space, allowing an in-depth evaluation of the functionality, effectiveness, and reliability of the system under examination.

Once again, in order to obtain a validation of the environment, a questionnaire was constructed that investigated the following aspects: demographic data, access device to the platform, truthfulness and efficacy of the replicated places, perceived degree of security, knowledge of the Metaverse and its uses, interactions developed in the virtual space, and validation in the use of the visor as a device.

Results

This integration harmonises ecological authenticity with experimental regulation: field observations preserve nuanced maintenance and decay indicators relevant to the CPTED 'image', while the immersive digital twin standardises lighting and navigation, facilitating scenario testing in regulated environments. The design consequently offers a direct assessment of transferability across CPTED dimensions and aids in prioritising interventions before real-world execution. Simultaneously, VR may undervalue maintenance/image owing to restricted decay indicators—an acknowledged constraint we consider a stress test for the virtual pipeline. The results of the second day were very satisfying: users found the experience pleasant, welcoming, safe, and accessible. They appreciated the accuracy of the reconstruction, the clarity of the elements, and the possibility of interaction with other users. However, they reported the need to improve graphical fluidity and movement. Most used the PC to access the virtual environment, while few used the visor, although those who did had a more immersive and immersive experience without discomfort. More than half felt that the virtual environment faithfully represented the real state of the park, conveying a medium-to-high feeling of safety.

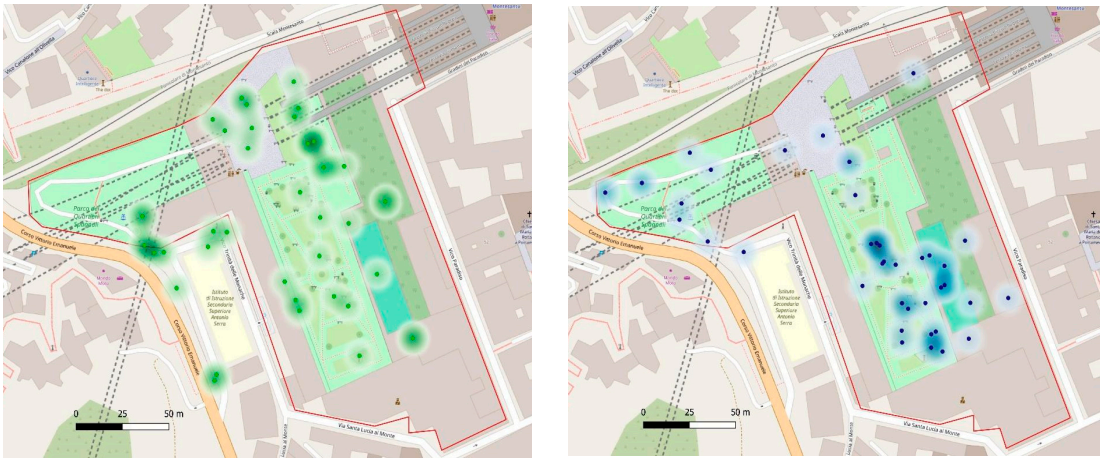
5. Validation and Results

The main objective of the work carried out was to understand and validate the perception of safety within urban parks, particularly in the Spanish Quarter, by comparing experiences in the real world and the virtual world. The results highlighted both points of contact and significant differences between the two environments, thus offering new perspectives for assessing urban safety using a digital approach.

The survey was conducted on a sample of fifty people, specifically students enrolled in the Architecture degree programme at the University of Naples.

The sample consisted of a heterogeneous sample of users of different ages. A portion of them participated in a detailed mapping of the actual park, focusing on issues such as disorientation, lighting, and maintenance. Using the Google My Maps tool and the questionnaire as a guide, each participant reported what they considered to be critical points in the park. In this first phase, the main observations included the lack of signage and the widespread absence of lighting, as well as a high level of disrepair, with dilapidated buildings and unkempt vegetation hindering visibility and walkability. This information was then imported into QGIS, where it was processed as concentration maps, allowing the most problematic areas of the park to be visually identified (Figure 5).

Subsequently, in order to compare the perceptions detected in reality with those generated in the virtual environment, a 3D virtual tour of the park was realised with the 3D Vista Virtual Tour PRO software (Version 2024.0), using the previously realised model of the park. At this point, a sample of 20 users were invited to explore the virtual park, at the same time as other users, and to answer targeted questions on disorientation, lighting, and maintenance (Figure 6).



(**a**) (**b**)

Figure 5. (**a**) Map of concentration of disorientation in reality; (**b**) Map of concentration of lighting in reality.

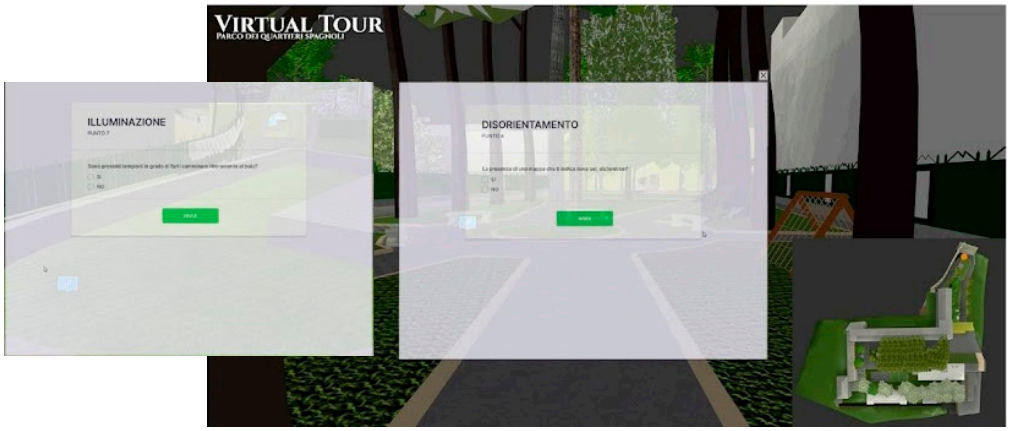
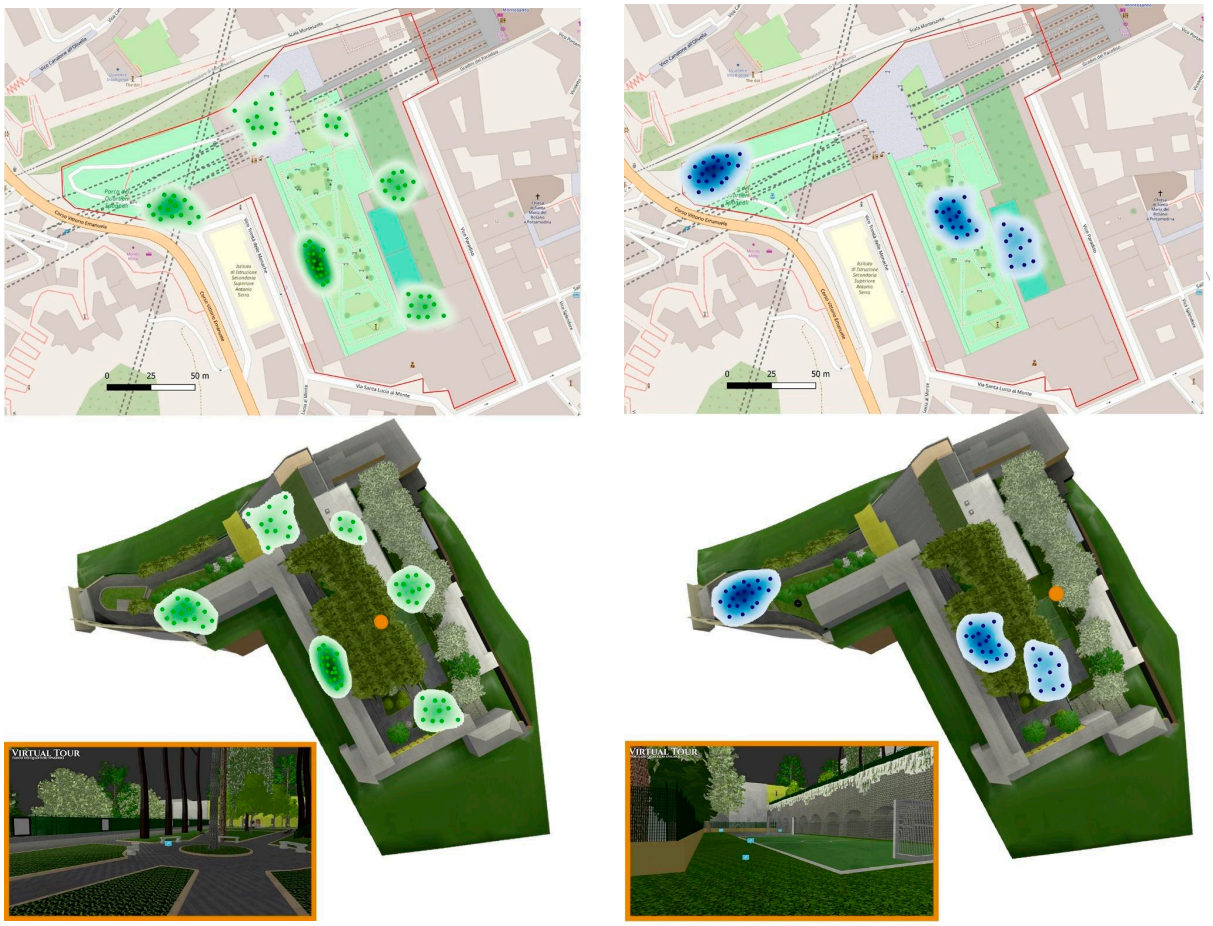


Figure 6. Examples of how questionnaires were disseminated during virtual tours in 3D Vista PRO.

The resulting comparison of the two environments produced interesting results (Figure 7). Regarding disorientation, it emerged that, although there was signage at the entrance, most users found it difficult to find their way beyond the initial threshold. However, navigation within the virtual park was more intuitive due to the spatial clarity of the model, although the need for orientation maps was reported. For the lighting, the impressions in the virtual mirrored those of the real visit: the lack of lights generated a low sense of security, suggesting the need to integrate adequate lighting systems to improve the enjoyment of the park even in the evening hours.

Regarding the maintenance of the park, the situation is different: the real visit showed that there are areas of the park that are in a state of extreme decay; this very important aspect, however, is not apparent in the virtual context, as it was difficult to represent it, and many users interpreted the elements of spontaneous vegetation as aesthetic choices rather than signs of neglect. This highlights a limitation in the ability of the 3D model to render the neglected conditions as effectively as an on-site visit. Another interesting aspect concerns the perception of safety in a group: both in the real and virtual world, users stated that they felt safer when in company, confirming that the presence of others can act as a deterrent to possible dangerous situations. Finally, the immersive experience in the Metaverse was rated positively by most participants. Many stated that the virtual environment, albeit with its limitations, renders a perception fairly faithful to reality and conveys a medium-to-high degree of safety. The experience was described as engaging and

useful, especially for those unfamiliar with the park, thanks to the possibility of interacting with other users and finding their way around easily.



(**a**) (**b**)

Figure 7. (**a**) Map of concentration of disorientation in the virtual environment; (**b**) Map of concentration of lighting in the virtual environment.

Our emphasis on safety-specific elements prioritises construction relevance over a wider user experience framework; future iterations may integrate standard presence, cybersickness, and usability metrics, while further formalising interoperability to improve comparability and reproducibility.

Therefore, the final objective of this study was to compare the individual perceptions had in the real park with those had in its virtual counterpart, identifying the common points through a comparison, but also the perceptive differences between real and virtual, thus bringing out hints, criticalities, and design suggestions. On the one hand, these results offer a useful basis for rethinking the virtual environment, improving it on the basis of the observations collected, but they also demonstrate how the integration of digital tools and traditional methods can enrich the analysis of urban safety, paving the way for new modes of participatory assessment and shared design of public spaces.

The analyses from the questionnaires administered in person to the sample, those in virtual environments, and those in the Metaverse made it possible to achieve several objectives, the first of which was to connect the perceptions of real and virtual users. It was therefore possible to study this link not only from a design point of view, but also from the point of view of the perception of users, who are the end users of urban design, especially

parks. Descriptive statistics, tests, and effect sizes for each CPTED dimension are reported in Appendix B.

In a broader and more complex urban design process, a further objective is to provide support to designers for the purposes of contextual analysis, which is indeed the result of user perceptions but takes into account everything that exists in traditional design.

Therefore, together, traditional design, Digital Twins, and virtual simulation improve the design.

6. Conclusions, Challenges, and Future Developments

The results obtained from the work carried out have shown how emerging technologies, such as the Metaverse and three-dimensional digital models, can be valid and innovative tools for investigating the perception of security in urban parks. The proposed methodology allowed us to investigate the same field, that of urban planning, but on a double front: on the one hand traditional urban planning research, with a comparative analysis of case studies and established methodologies, and on the other hand experimentation in the field of computer graphics and the construction of immersive environments. Specifically, studies were analysed that show how the physical design, visual accessibility, and spatial layout of urban parks directly influence the perception of safety. At the same time, the importance of balancing security requirements with the need for privacy and comfort on the part of different user groups emerged. In the workflow, in parallel with the urban planning analyses, a virtual environment faithful to the park of the Quartieri Spagnoli was built, thanks to a methodological procedure that included on-site surveys, three-dimensional modelling through software such as Archicad, SketchUp, and Blender, and finally the publication of the model on immersive platforms such as Spatial.io. The multidisciplinary approach adopted also laid the foundations for future developments in the field of IoT and DTs, which, when combined with the virtual environment, would allow the model to be constantly updated on the basis of environmental and biometric data collected in real time. This would open up even wider scenarios, such as the simulation of behaviour, the prediction of malfunctions, the optimisation of maintenance, and even the prevention of urban crime.

The analysis of perceptions, then, carried out by means of questionnaires in the case of both the real and the virtual visit, was of fundamental importance as it revealed differences but also significant convergences in the two approaches. The maps produced showed that issues such as disorientation, poor lighting, and degradation were perceived in both contexts, albeit in different ways. However, the virtual environment allowed for smoother navigation, facilitating spatial orientation and offering an immersive experience, especially when experienced in groups. This last aspect highlighted an interesting finding: the perception of safety tends to increase when the experience is shared, suggesting the key role of the social dimension also in augmented reality.

In conclusion, user perceptions noted that both on-site and virtual reality align with principles of environmental psychology and CPTED: enhanced lighting improves perceived visual control and natural surveillance, while clearer wayfinding enhances legibility and diminishes disorientation. These mechanisms depend on prominent, global indicators that immersive DTs effectively replicate, elucidating the significant cross-setting convergence we observe. In contrast, maintenance/image relies on detailed indicators of care or neglect—such as surface wear, patina, litter, broken edges, and micro-damage—that conventional VR pipelines frequently under-represent due to limitations in texture resolution, shading, and asset budgets; thus, this aspect is often underestimated in VR. Immersive Digital Twins are prepared to facilitate pre-implementation testing of lighting configurations, wayfinding, and signage, emphasising route and node prioritisation while evaluating nocturnal scenar-

ios under regulated conditions. Maintenance-oriented decisions should be evaluated in situ or simulated using high-fidelity assets (such as high-frequency textures and photogrammetry) and supplemented with contextual audio and crowd dynamics to communicate stewardship signals. Methodologically, we will broaden the measurement to encompass presence, comfort/cybersickness, and usability scales, replicate across headsets to examine generalisability, and formalise interoperability while documenting device heterogeneity. Collectively, these measures rectify the asymmetry identified across CPTED dimensions and transform the DT into a resilient, reusable platform for participatory safety design in urban parks. This study has limitations that constrain the scope and the robustness of inference. The two cohorts were modest and based on convenience (50 on-site; 20 VR), comprising different individuals across settings; consequently, variations may partially stem from cohort composition rather than solely from the environment. Scope of measurement: We concentrated on safety elements associated with CPTED (self-reports). This wave did not collect standardised constructs such as presence, cybersickness/comfort, and usability, which restricts comparability with XR UX benchmarks and our capacity to attribute variance to experiential factors. Device and content accuracy: The immersive environment employed a Quest 2 framework utilising Unity for authoring, incorporating levels of detail (LODs) and 2048-pixel textures. Although performance targets were achieved, standard budgets and shading may inadequately reflect subtle decay indicators (litter, surface wear, micro-damage), potentially diminishing sensitivity in the maintenance/image aspect. Comfort and procedure: Despite the absence of significant discomfort and the implementation of snap turns, and an approximately 15-min practice session, lingering VR-induced symptoms may still serve as a potential noise source. External validity and replicability: The findings pertain to a single park, route, and device/toolchain; the generalisability across various morphologies, times of day, user profiles, and headsets has yet to be evaluated. In the future, we will address these limitations by employing within-subject or matched-cohort designs with larger, more diverse samples, broadening measurements to encompass presence, comfort/cybersickness, and usability scales, enhancing the digital twin with higher-frequency textures, photogrammetry, and improved night lighting, and replicating the study across various devices and locations utilising a documented, interoperable pipeline. The complete item wording and summary results are included in the Appendix A to ensure transparency and facilitate reuse.

A further element mapped was that of design suggestions. Participants highlighted the lack of essential elements for the comfort and safety of the park, such as drinking fountains, clear signage, increased lighting, and better maintenance of greenery and historic buildings. This information offered concrete ideas for reorganising the virtual environment, not only updating it with new elements, but also rethinking its spatial layout in a design key.

The challenges faced along the way—from the realistic representation of degradation to the technical management of complex digital models, and the collection and interpretation of perceptual data—outline a field of study that is still evolving, but which is rich in potential. For the future, it will be crucial to expand the use of these tools within urban decision-making processes, integrating them with planning and management policies for public spaces. In this perspective, the combined use of DTs, the IoT, and the Metaverse can become a powerful ally for smartcCities, capable of supporting more informed, inclusive, and citizen-oriented decisions. Participatory planning, fuelled by the virtual and real experiences of users, thus represents not only an opportunity for technological innovation, but also a concrete path towards a safer, more sensitive and human city.

Author Contributions: Conceptualization, A.L. and M.G.; Methodology, M.G. and A.L.; Software, L.C.; Validation, M.G. and A.M.; Formal analysis, A.M. and F.S.; Investigation, A.L.; Resources, L.C. and F.S.; Data curation, L.C. and F.S.; Writing—original draft, A.L. and F.S.; Writing—review & editing, A.L.; Visualization, L.C. and A.M.; Supervision, M.G. and A.L.; Project administration, M.G.; Funding acquisition, M.G. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: Ethical review and approval were waived for this study due to Italian GDPR form and the Ministry of Health Decree of 8 February 2013 ("Criteri per la composizione e il funzionamento dei comitati etici").

Informed Consent Statement: Informed consent for participation was obtained from all subjects involved in the study.

Data Availability Statement: Data supporting the findings of this study are available upon request to the corresponding author. Some data cannot be shared publicly due to privacy or intellectual property restrictions.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Cross-study comparison of approaches used to assess park safety perception and related digital methods.

Study Bucket	Environment	Typical n	Measures	Stimulus Fidelity	CPTED Dimensions	Validation	References
Field surveys in parks	On-site	30–500	Self-report, mapping	High context; low control	Lighting, surveillance, image, wayfinding	Rare (vs. other parks)	[24,30,31]
Digital Twin planning	Desktop DT	—	Simulated KPIs	Data-rich; user-poor	Access control, surveillance (proxy)	Scenario vs. baseline	[9,18,25]
Immersive VR/Metaverse	Head-mounted/desktop	15–60	Self-report, tasks	Controlled lighting/signage; weak decay cues	Wayfinding, lighting	Seldom vs. field	[4,5,26,28]

Appendix B

Table A2. Juxtaposes on-site (n = 50) and VR (n = 20) scores across each CPTED dimension on a 1–5 scale. For each row, we include the mean (M) and standard deviation (SD), the difference Δ = VR − On-site (positive indicates greater values in VR), the independent-samples test employed (Welch's t or Mann–Whitney), the *p*-value, and the effect size (Hedges' g)—≈0.2 denotes small, ≈0.5 medium, and ≈0.8 big. Where applicable, spatial correlation (ρ) encapsulates the similarity between on-site and VR spatial patterns. Scores are encoded such that elevated values signify more perceived safety.

Dimension (CPTED)	On-Site Mean (SD)	VR Mean (SD)	Δ (VR − On-Site)	Test	*p*-Value	Effect Size	Spatial Correlation (ρ)
Wayfinding/Disorientation	3.20 ± 0.30	3.40 ± 0.50	+0.20	Welch t	0.107	g = 0.54	—
Lighting at night	2.70 ± 0.55	2.68 ± 0.50	−0.02	Mann–Whitney	0.884	g = −0.04	—
Maintenance/Image	3.40 ± 0.70	3.05 ± 0.66	−0.35	Welch t	0.056	g = −0.50	—
Overall perceived safety	3.20 ± 0.60	3.30 ± 0.57	+0.10	Welch t	0.518	g = 0.17	—

Appendix C

Questionnaire items and measurement.

Unless otherwise noted, all items use a five-point Likert scale. Scores are coded such that higher values indicate higher perceived safety; items marked as reverse-coded are inverted before computing dimension means.

Table A3. Safety perception items used in both settings (on-site and VR).

Item/Indicator	Scale/Format
Wayfinding/Disorientation—I felt disoriented while following the path.	Likert 1–5 (reverse-coded)
Wayfinding/Disorientation—Wayfinding cues (landmarks/signage) were clear.	Likert 1–5
Lighting at night—The path was sufficiently illuminated at night.	Likert 1–5
Lighting at night—Lighting coverage was uniform along the route.	Likert 1–5
Maintenance/Image—Signs of neglect (litter, damage, wear) reduced my comfort.	Likert 1–5 (reverse-coded)
Maintenance/Image—The overall image of the park conveyed care and stewardship.	Likert 1–5
Overall perceived safety—Overall, I felt safe in this environment.	Likert 1–5

Scoring: for each dimension, average its items (after reverse-coding) to obtain a composite score on 1–5.

Table A4. VR-specific items (context & UX).

Item/Indicator	Scale/Format
Previous VR experience	Yes/No
Familiarity with the real place	Yes/No
[If not familiar] Visit intention after VR	Yes/No
Access device	PC/Smartphone/Headset
Perceived realism of the virtual place	Likert 1–5
Perceived safety in the virtual place	Likert 1–5
Effectiveness of replication (technology)	Likert 1–5
Definition of the Metaverse (your view)	Multiple choice
Difference: virtual environment vs. Metaverse	Yes/No
Adjectives describing the VR experience	Multiple choice
Most striking aspect of the VR experience	Open-ended
Element distinguishability	Likert 1–5
Improvements needed in the virtual environment	Open-ended
Safer in real life or in VR?	Real life/Virtual
Interaction with other users	Yes/No
Type of interactions	Visual/Audio/Textual (chat)
Number of people met in VR	1–5/5–10/10–15/15–20/20+
Involvement/immersion	Likert 1–5
Impact on emotions and well-being vs. physical spaces	Likert 1–5

Table A5. Headset-only add-ons.

Item/Indicator	Scale/Format
First impression when putting on the headset	Surprising & engaging/Interesting but confusing/Normal/Disappointing
Comfort while wearing the headset	Likert 1–5
Ease of use of the headset	Likert 1–5
Immersion compared to the real world	Likert 1–5
Physical discomfort (dizziness, nausea, eye strain)	Yes/No
Satisfaction with VR experience	Likert 1–5
Intuitiveness of headset controls	Likert 1–5
Usefulness for training/entertainment/simulation	Yes/No

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