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Designing social immersive virtual environments for the Metaverse: The case study of MetaLibrary

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Abstract: Background Over the last few years, the rapid advancement of technology has led to the development of many approaches to digitalization. In this respect, metaverse provides 3D persistent virtual environments that can be used to access digital content, meet virtually, and perform several professional and leisure tasks. Among the numerous technologies supporting the metaverse, immersive Virtual Reality (VR) plays a primary role and offers highly interactive social experiences. Despite growing interest in this area, there are no clear design guidelines for creating environments tailored to the metaverse. **Methods** This study seeks to advance research in this area by moving from state-of-the-art studies on the design of immersive virtual environments in the context of metaverse and proposing how to integrate cutting-edge technologies within this context. Specifically, the best practices were identified by i) analyzing literature studies focused on human behavior in immersive virtual environments, ii) extracting common features of existing social VR platforms, and iii) conducting interviews with experts in a specific application domain. Specifically, this study considered the creation of a new virtual environment for MetaLibrary, a VR-based social platform aimed at integrating public libraries into metaverse. Several implementation challenges and additional requirements have been identified for the development of virtual environments (VEs). These elements were considered in the selection of specific cutting-edge technologies and their integration into the development process. A user study was also conducted to investigate some design aspects (namely lighting conditions and richness of the scene layout) for which deriving clear indications from the above analysis was not possible because different alternative configurations could be chosen. **Results** The work reported in this paper seeks to bridge the gap between existing VR platforms and related literature in the field, on the one hand, and requirements regarding immersive virtual environments for the metaverse, on the other hand, by reporting a set of best practices which were used to build a social virtual environment that meets users' expectations and needs. **Conclusions** Results suggest that carefully designed virtual environments can positively affect user experience and interaction within metaverse. The insights gained from this study offer valuable cues for developing immersive virtual environments for the metaverse to deliver more effective and engaging experiences.

Keywords: Metaverse; Design guidelines; Virtual environments; Immersive virtual reality; User study; Social platforms

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1 Introduction

Over the past decade, technological advancements have driven innovative digitalization approaches, focusing on solutions that enhance access to digital content[1] and connect users worldwide[2]. Among the cutting-edge technologies involved in this process, immersive virtual reality (VR) is attracting increasing attention from practitioners and industries[3,4], because the capabilities of immersing users and providing them with interactive experiences are regarded as strategic opportunities in various fields[5]. For example, several studies have recognized its benefits in the educational domain[6,7]. The high-level of immersion available through reconstructed virtual environments, the possibility of interacting with virtual content in a natural way, and multiplayer functionalities that enable the creation of social experiences are some of the features that make VR a key component of metaverse applications[3,8].

The metaverse is regarded as the next generation of the Internet[9] and is expected to facilitate seamless interactions among users, represented as digital avatars in persistent, interoperable 3D environments[10] that converge by progressively blending the physical and digital worlds[11]. In this context, investigating the relationships between users and their virtual surroundings is a major research priority in behavioral studies on immersive VR experiences in metaverse[12]. In particular, it has been claimed that human behaviors and attitudes toward the adoption of immersive VR technologies can be improved by well-designed environments tailored to user needs[13]. Based on these considerations, the present study specifically focuses on immersive VR experiences and investigates the design principles for building virtual environments for metaverse.

Although assessing the influence of the surrounding environment on user behavior presents numerous challenges[14], various studies have been conducted in this direction[15,16]. For example, the work reported in[15] showed that modulating the architectural elements of a virtual environment (e.g., narrowing the sidewalls, increasing the window sill height, or increasing/decreasing the ceiling height) has a significant impact on affective state of the user, whereas the study presented in ref. [16] highlighted the effects of virtual environments with different levels of visual richness on perception and physical performance of the user.

Although the literature warns about possible effects of virtual surroundings on user experience, to our best knowledge, there is a lack of clear suggestions or guidelines to be followed by developers and creators when designing immersive virtual environments targeted at metaverse[17]. This research gap can probably be ascribed to the continuous changes in the underlying design principles, owing to the necessity of following the requirements set by new conditions and contexts[18], as well as by the availability of new hardware and software.

This study attempts to fill this gap by focusing on a specific case study involving the construction of a digital library in metaverse. This is just one of numerous metaverse applications, but it has been found to be among those that could benefit more from the massive adoption of cutting-edge architectural design criteria[19]. In fact, the digital transformation that has taken place in recent years can be considered an important opportunity for public libraries to confirm their role as key institutions for the preservation and valorization of culture as well as primary centers of intellectual life[20]. For this purpose, ways to provide readers with enhanced experience and personalized services should be devised.

In particular, the work reported in this paper builds upon an existing platform called MetaLibrary[21], which was developed in the framework of the Reading (&) Machine initiative funded by Fondazione TIM. The MetaLibrary tried to integrate the system of the city of Turin's public libraries into the Metaverse, by enabling users to access a shared virtual library. Within this virtual library environment, users can connect with other readers, participate in events where authors are invited, and make use of an innovative book-recommendation system that combines common knowledge about past readings with the current interests and mood of the user, gathered through an engaging interface (more details are given in ref. [22]).

The original version of MetaLibrary was developed as a proof-of-concept to explore the feasibility of integrating Turin's public libraries with metaverse. Graphical aspects received less attention in favor of developing the platform's functionalities. The library environment was mainly characterized by cartoon elements, and its design did not consider users' experiences and perceptions of the virtual surroundings.

Therefore, we decided to initiate a major systematic redesign of the virtual environment. This work illustrates the process that led to the development of a new version of MetaLibrary. To guide the design of the new environment, an intense analysis was conducted to extract the best practices regarding several design factors from studies in the literature and existing social VR platforms. Experts from the domains considered were also included. Moreover, a user study was conducted to evaluate two design factors (lighting conditions and scene layout richness), for which it was not possible to extract clear indications based on the above analysis.

The best practices identified in this study can be regarded as a set of considerations that can be leveraged to guide the design and development of immersive virtual environments for the metaverse in the considered and other application scenarios.

2 Related work

This section reviews previous studies aimed at designing novel virtual environments or evaluating them with end users. Additionally, some details are provided on the MetaLibrary platform with the goal of presenting its main characteristics and functionalities.

2.1 Design of virtual environments for the metaverse

As stated earlier, the current literature does not provide clear guidelines or recommendations for designing virtual environments. Nevertheless, studies have been conducted to evaluate the impact of design choices on end-users when navigating virtual spaces. The findings of these studies provide a partial but relevant picture of the design choices that should be considered when building a virtual environment for metaverse.

A cornerstone work in this respect is ref. [18], in which the authors, drawing on the results of a qualitative experiment, proposed terminology to refer to the different types of creative spaces that should be considered during the design of virtual environments. Specifically, the following types of spaces were identified: i) personal spaces, which enable individual mental and deep work and hence are helpful in reducing distractions or other simulations; ii) collaboration spaces, which allow groups of users to work or have face-to-face discussions; iii) presentation spaces, which can be leveraged to present, share, or consume knowledge in a one-directional way; iv) making spaces, which are areas devoted to practical work or conducting experimentations; and v) intermission spaces, which are meant to connect with other spaces and can be regarded as areas for transferring, recreating, and having breaks.

Regarding the richness of the virtual environment, the literature review in ref. [14] highlighted the importance of focusing on the correct levels of detail required for each specific scenario, rather than trying to replicate the overall physical space. Achieving a high-level of realism (e.g., using high-fidelity geometries, textures, and lighting) is advised only for interactable elements in the environment to help users better identify elements that play a more important role in the virtual environment. Moreover, the literature review confirmed the need to present elements that can help recall the context or characterize the experience in a virtual environment. Finally, openings to the outdoors (e.g., through windows) can help users construct a mental model of the environment and increase their sense of presence.

Another interesting study[15] investigated spatial perception in immersive virtual environments. The authors requested the participants of a user study to perform reading comprehension tasks in four different environments generated by manipulating ceiling height and type, and several qualitative dimensions were evaluated. Differences were observed only in terms of emotional responses and room appreciation, with participants preferring higher ceilings.

Perception aspects were also investigated in ref. [23], which reported the results of a neurocognitive examination aimed at studying the connections between human emotions and the properties of surrounding spaces. In particular, the effects of changing geometric properties (i.e., protrusion, curvature, scale, and proportion) on human emotions were explored. The study pointed out that larger and more symmetrical virtual spaces give users positive emotional responses when the environment is simple and characterized by curved spaces. Conversely, in complex environments, positive emotional responses were connected to protruding and asymmetric spaces.

The work reported in ref. [24] aimed to investigate the visual orienting and exploratory behaviors of users immersed in virtual environments. By tracking gaze movements, it was observed that users paid particular attention to virtual objects exposed to novel or unconventional information. Moreover, users primarily focus their attention on virtual objects that suggest or are related to the functionalities that they expect to find in a specific virtual environment, given the application context.

In the study conducted in ref. [25], a parametric model (a framework) was created to assess how progressive changes in sidewall distance, window and ceiling heights, as well as the color of the environment, can affect emotional states within virtual environments. By asking users to experience 54 virtual architectural designs and analyzing the results, the authors concluded that negative feelings were stimulated by narrowing the sidewalls, elevating the windowsill height, or adjusting the ceiling height upward or downwards.

A systematic literature review reported in ref. [26] demonstrated the importance of natural elements in virtual environments. Specifically, several studies analyzed in this systematic review demonstrated that exposing users to biophilic patterns (a concept adopted in the building industry to describe designs aimed at connecting the inherent human need to affiliate with nature in modern built environments by exposing people to natural features) has the potential to reduce stress, making users feel positive emotions and moods similar to those perceived in the real environment.

The study reported in ref. [27] focused on the effects of interior color schemes on human emotions, physiological responses, and task performance. More specifically, users involved in the study were asked to perform a proofreading task immersed in four virtual environments that presented different color schemes: red, white, blue, and green. The results showed that the red schema was significantly warmer, more oppressive, thrilling, tenser, and unpleasant than the others. Better user performance was observed with a white schema. Finally, a significant reduction in the heart rate (interpreted as the physiological response to the experience) was measured in the blue, white, and green scenarios.

Finally, the authors of ref. [28] conducted an empirical field study aimed at comparing a real urban environment with its computer-simulated counterpart, recreated using sounds recorded on-site, high-fidelity visual details, and animated elements for both daylight and nighttime scenarios. The study showed that the emotional response observed in the users when exploring the reconstructed environment did not necessarily correspond to the real one, and differences were observed between the day and night conditions, as users considered the nighttime more realistic than the daytime but also reported a reduced sense of safety in this condition. However, additional research is required to investigate the effects of daytime and nighttime conditions on other designs, such as indoor scenarios.

2.2 MetaLibrary

MetaLibrary[21] is a VR-based social platform designed to engage readers and authors and make them meet through metaverse. The goal of the platform is to support a community of users who are passionate about books, and to create an immersive space where they can discuss relevant topics and receive suggestions for further reading from the authors, the staff of a real public library. In its original implementation, the platform featured a cartoonish style for both the avatars and environment, as depicted in Figure 1.

Figure 1 Avatar and virtual environment of the MetaLibrary as implemented in ref. [21].

The virtual environment of MetaLibrary includes several rooms dedicated to specific functionalities of the platform. The following rooms were considered.

• Central hub: The area where users spawn and from which access to all other rooms is provided.

• Room of the day: In this room, users receive five recommendations, that is, a list of five books based only on a given topic that is changed daily and specified by the library administrator. Recommended books were selected based on the similarity between the daily topics and words included in the title or description of the book. The appearance of this room is adjusted to reflect the current topic of interest.

• Most-read room: This room provides users with the top ten most-read books based on data regarding books borrowed from public libraries in Turin.

• Conference room: Users have the opportunity to participate in conference events. A user, such as the author of a book or an invited speaker, can act as a presenter, delivering a talk to the audience. The layout of the room was designed to mimic the structure of a theater or a real conference venue, composed of a central stage reserved for the speaker(s) and several seats where attendees could observe and engage with them.

• Search rooms: Private rooms that users can enter to interact with an AI-based recommender system. Recommendations are formulated by considering book rent history, as well as user preferences and mood gathered through a simple game[22]. Owing to privacy concerns, a search room was created for each user, allowing them to explore their own recommendations privately. Access to this room is provided through a series of portals.

3 Materials and methods

This section illustrates the overall process followed in the redesign of the MetaLibrary virtual environment, including the analysis steps.

3.1 Design process

The design of the new virtual environment began with interviews conducted with expert staff from the following public libraries in Turin: Biblioteca Civica Centrale (https://bct. comune. torino. it/sedi-orari/

centrale), Bianca Guidetti Serra Library (https://bct.comune.torino.it/sedi-orari/bianca-guidetti-serra), and Primo Levi (https://bct.comune.torino.it/sedi-orari/primo-levi). Before the interviews, the original version of MetaLibrary was shown to people who visited the libraries, thus allowing experts to collect feedback from common users. Comments provided by users were elaborated upon by experts who reported them during interviews.

As anticipated, the design of the environment done in[21] did not consider aspects concerning users' experience and perception of the virtual surroundings, since the main aim was to develop the platform's functionalities rather than to make the environment visually appealing. Therefore, in addition to the considerations related to platform usability for a specific case study, the following general limitations emerged:

• The general style (i. e., cartoonish) represents both the virtual environment and avatars. The style defined in[21] was not generally appreciated by users who perceived the platform as a game rather than a social platform. The experts also noted that the level of satisfaction varied based on the users' backgrounds and attitudes toward technology. This comment aligns with findings of previous work like, e.g., ref. [29].

• Style inconsistencies among rooms. Users lamented confusion owing to marked differences in architectural structure and furniture layouts in the environment.

• Lack of areas dedicated exclusively to social activities. A chilled environment where informal conversations among the users may occur was not included in the original platform, and users were forced to use the central hub (which is generally crowded) or one of the ad hoc rooms introduced above, mixing the scope/functionalities of these spaces.

It is worth observing that the contribution of domain experts does not hinder the generalizability of the current work, as identified limitations could be largely extended to the design of virtual social environments in general.

Based on the reported limitations, the design of the new version of the MetaLibrary platform considers the following requirements:

• The overall style should avoid cartoonish elements in favor of more realistic assets that convey the platform's potential for hosting not only recreational activities, but also more serious and professional initiatives. This requirement refers to both the environment and representation of the avatars. The interviews also highlighted the necessity of considering methods to target heterogeneous and multi-age user categories, as noted in previous studies[29].

• Although diversity in the environment can help users distinguish between different areas of the platform, the design should include coherent elements to prevent users from becoming disoriented while navigating, highlighting the need for a well-ordered and coherent environment (in agreement with the findings of previous studies[17]).

• The environment should be endowed with areas specifically designated for social activities. This requirement is consistent with findings in the literature that emphasize the importance of designated areas for social interaction[14].

The best practices derived from the interviews were complemented by findings obtained from the analysis of the relevant literature. These findings are summarized in Table 1.

Finally, representative social VR platforms and VR applications were tested/analyzed to inspire the design of a new virtual environment. Specifically, the following platforms/applications were considered.

• VRChat (https://hello.vrchat.com/): This platform is characterized by heterogeneous environments in terms of style (e.g., realistic or cartoonish) and content (appearance and quantity). A consistent style was not found on this platform because users can create and upload their own virtual worlds to host their experiences. The following features were observed among the most popular environments: i) high ceilings,

Table 1 Best practices extracted from the analysis of the literature

Source	Best Practice
Thoring et al.[18]	Consider the spatial qualities and type of creative spaces when designing environments to easily accommodate different kinds of activities. Each space should be adaptable to support various user needs and tasks. Leveraging flexible designs enhances users' experience and maximizes the functionality of the environment.
Neo et al.[14]	High-levels of realism should be prioritized for elements with which users directly engage, in order to enhance users' interaction while preventing unnecessary resource consumption.
Chat et al.[15]	Using open and high ceilings to positively influence users' emotional responses.
Shemesh et al.[23]	Prioritize environments with larger, symmetrical, and curved spaces for simple settings, and incorporate protruded and asymmetric elements in complex settings to enhance positive emotional responses.
Lee et al.[24]	Designing environments with novel and contextually relevant objects to capture users' attention and guide exploratory behavior.
Presti et al.[25]	Prioritize wide spaces and lower windowsills to enhance comfort for the user and avoid negative emotional responses due to the perception of inadequate lighting.
Mollazadeh et al.[26]	Integrate biophilic patterns to make the users feel positive emotions.
Cha et al.[27]	Use specific color schemas to enhance performance and reduce physiological stress.
Bishop et al.[28]	Consider the specific emotional responses to day- vs night-time conditions for adjusting the sense of realism and safety.

ii) open spaces, iii) minimal rooms, and iv) limited biophilic designs.

• RecRoom (https://recroom.com/): Similar to VRChat, users can create their own scenarios. In general, virtual environments are characterized by a low-poly style, high ceilings, open spaces, minimal rooms, and natural elements.

• Mozilla Hubs (https://hubs. mozilla. com/): Virtual environments are created by users; hence, the analyzed environments present heterogeneous characteristics. The design tends to be minimal and is characterized by cold-colored schemes.

• Spatial (https://www. spatial. io/): Environments created by users are generally characterized by a low-poly and cartoonish style. Performance constraints limit the number of vertices used for the construction. The most popular environments are used for art exhibitions immersed in natural contexts, and tend to have high ceilings with openings, open spaces, and minimal rooms.

• Zepeto (https://web. zepeto. me/en): Virtual environments are heterogeneous and have different styles. The most popular applications typically involve outdoor areas. The architecture of the environment is simple and is usually inspired by the real world: high ceilings, large windows, sharp corners, and minimal rooms. The lighting was mainly natural, and the colors softened.

• Decentraland (https://decentraland.org/): These environments are created by users with a game engine; hence, they exhibit different characteristics. The architecture of these environments often shows complex shapes and rarely includes simple rectangular rooms, because curved forms are often used. The most commonly adopted style is a low-poly and cartoonish style.

• Second Life (https://secondlife. com/): Virtual environments present a high-level of realism, and 3D models with a high-poly count can be uploaded. In general, environments vary widely based on user creativity and design. They often feature various landscapes ranging from urban cityscapes to natural settings. Buildings and structures can be elaborate or simple and reflect user tastes and preferences. The use of high-fidelity textures and lighting effects enables a high-level of customization and realism.

• Tangra (https://tangra. link/): In contrast to previous platforms, graphics are generally more realistic. Architecture varies significantly depending on the functionalities available in the environment. Generally, they present common features, such as a high ceiling, natural elements, natural lighting, and cool colors.

• Viverse (https://www.viverse.com/): Similar to other platforms, the environments are heterogeneous but usually present a low-poly and cartoonish style. Open spaces and natural elements are generally included.

• Meta Horizon Workrooms (https://forwork. meta. com/it/horizon-workrooms/): Environments are designed to facilitate virtual collaboration and productivity. They typically feature sleek and modern virtual meeting spaces, with customizable layouts and furnishings. High-quality graphics are used to improve users' sense of presence and keep them engaged during meetings. The rooms that host the experiences generally have a semicircular shape, are furnished in a minimal way, and have high ceilings and large windows from which users can see a natural landscape. These windows also provided a natural lighting environment. Both cold-colored and warm-colored schemes were used.

Table 2 summarizes the common design practices shared by multiple platforms and applications that were leveraged to redesign MetaLibrary. Many of these characteristics (e.g., high ceilings and open spaces, biophilic elements, and natural lighting) align with findings already reported in the literature.

Table 2 Best practices extracted from the analysis of the social VR platforms and VR applications

Source	Best Practice
VRChat, Spatial, Zepeto, Tangra, Meta Horizon Workrooms	Use high ceilings, open spaces and large windows to provide a sense of openness.
RecRoom, Spatial, Tangra, Viverse	Enhance the environments with biophilic design aspects to create a more realistic and pleasant atmosphere.
Mozilla Hubs, Zepeto	Adopt an adequate color scheme to provide simple and clean visual aesthetics.
Second Life, Tangra	Incorporate lighting effects to increase the realism of the environment.
Second Life, Viverse	Utilize the proper level of realism for representing the avatars and the objects.
Decentraland	Focus on shape of the rooms by incorporating curved forms to improve visual interest.

3.2 Implementation

The application of the best practices presented in Section 3.1 led to the creation of a new virtual environment for the MetaLibrary platform, which is depicted in Figure 2(a).

Unlike the previous version of the virtual environment, cartoonish-style elements were avoided in favor of a more realistic appearance for both the environment and avatars. This design choice is consistent with the findings of refs. [14] and [30].

According to scientific literature, large and open spaces are generally preferred[15,25] for both perceptual and emotional responses. This was confirmed by almost all the social VR platforms analyzed. Therefore, we decided to use a high ceiling and interconnected rooms without doors (Figure 2(b)).

In terms of curvature, the room walls tend to be curved and the environment presents several symmetric elements (as proposed in ref. [23]). The curvatures and symmetries of the rooms are shown in Figure 2(a).

The furniture placed in the environment recalls the context of a previous work on public libraries[24] and includes tables and chairs (as depicted in Figure 2(c)). Shelves with many books (as would be expected in a library) were not included to help users focus on interactive virtual objects (i.e., recommended books) and avoid confusion[14].

Based on the findings of refs. [25] and [26], all spaces were equipped with large windows (i.e., transparent walls) that ensured a good level of lighting and provided a view of the natural elements outside (as shown in Figure 2(c)).

The outcomes reported in ref. [27] are used to define the color schema of the environment. White and blue are the dominant colors in the environment.

Moving into a more detailed description of each room, the central hub (Figure 2(d)) was designed by imitating the main hall of the Shanghai Library East[31]. This was done after observing that in contrast to the architecture of public libraries in Turin, the Shanghai Library East presents some of the characteristics mentioned above; hence, it was considered a good example to reproduce in VR. According to the

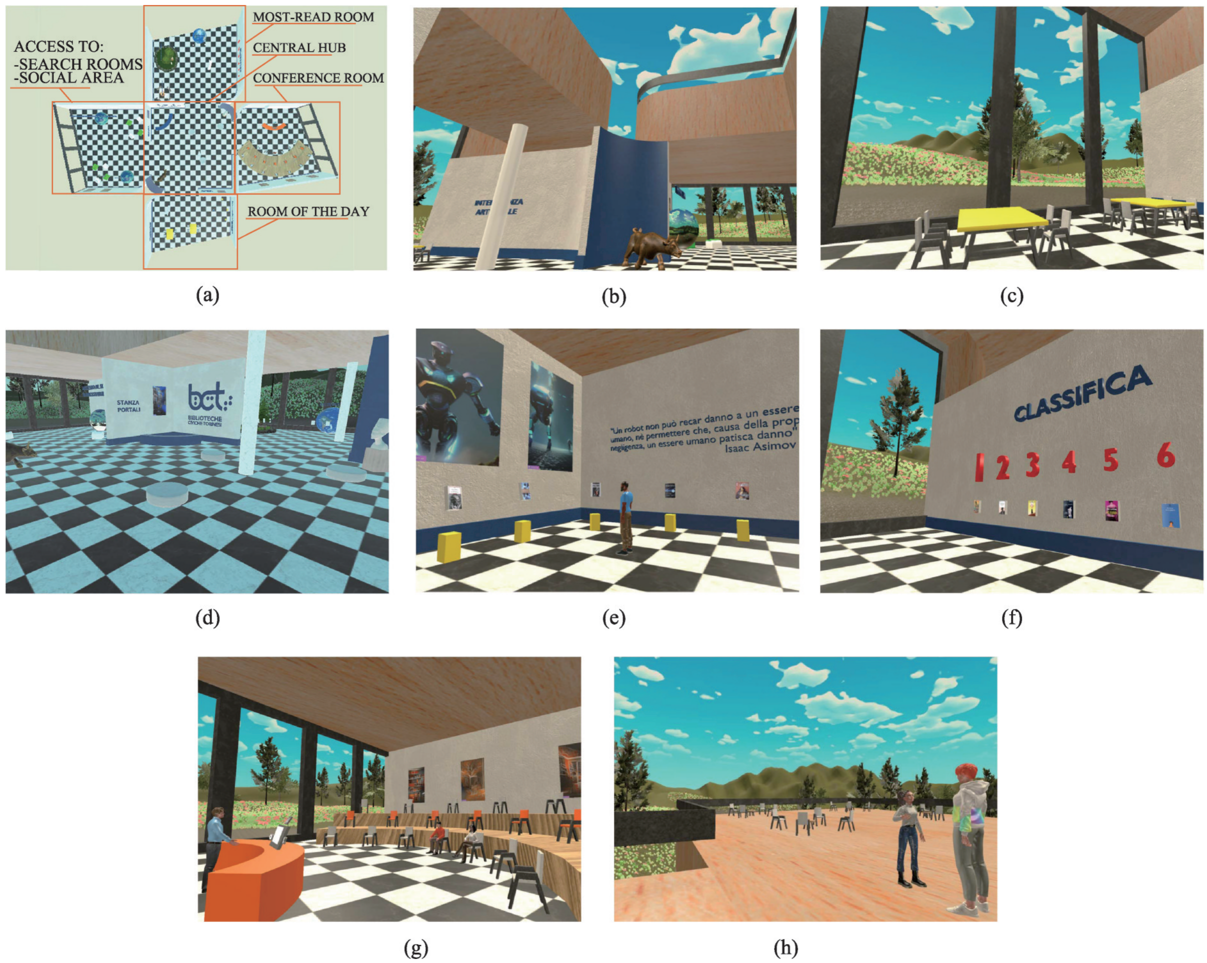

Figure 2 The redesigned virtual environment of MetaLibrary: (a) overview; (b) example of high ceilings and interconnected rooms; (c) furniture included in the environment; (d) central hub; (e) room of the day; (f) most-read room; (g) conference room; and (h) area dedicated to social activities.

terminology proposed in ref. [18], the central hub can be regarded as an intermission space. In fact, it is a large open space in which users can spawn. The hub was also leveraged to provide access to other rooms. Similar to the main hall of the Shanghai Library East, it is characterized by a high ceiling with curved walls. In contrast to the real library in Shanghai, all other rooms are on the same floor because navigating the environment using stairs or ramps could cause motion sickness in immersive VR[32]. Large openings in the external environment are uniformly distributed in this area (as suggested in ref. [26]).

The room of the day and the most-read room present the characteristics of a personal space[18]. More specifically, the rooms feature an appealing and functional environment in which users can immerse themselves in acquiring knowledge about the topic of the day and analyzing the most read books. Both rooms were designed considering the internal rooms of the Shanghai Library East as a reference and were positioned opposite each other to create symmetry within the central hub.

In the room of the day, distinctive elements aligned with the given topic (e.g., images and quotes from relevant books) were displayed on the walls (Figure 2(e)). The customization of rooms with distinctive elements has been proven to support work culture and engagement[33]. The five selected books showcased in this room were placed on dedicated pedestals to ensure that they were highly visible and well highlighted. This setup aims to capture users' attention and underscore the significance of book content, as suggested in ref. [14]. The room also presents furniture (i.e., tables and chairs) to evoke an environment dedicated to focus activities. The tables and chairs in the room invite users to sit and consult books, thereby facilitating interaction. This aspect promotes socialization and the exchange of knowledge, fostering an inclusive and collaborative environment.

In the most read room, one of the walls was dedicated to displaying the book rankings (Figure 2(f)). The numbers are highlighted in red to attract the attention of users and create a focal point within the space. In addition to serving as a point of interest, rankings provide users with information on book popularity, encouraging them to explore new readings.

A conference room (Figure 2(g)) can be regarded as a presentation space. It was designed with a traditional semicircular structure. The tiered seating arrangement allowed users to clearly view the presenters and the large screen behind them, thus fully engaging the audience at the conference.

Finally, the social activity area (Figure 2(h)) can be regarded as a collaborative space. This area is located on the terrace of the building. It was dedicated to informal meetings and interactions. These aspects are crucial for fostering a sense of community and socialization. Similar to outdoor environments that are visible through openings, this space also incorporates biophilic elements.

Implementing a high-performance and visually cohesive virtual environment in real-time poses several challenges, including the optimization and consistency of the visual style.

One of the main challenges was optimizing the application and embedding 3D assets in the platform. This was required to ensure smooth rendering, as low-performance may lead to motion sickness or a low-frame rate, particularly for users exploiting immersive VR. Given the need to render numerous objects from a user's perspective, a balance between visual fidelity and performance is required. Each 3D model was designed with a minimal polygon count to reduce the processing load, while preserving visual quality.

Additionally, texture and material optimization helped reduce memory demand, allowing for responsive and smooth navigation and interaction. Asset bundling and dynamic loading strategies were implemented to load objects as needed to prevent system overload.

Managing collisions with 3D objects was also challenging, particularly in scenarios involving large number of objects. Defining accurate collision boundaries for numerous objects in a confined space is resource intensive, particularly for VR. To mitigate this issue, simplified box colliders (such as cubes, spheres, and capsules) were used for non-interactive objects; 3D models were enclosed inside these simplified box colliders to prevent objects from overlapping with the virtual body of the user, while minimizing any impact on performance.

As mentioned, the other major challenge was maintaining visual cohesion. This was achieved by ensuring that each 3D model adhered to a consistent design workflow. Specifically, after modeling a new object, it underwent a revision process to ensure that uniform color schemes, texture resolutions, and lighting effects were used, thereby creating a consistent aesthetic once embedded in the virtual environment.

Finally, lighting and shadows pose further challenges, because a credible lighting setup can significantly enhance the virtual experience. Dynamic lighting must be carefully optimized because real-time shadows are computationally expensive, particularly in VR.

3.3 Technologies

After presenting the characteristics of the virtual environment and challenges related to its implementation, this section outlines the selected cutting-edge technologies used to build the MetaLibrary platform.

This selection was guided by the goal of coping with the implementation challenges (reported above) and additional needs (e.g., accessibility and compatibility of the proposed platform) that were considered crucial for this work.

The requirements for the selected technologies and specific tools adopted are presented below: To create a virtual environment and populate its rooms with interactive 3D assets, two primary tools were used: i) Blender, a comprehensive graphics suite for 3D modeling, and ii) Unity (version 2020.3.4), the game engine responsible for running the platform's core logic. The selected tools represent some of the most widely used three-dimensional modeling suites and computer graphics-based game engines[34]. In particular, the adoption of open-source suites such as Blender was crucial, as they can facilitate collaboration among developers, enable the reuse and extension of existing work, and significantly accelerate the development of virtual environments. Moreover, the use of widespread engines such as Unity can bring benefits in terms of software accessibility, as well as the availability of software packages and assets that can be quickly and easily integrated into the VR application development flow. Regarding implementation challenges, Blender made it possible to control the topology of the meshes, ensuring that 3D objects with a minimal polygon count were generated. Blender also helped with texture and material optimization. Unity-supported asset bundling, dynamic loading strategies, optimized collision detection methods, and the use of its baked lighting options with strategically placed real-time lights helped to develop a platform that can effectively balance appropriate lighting and performance.

The platform was designed primarily for use with an Oculus MetaQuest 2 VR headset. This headset addresses several key needs in scientific research as it provides a high-quality and affordable solution for creating immersive VR experiences[35]. Specifically, as a standalone device, Oculus Meta Quest 2 eliminates the need for large sensor-embedded spaces, high-performance computers, and complex setups. Moreover, its compatibility with popular development tools enables efficient creation and customization of VR applications to meet specific experimental requirements.

The OpenXR framework was leveraged to handle VR functionalities using the XR Interaction Toolkit. OpenXR provides a unified interface for the XR hardware and software, simplifying the development process of virtual experiences and promoting interoperability. In this study, the use of the open-source OpenXR standard through the XR interaction toolkit makes it possible to enhance the compatibility and accessibility of the proposed VR platform across multiple devices and frameworks[36].

The logic, scripts, and components that control the functioning of the platform were developed using the MS Visual Studio suite, which was integrated with the Unity game engine to provide a streamlined development workflow. All scripts were written in C#. In addition, a natural outdoor environment was created using the Unity Terrain Sample Asset Pack. As a free resource provided by Unity[37], it offers a cost-effective solution for creating and modifying terrain assets to address the specific development needs of this study, that is, generating a landscape asset optimized for the performance requirements of a VR application. This ensured that the terrain was visually appealing while maintaining an efficient rendering performance, even on lower-end hardware.

For the avatars populating the virtual environment, in line with previous studies[38], a full-body humanoid representation generated using the Ready Player Me online tool was chosen. Ready Player Me is required for the quick creation of customizable cross-platform avatars for virtual environments. Its integration with popular graphics engines, such as Unity, makes it an essential tool for developers aiming to simplify avatar creation and enhance user immersion across multiple platforms, without the need for extensive modeling expertise[39].

Once imported, the Ready Player Me avatars were further optimized with simplified rigging and Inverse Kinematics systems within Unity to ensure smooth and responsive movement while minimizing resource demands. To streamline the animation process, prerecorded animations from Mixamo were integrated, allowing human-like avatar movements without the need for custom animation. Available animations were adjusted within Unity to ensure smooth transitions and maintain high-performance, effectively enhancing interaction fluidity without affecting the overall performance.

4 User study

Although most of the choices regarding the redesign of the MetaLibrary were based on the best practices presented in Section 3.1, two factors, namely the lighting conditions and layout of the environment, required a dedicated investigation, as anticipated. To the best of our knowledge, there were no actionable elements gathered through the analyses described above that could anticipate the impact of these factors on user engagement and perception of the virtual environment. More specifically, it was observed that there are limited guidelines regarding the use of artificial lighting in virtual environments because in most cases studies focused only on natural lighting. Regarding the layout, that is, the number of objects/furniture within the environments and their arrangement, a significant gap in the scientific literature concerning this specific aspect was observed. Although additional factors might have been included in the analysis, we decided to focus solely on lighting and layout because the combined effects of multiple factors on the collected data could have hindered the analysis of the results, leading to potentially misleading interpretations.

Based on the realization obtained following the process reported in Section 3, several configurations of the platform environment were generated and compared through a user study. The study requested participants to perform three different tasks in the resulting environments with the aim of obtaining useful insights into the best combination of the considered factors for a given task.

4.1 Procedure and tasks

Two conditions can be identified for lighting and layout. The following lighting conditions were considered: i) daytime with natural lighting (referred to as D), and ii) nighttime with artificial lighting (N). Regarding the layout, environments full of objects (F) or empty objects (E) were investigated. Four experimental configurations are obtained by combining the aforementioned conditions: D+F, D+E, N+F, and N+E.

The redesigned virtual environment of the MetaLibrary platform was set up based on the above configurations, and the participants were invited to perform three tasks to judge its suitability from different perspectives. In the first task (referred to as T1), participants were asked to attend a presentation held by a nonplayer character (NPC) in a conference room. The presentations lasted less than two minutes and covered topics related to famous books and authors. In the second task (T2), the participants were located in the room of the day and were requested to interact with the two books exhibited therein, with the final aim of obtaining information on the books themselves and the topic of the day. Finally, in the third task (T3), the participants were invited to interact with three avatars in the social activities area. The avatars were NPCs that had been programmed to provide their opinions on books.

Figure 3 shows the three tasks and environmental configurations considered in this study.

The experiment was arranged following a 3×2×2 (tasks, lighting conditions, and layout conditions) within-subjects design. More specifically, after completing a demographic questionnaire and receiving general instructions on the experiment, the participants were invited to familiarize themselves with the MetaLibrary platform and its basic commands for navigating the environment using Oculus MetaQuest 2. Specifically, as in[21], an approach based on continuous movement was leveraged to allow participants to navigate a virtual environment.

When they felt confident and received instructions on the tasks, they were moved to the spaces allocated to them. For each task, the participants completed the required operations (i.e., listening to the presentation and interacting with books and avatars) using all four configurations.

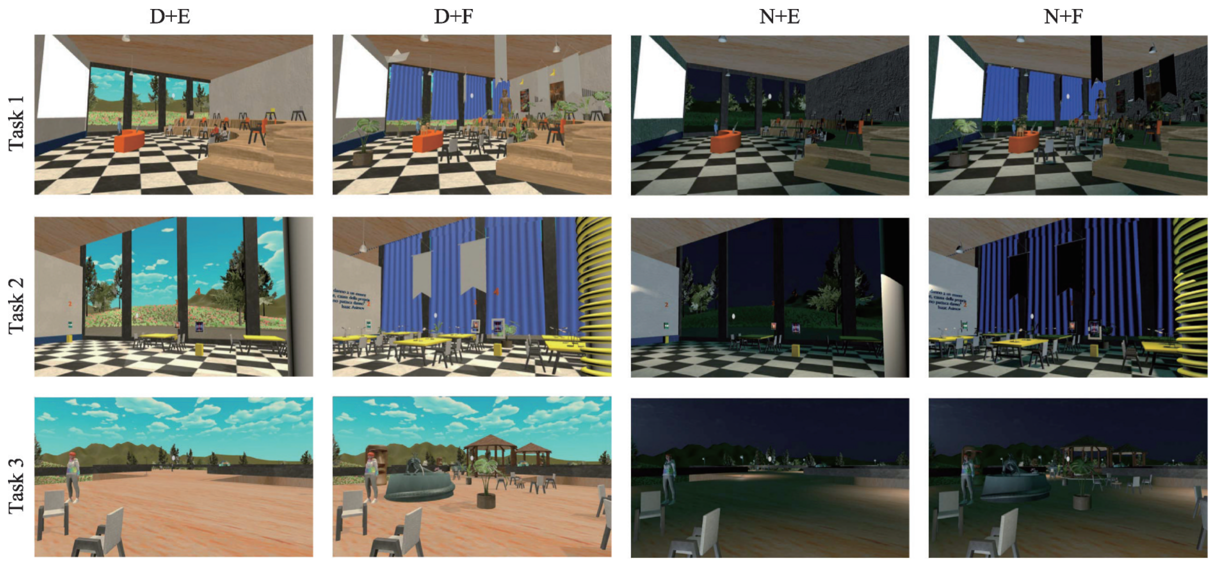

Figure 3 Configurations of the virtual environment and tasks included in the study.

The order of the tasks and configurations to which each participant was exposed was randomly selected to limit the learning effects. At the end of the experiment, a posttest questionnaire was administered to the participants.

4.2 Evaluation metrics

Both objective and subjective aspects were considered during the experiment. The objective dimension was chosen to collect *fixation time*, that is, the time the participants spent looking at specific elements considered relevant for the execution of the task. Specifically, in T1, participants were expected to direct their attention to the large screen displaying the topic presented by the NPC on stage. In T2 and T3, the expected targets were a given book in the room of the day and NPCs, respectively. Thus, the time spent observing these elements was determined. The analysis of fixation time is expected to provide useful insights into user engagement because high values of this metric indicate that users are focused on assigned tasks. High concentration may be ascribed to the perception that the environment was not a confusing or distracting element of the experience.

For the subjective dimension, the analysis focused on aspects related to attractiveness. More specifically, the post-test questionnaire asked participants to rate each configuration (i. e., D+F, D+E, N+F, and N+E) according to the 28 adjective pairs of the AttrakDiff tool[40] for each of the three tasks. Each pair was ordered on a scale of intensity (1-to-7) and referred to four subscales: pragmatic quality (PQ); hedonic quality, split into identity (HQ-I) and stimulation (HQ-S); and overall attractiveness (ATT).

Finally, participants were asked to rank the four configurations and provide general comments on their experiences.

4.3 Participants

Overall, 20 participants (13 male and seven female) were included in the study. Participants were aged between 24 and 34 years (M = 26.04, SD = 2.39). According to the data collected through the demographic questionnaire, the sample can be regarded as heterogeneous regarding familiarity with VR; 55% of the participants regularly used this technology, whereas the remaining reported limited (35%) or no experience (10%). Regarding the use of virtual and social media platforms, participants were not used to operating with them (95%). In contrast, most participants (75%) reported frequent use of video games.

5 Results

The statistical significance of the collected data was analyzed using the RealStatistics tool with three-way repeated-measures ANOVA. Two-factor or one-factor repeated-measures measure ANOVA with Bonferroni correction was used as a follow-up when appropriate. The normality assumption was verified using the D'Agostino-Pearson test. Finally, statistical analysis of the rankings was performed using the Friedman test and Wilcoxon Signed-Rank test for paired samples.

5.1 Objective results

Figure 4 shows the average percentage of fixation time, that is, the ratio between the time the participants spent looking at the given target and the overall completion time of the task.

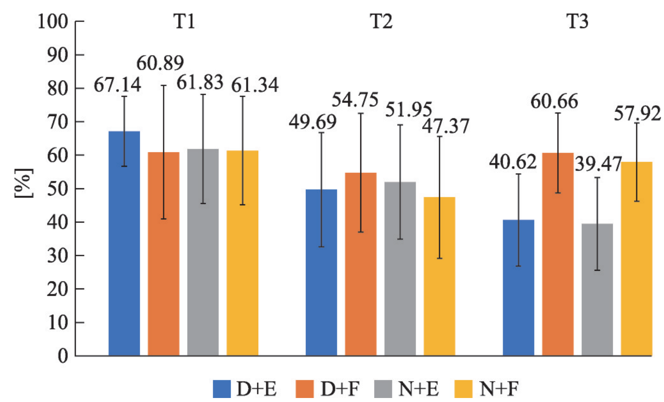

Figure 4 Objective results regarding fixation time.

Analyzing the main effects of the three factors (tasks, lighting conditions, and layout conditions), statistical significance was found for the tasks (T1:58.80% vs. T2:49.94% vs. T3: 45.67%, $p < 0.001$) and layout conditions (E: 47.78 vs F: 53.15, $p = 0.008$). More specifically, the follow-up analysis of the tasks revealed statistically significant differences between T1 and T2 ($p = 0.011$), and between T1 and T3 ($p = 0.001$).

These results indicate that regardless of the lighting and layout conditions, the participants focused more on the given target in T1 than in T2 and T3. Moreover, when the environment was characterized by a rich layout, that is, in condition F, the participants focused more on the given target than on the other layout conditions, regardless of the tasks and lighting conditions.

A significant interaction was found between the tasks and layout conditions ($p < 0.001$), indicating that the effect of one of the two factors (e.g., the layout condition) on fixation time also depends on the task. Table 3 reports the detailed comparisons of all configurations.

Table 3 *P*-values of the follow-up analysis conducted on fixation time to study the interaction effect between the task and layout factors. Bold font indicates satistically significant differences

	T1×E $\mu = 60.48$ ($\sigma = 10.68$)	T1×F $\mu = 57.11$ ($\sigma = 14.91$)	T2×E $\mu = 46.82$ ($\sigma = 15.02$)	T2×F $\mu = 36.05$ ($\sigma = 14.66$)	T3×E $\mu = 47.06$ ($\sigma = 12.65$)	T3×F $\mu = 55.29$ ($\sigma = 8.76$)
T1×E	–	0.242	**0.005**	**0.002**	**< 0.001**	0.083
T1×F		–	0.056	0.055	**0.001**	0.628
T2×E			–	0.908	**0.003**	**0.005**
T2×F				–	**0.002**	**0.005**
T3×E					–	**<0.001**
T3×F						–

5.2 Subjective results

Figure 5 shows the average scores assigned by the participants to the 28 adjective pairs in the AttrakDiff tool.

Starting with the PQ subscale, a significant main effect was found for tasks (T1:5.39 vs T2:4.90 vs T3: 5.11, $p = 0.009$) and layout conditions (E: 5.68 vs F: 4.58, $p < 0.001$). The follow-up analysis for the task

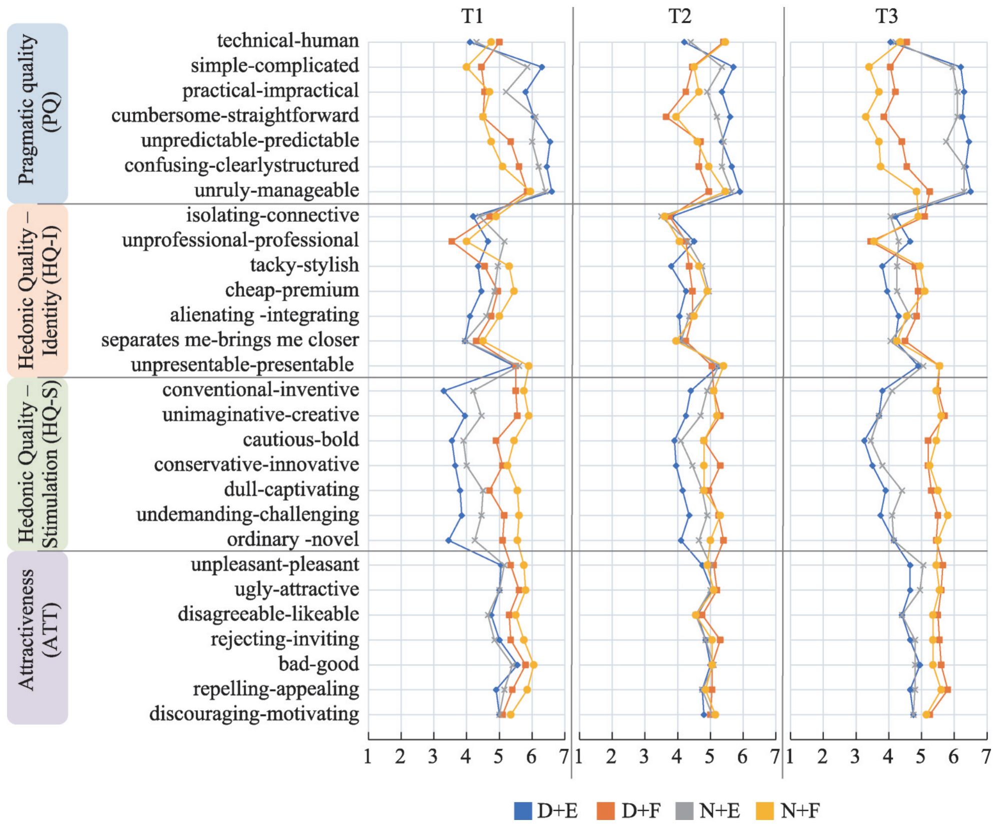

Figure 5 Subjective results regarding attractiveness based on the AttrakDiff tool[40].

factor indicated significant differences between T1 and T2 ($p = 0.002$) and between T1 and T3 ($p = 0.023$). Similar to the fixation metric, these results indicate that the pragmatic quality of the environment was rated differently depending on the task, with higher scores assigned to T1 than to T2 or T3. Moreover, Layout E was generally rated as more usable than Layout F. This preference is easily noticeable in Figure 5, where the blue (D+E) and gray (N+E) lines represent higher values than the orange (D+F) and yellow (N+F) lines.

Again, considering the interactions, a significant effect was found between the tasks and layout conditions ($p = 0.007$). Detailed comparisons are presented in Table 4.

Table 4 *P*-values of the follow-up analysis conducted on the PQ subscale of the AttrakDiff tool to study the interaction effect between the task and layout factors. Bold font indicates statistically significant differences

	T1×E $\mu = 5.85$ ($\sigma = 0.56$)	T1×F $\mu = 4.93$ ($\sigma = 1.03$)	T2×E $\mu = 5.26$ ($\sigma = 0.93$)	T2×F $\mu = 4.55$ ($\sigma = 1.06$)	T3×E $\mu = 5.94$ ($\sigma = 0.69$)	T3×F $\mu = 4.28$ ($\sigma = 1.09$)
T1×E	–	**< 0.001**	**0.003**	**< 0.001**	0.484	**< 0.001**
T1×F		–	0.109	0.084	**0.001**	**0.004**
T2×E			–	**0.001**	**0.005**	**< 0.001**
T2×F				–		0.200
T3×E					–	**< 0.001**
T3×F						–

For the HQ-I subscale, no statistically significant differences were found in the three-way ANOVA test for either main or interaction effects. With respect to the HQ-S subscale, a significant effect was identified for the lighting (D: 4.54 vs N: 4.82, $p = 0.046$) and layout (E: 4.06 vs F: 5.30, $p < 0.001$) conditions. These results indicated that the N and F conditions were more stimulating and engaging than the D and E conditions, respectively. A significant interaction effect was found between the tasks and layout conditions ($p = 0.018$). Table 5 reports the detailed comparisons.

Table 5 *P*-values of the follow-up analysis conducted on the HQ-S subscale of the AttrakDiff tool to study the interaction effect between the task and layout factors. Bold font indicates statistically significant differences

	T1×E $\mu = 3.95$ ($\sigma = 1.30$)	T1×F $\mu = 5.36$ ($\sigma = 0.79$)	T2×E $\mu = 4.40$ ($\sigma = 1.18$)	T2×F $\mu = 5.08$ ($\sigma = 0.59$)	T3×E $\mu = 3.84$ ($\sigma = 1.26$)	T3×F $\mu = 5.46$ ($\sigma = 0.64$)
T1×E	–	**< 0.001**	**0.079**	**< 0.001**	0.681	**< 0.001**
T1×F		–	**0.001**	0.096	**< 0.001**	0.498
T2×E			–	**0.006**	**< 0.001**	**< 0.001**
T2×F				–	**< 0.001**	**0.015**
T3×E					–	**< 0.001**
T3×F						–

Regarding the ATT subscale, only the main effect of the layout factor was found significant (E: 4.88 vs F = 5.35, $p < 0.001$). The participants judged Layout F to be more appealing and attractive than Layout G, regardless of the task and lighting conditions.

Finally, participants were asked to rank the configurations in terms of their overall satisfaction. Statistically significant differences were observed only at T1 ($p < 0.001$). Unfortunately, it was not possible to identify a clear ranking among the four configurations owing to the lack of significant differences when performing pairwise comparisons (Table 6 reports the outcomes of the statistical analysis). The analysis revealed that the D+E configuration was less preferred than the D+F ($p = 0.001$), N+E ($p = 0.018$) and N+F ($p = 0.002$) ones.

Table 6 *P*-values of the pairwise comparison conducted on the ranking for T1 ($p < 0.001$). Bold font indicates statistically significant differences

	D+E *med* = 4	D+F *med* = 2	N+E *med* = 2.5	N+F *med* = 2
D+E	–	**0.001**	**0.018**	**0.001**
D+F		–	0.194	0.759
N+E			–	0.399
N+F				–

5.2 Discussion

Analysis of the objective metric revealed significant effects related to the tasks to be performed by the participants in the virtual environment. In the devised experiment, attending a conference attracted more attention from the participants than interacting with books and other avatars. This can be ascribed to the architectural elements adopted in the original MetaLibrary. The conference room had a semi-circular structure that helped the participants focus their attention on the content being presented on stage. Conversely, the other tasks were conducted in open spaces (a wide room in T2 and a terrace in T3). This observation confirmed that the design of virtual environments should be tailored to the specific tasks that users must perform.

Another outcome was regarding the layout of the virtual environment. For tasks that required the participants to direct their attention to the given targets, the presence of potentially disturbing elements made them less prone to exploring the environment with the gaze.

Subjective measurements collected using the AttrakDiff tool showed that the PQ of the environment varied significantly, depending on the considered tasks and layout conditions. The conference room environment was rated as more usable than the others. Moreover, layouts that presented a lower number of objects were considered more usable than crowded layouts, confirming the disturbing effects of such elements.

However, for the HQ-S subscale, the F condition was rated as more stimulating than the E condition.

From the above observations, it can be concluded that a correct balance should be found between PQ and HQ-S, as simpler the layout, the higher the usability, but lower the stimulation and engagement.

The significant interactions between the tasks and layout conditions observed for both objective and subjective metrics indicate that these two factors are strictly connected.

Regarding lighting, only a slight preference for the N condition over the D condition was observed for the HQ-S subscale. Further studies are required to investigate this.

6 Conclusion

This paper presents the design of immersive environments for Metaverse, considering a case study of a virtual reality (VR) platform devised to offer social experiences to users of virtual libraries. By conducting interviews with experts in the field and a review of relevant works in the literature and existing VR-based social platforms, a number of best practices have been identified that guided the redesign of the virtual environment for the considered platform.

Best practices can be summarized as follows.

- The design of versatile spaces should incorporate high ceilings, open layouts, and large windows to foster a sense of openness, support diverse activities (e.g., learning, socializing, and working), and positively influence users' emotions, thereby creating a welcoming atmosphere.
- The implementation of flexible layouts enhances the user experience while simultaneously optimizing the environmental functionality of the design.
- It is recommended to set realism as the primary objective only for interactive elements such as avatars and objects to prevent unnecessary resource consumption. The incorporation of lighting effects can significantly augment the realism of the environment, as it tends to enhance user engagement.
- In simple settings, focusing on larger, symmetrical, and curved spaces is suggested to create visual interest, whereas in complex settings, the addition of asymmetrical and protruding elements is advised to enhance positive emotional responses.
- The incorporation of biophilic design elements including natural patterns and textures can facilitate the creation of a more realistic and agreeable ambience that encourages positive emotional states.
- Color schemes that provide a clean and visually aesthetic environment should be selected to enhance user performance and reduce physiological stress.

Finally, it is recommended that emotional responses to daytime and nighttime conditions be considered to adjust perceived realism and ensure a sense of safety.

In addition, a user study was conducted to validate the design choices regarding two factors (lighting and layout) that could not be derived from the above analysis. The study was limited to lighting and layout because considering multiple factors simultaneously could have complicated the interpretation of the observed results. This complexity arises from difficulties in disentangling the combined effects resulting from the concurrent variation of multiple factors.

Although this study presents a rich set of best practices that could support many design choices, further studies are needed to investigate certain aspects in greater depth to fill the identified gaps. For instance, the effect of lighting conditions requires additional investigation because a clear preference was not observed, except for some aspects concerning attractiveness. Moreover, future analyses should be conducted to better investigate the observed interaction effects between the considered factors. In this respect, a study arranged as a breakdown analysis could provide deeper insights into these interactions and their implications.

Possible future work could also be devoted to analyzing aspects that were not addressed in the proposed study. For example, future research could examine the effects associated with animated elements, such as comparing static and dynamic environments, the impact of nonplayer character (NPCs) movements, and avatar interaction on users' immersion, and how sound should be considered in the design of new virtual environments. Finally, investigating dynamic lighting adjustments and analyzing the effects of varying levels of user interactivity and customization on presence could offer new opportunities for future research.

The tasks are another dimension that deserves attention. As indicated by the user study results, the tasks to be performed play a crucial role in designing the environment. However, other task types should be investigated to increase the generalizability of the results.

Finally, it is important to note that the current work has leveraged a specific case study. As mentioned, MetaLibrary was selected because it presents most of the characteristics of social VR platforms, thus offering a concrete framework for applying and validating the identified best practices. However, the generalizability of these best practices should be investigated by considering different application scenarios and conducting comparative studies to quantitatively assess the impact of the design choices.

Declaration of competing interest

We declare that there are no competing interests.

CRediT authorship contributions statement

Alberto Cannavò: Data curation, Methodology, Supervision, Writing-original draft, Writing-review & editing. **Giorgio Arrigo:** Conceptualization, Software. **Alessandro Visconti:** Conceptualization, Methodology, Software, Supervision, Writing-review & editing. **Federico De Lorenzis:** Conceptualization, Investigation, Validation, Writing-review & editing. **Fabrizio Lamberti:** Conceptualization, Project administration, Supervision, Writing-review & editing.

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