Dreamscape Bricks VR: An Experimental Virtual Reality Tool for Architectural Design

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Abstract. In this paper, we propose a VR design tool framework called DREAMSCAPE, which adopts a direct manipulation approach focusing on embody, experience, and manipulation activities in design. The framework defines a VR design process using intuitive controls without being limited by the preconceptions of conventional CAD systems. To establish and demonstrate the framework, we designed and developed a VR design tool called Dreamscape Bricks VR in Unreal Engine 4, using LEGO bricks as base components in a high-fidelity interactive design environment. We conducted user tests and administered questionnaires assessing usability, performance, and comfort. Results showed that the user experience of the tool is positive. The developed tool is expected to establish the abstract framework and provide insights into the future of VR design tools with implications on design education.

Keywords: virtual reality, architectural design, VR in design education, room-scale VR, metaverse.

1 Introduction

Virtual Reality (VR) is a technology that creates a computer-simulated virtual environment that can be explored and interacted with [1, 2]. VR has been increasingly used in architectural design and visualization for years, providing users with an early immersive experience of architectural products. VR can be used to understand architectural design issues better. However, as the available VR design tools used by architects are mostly imported from other disciplines, i.e., conventional 3D computer-aided design (CAD) tools or adopted versions of existing architectural design tools, it is still a long way from reaching its full potential in architectural design and education.

We conceptualized dreamscapes as a mid-ground between imagination and perception, where designers are bodily present in their ideas while they conceive them. The concept is not unlike dreams, where the creator of the environment is also the one who explores and interacts with it. This is the main idea behind Dreamscape Bricks VR, the experimental immersive virtual design environment we introduce, facilitating users to experience their architectural creations by building and interacting with them in virtual reality. We designed the DREAMSCAPE framework inspired by the notion of dreams tempting us to leave conventional preconceptions to imagine how things could have been different instead of focusing on what things are [3]. The framework aims to provide architectural design potentials of immersive virtual reality, which can reach beyond the preconceptions of 3D modeling and provide users with new and intuitive ways of seeing, perceiving, and interacting with the designed space.

This paper presents Dreamscape Bricks VR, a prototype experimental design tool using the DREAMSCAPE framework, which was developed for use in architectural design and education. This tool aims to provide an intuitive design environment for users in immersive virtual reality using LEGO bricks as base design components. The approach is anticipated not only to produce the tool itself but also to establish the abstract framework and start a debate about the future of VR design tools and their implications on design education.

1.1 Methodology

The use of virtual reality in architectural design promises to be more than a representation tool or yet another CAD technology development. VR is an effective immersive environment with many potentials for the architectural design process. To isolate the VR design experience from the preconceptions of conventional 3D modeling, the proposed tool must be stripped of CAD tools' existing vocabulary and grammar. Only then the original opportunities and potentials of VR can emerge.

To overcome the issues mentioned above, we introduce an abstract VR design framework called DREAMSCAPE (a backronym of Digital Reality Environment as A Medium for Studio Collaboration in Architectural Production & Education). The DREAMSCAPE framework envisions platforms for architects to simultaneously design, collaborate and represent their architectural designs, works or sketches in VR, using a more intuitive design environment based on real-world semantics and interactions rather than importing and forcing the legacy CAD and 3D modeling vocabulary and interactions to VR.

The framework proposes a more intuitive design environment based on real-world semantics and interactions rather than importing the 3D modeling semantics and interactions to VR. Therefore, Dreamscape Bricks VR uses LEGO pieces as modular building components, allowing high fidelity simulation of LEGO building with the same components and the same set of rules between digital and physical media.

To initiate and demonstrate the DREAMSCAPE framework, we developed Dreamscape Bricks VR, an immersive virtual reality design tool that uses LEGO bricks as base components. Then, we conducted a user test study with twelve participants to assess the proposed design tool. Finally, the results of the test study and the insights of the developed tool were analyzed and discussed.

2 Background and Related Work

Building models and mockups is a critical part of the conventional architectural design process, where the model is the first step for building the design in physical reality. The introduction of CAD and 3D design software has enabled designers to support the model making or even skip the physical part of the process altogether and create a virtual model on a computer. Now, VR technology holds the promise to take this one step further and enable designers to build a virtual model directly in the virtual medium. However, the interaction design and optimization of existing CAD systems tend to address the limitations of current legacy technologies. These interaction methods are not intended for immersive VR. Modeling in VR is still a challenging task as it requires us to reconsider the human-computer interaction in digital design while enabling users to interact with virtual objects in a natural and intuitive way and addressing the potentials of VR and immersive technologies.

The review of academic literature shows growing interest in the field of VR in general and VR in architecture in particular [4, 5]. Several studies have focused on the use of VR in education [6–8]. Other studies focus on VR in architectural design and education [9–12], urban applications of VR [13, 14], and VR in architectural heritage [15–17]. It can be argued that the availability of consumer-level VR devices such as Oculus Rift and HTC Vive, and the increasing number of VR applications in architecture and design motivated researchers to investigate the potential of VR technology in design in recent years.

Currently, several commercially available VR tools can be used to create and visualize architectural models and environments. While some VR tools primarily allow users to visualize 3D models that are created using another modeling software [18], others also enable users to create their model in VR environments, which we call "VR design tools" in the current study. Table 1 shows a feature comparison of some of the popular and commercially available VR design tools for PC VR platforms.

Table 1. Feature comparison of popular VR design tools and Dreamscape Bricks VR.

	Model Creation	Object Transformation	Animation support	Multiple users
Adobe Medium	3D Mesh, Prefabs	Sculpting	-	-
Quill	Particles, Prefabs	Brush painting	Yes	Yes
Blocks	3D Mesh, Prefabs	Sculpting, mesh editing	-	-
Google Tilt Brush	Particles, Prefabs	Brush painting	-	Yes
Microsoft Maquette	3D Mesh, Particles, Prefabs	Sculpting, brush painting, mesh editing	-	Yes
Masterpiece VR	3D Mesh, Particles, Prefabs	Sculpting, brush painting, mesh editing	Yes	-
Gravity Sketch	3D Mesh, Particles, Prefabs	Sculpting, mesh editing	-	-
Dreamscape Bricks VR	Prefabs	Brick building	Yes	Yes

These tools have been used to create VR environments for a wide range of applications, such as training, education, and entertainment. However, we did not find any VR tools that enable users to create and interact with their building intuitively, using simulated real-life components. The work of Raikwar et al., which simulates a physical educational assignment in VR [12], has a similar approach, yet its interactions (such as snapping objects by defined increments, rotational snapping by defined degrees) and graphical user interfaces (two-dimensional menu windows, buttons, drop-down menus) are also a reflection of a conventional CAD tool in VR. In reviewed VR design tools, object interaction methods are also heavily legacy CAD inspired (e.g., move, rotate, snap, select/deselect, group/ungroup, zoom in/out, undo/redo, etc.). Since we cannot replicate these transformations and interactions with physical objects, comparing a design activity with these tools versus a physical environment would affect the final product with too many variables.

Dreamscape Bricks VR, which uses modular building components (i.e., virtual LEGO pieces), is tailor-made for the current study, which can be used to compare design processes in the physical environment versus in VR in future research.

3 Design and Development of the Tool

The main objective of the "Dreamscape Bricks VR" tool is to create an immersive environment that enables users to interact with the virtual world in a way similar to how they would interact with real-world objects, where they create, experience, and modify their designs iteratively in real-time in virtual reality.

The DREAMSCAPE framework proposes a design process based on three activity types: (1) *embodying* conceptual design ideas, (2) *experience* the preliminary design output, (3) *manipulate* the design output to conceive new ideas (see Figure 1). These three activities are carried out iteratively in spatial and temporal succession. The tool should aid architectural design professionals and students to come up with initial design ideas visualizing, comparing, and embodying these conceptual design ideas interactively [19]. It should also facilitate the designers to see, experience, and discover features and understand relationships of their design [20] as a spatial setting while designing in an immersive virtual environment. Finally, the tool should allow users to participate in stimulating design interactions and manipulations, enhancing the design iterations with the opportunities of VR.

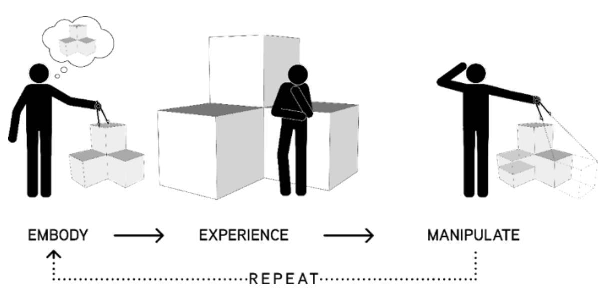

Fig. 1. The threefold design activity flow proposed by the DREAMSCAPE framework.

The main design challenge of the tool is to create an immersive environment where users can *experience* their creative ideas interactively and constructively while they are designing them. The tool should give users the freedom to *embody* their ideations using intuitive design components. The interactions with design components should be intuitive so that users can manipulate their own design by freely attaching, detaching, moving, removing, or modifying the design components in familiar ways from the physical world. Table 2 shows a comparison of the workflows of legacy CAD with point-and-click interactions and a proposal with direct manipulation approach.

Table 2. Comparing the user interactions between legacy CAD and the proposed approach when extruding an object.

	Legacy CAD workflow	Direct manipulation workflow
Commands and interactions	1. Select a polygonal face 2. Selected face gets highlighted 3. Select the "extrude" command 4. Point to the new location 5. Click to execute the command	1. Touch a surface with hands 2. Haptic feedback given and the selected surface gets highlighted 3. Hold and pull the surface to make an object bigger

The legacy CAD workflow forces the user to think within the possibilities of available CAD commands. It requires training and a certain period of practice before the users can get fluent with these interactions. Instead, our approach is a relatively intuitive and natural interaction that requires no training.

The direct manipulation approach is based on the idea of enabling users to directly manipulate virtual objects through the use of intuitive and straightforward visual and physical actions [21, 22]. A direct manipulation interface can be defined as enabling users to perform actions upon virtual objects using direct hand gestures or other direct physical actions. This approach enables users to interact with virtual objects in a similar way to real-world objects. Previous research has shown that the lack of intuitive direct manipulation 3D modeling and digital prototyping tools is a major limitation compared to VR [23, 24].

Therefore, the new VR design tool should be designed not to require users to rely on an old design vocabulary or a new design grammar. Users should be able to manipulate the existing design components in a natural way. Returning to intuitive design interactions such as the intuitive use of the light pen in Sutherland's Sketchpad [25] can facilitate innovative virtual design instead of sticking to a design vocabulary shaped by the current limitations of legacy CAD technologies, and allow the evolution of authentic new approaches and techniques of designing in immersive virtual reality.

In this study, we propose Dreamscape Bricks VR as an experimental immersive virtual design environment that enables users to experience their architectural creations using virtual LEGO pieces by building and interacting with them in VR.

The tool was developed using Unreal Engine 4 (UE4), and it is intended for PC tethered VR systems and tested on the Oculus Rift / Rift S / Quest 2 (via Oculus Link) and HTC Vive VR headsets. We describe the features and the implementation of Dreamscape Bricks VR below.

3.1 LEGO Components

The LEGO system is a well-known and popular building toy designed to be modular, using bricks of different sizes and types that can connect to one another. This allows the creation of complex structures through the use of the different types of LEGO pieces as modules. There is a great potential for using LEGO bricks in architecture and design education. The inherent variability and modularity of LEGO bricks is a significant quality that can be leveraged to support creativity and experimentation in design.

The use of LEGO in the design, robotics, and education fields has been extensively studied and explored by researchers and academics [26–31], providing evidence that LEGO can be used to support creativity and experimentation in design [28, 32]. The LEGO system is also consistent and straightforward, with a rule system that is easy to understand and follow. Furthermore, LEGO bricks provide a wide range of functions and aesthetic expressions. These features of the LEGO system provide designers with a great opportunity to design and simulate their ideas for real-world problems.

The high analogy between physical and digital LEGO pieces allows a direct manipulation interface in LEGO-based CAD software. Therefore, we used LEGO bricks as base design elements in our experimental VR design tool.

LEGO pieces are the primary building block of the LEGO system. The basic LEGO bricks are compatible with each other in terms of design size. Although a LEGO piece is often called a brick, brick refers to only one type of piece that has the height of three plates. Despite the excessive varieties of pieces, we can classify the essential LEGO pieces we use in this study under five main categories: bricks, plates, slopes, tiles (flats), and panels (Fig. 2).

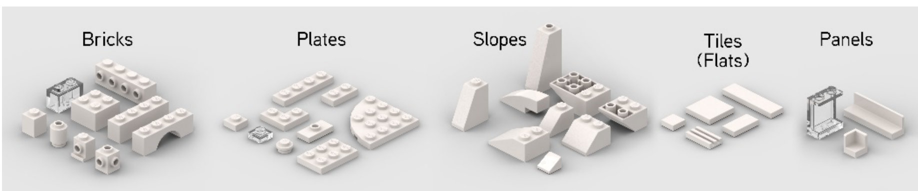

Fig. 2. LEGO pieces classified by type.

The LEGO system is a versatile tool for working in various scales and levels of complexity. It can be used to study and design at a building component scale or at a city layout scale. Therefore, it is important to define the human scale, which will allow us to correlate the dimensions of the LEGO system to the dimensions of the human body. We accept the human scale in the LEGO system to be relative to the size of a Minifigure. When we consider the height of a Minifigure (4 cm) to be equal to the average human height (170 cm), we can define a LEGO/human ratio of 1:42.5. Figure 3 shows the dimensions of a LEGO brick, a LEGO Minifigure 42.5 times upscaled and compared with a human figure, and relative sizes of a LEGO brick on 42.5:1 scale.

Although the elements of a LEGO brick are officially known as studs and tubes [33], the patent file of LEGO bricks defines the studs as "primary projections" and tubes as "secondary projections" [34]. Also, there is no global consensus on the name of the other elements of a LEGO brick. For terminological consistency, the component names used in this study are defined in Figure 4.

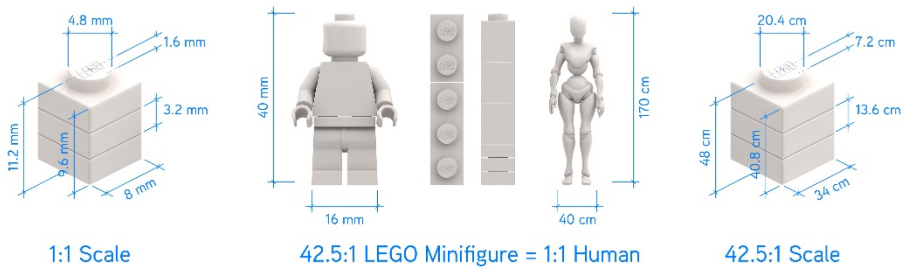

Fig. 3. Dimensions of a LEGO brick, a LEGO Minifigure, and a human figure compared in size and scaled to each other.

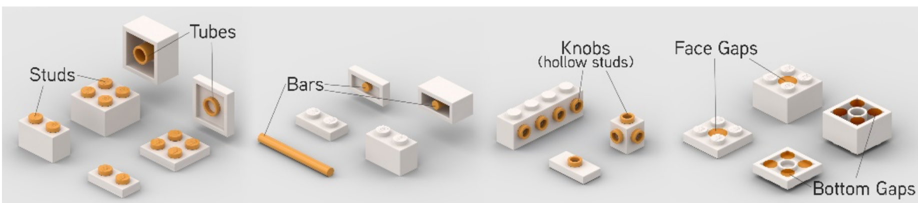

Fig. 4. Elements of a LEGO piece illustrated.

In our experimental design tool, Dreamscape Bricks VR, users will be able to build with virtual LEGO bricks based on the real-life connection possibilities of these elements. The initial idea was to make the virtual LEGO pieces snap to plate height (3.2 mm) increments in the vertical axis and half a brick wide (4 mm) increments in horizontal axes, allowing users to place them in a 3D grid. However, feedback from the previous study, where first-year design students evaluated the use of LEGO-based CAD for designing life pods, revealed that the participants demanded realistic connections that would prevent physically impossible connections, as well as structural stability check [29]. This feedback led us to implement more realistic physical connections between virtual bricks.

The virtual LEGO pieces were designed to follow the same building rules as physical LEGO pieces, using a polarity-based connection algorithm. Table 3 shows the connection socket polarity between elements of a LEGO piece. For instance, when a stud fits into a tube, the stud is the plug (stud+), and the tube is the socket (stud-) end. When a tube fits on a face gap, the tube is the plug (tube+), and the face gap is the socket (tube-) end.

We used Unreal Engine 4's Blueprint Visual Scripting system to create the polarity-based brick connection system. The plug and socket polarity was defined in the attachment Blueprints of Dreamscape Bricks VR. We then created and positioned the corresponding sockets for each element in all brick types. Figure 5 shows a 2x2 brick with its studs (four stud+ sockets), bottom gaps (four stud-), tube (one stud-, one tube+), and face gap (one tube-) defined in Unreal Engine 4's Socket Manager as an example.

Table 3. The matrix of connection socket polarity between elements of LEGO bricks.

	Bottom Gap (stud-)	Tube (tube+ / stud-)	Face Gap (tube-)	Bar (bar+)
Stud (stud+)	(stud+, stud-)	(stud+, stud-)	-	-
Tube (tube+ / stud-)	-	-	(tube+, tube-)	-
Knob (stud+ / bar-)	(stud+, stud-)	(stud+, stud-)	-	(bar-, bar+)

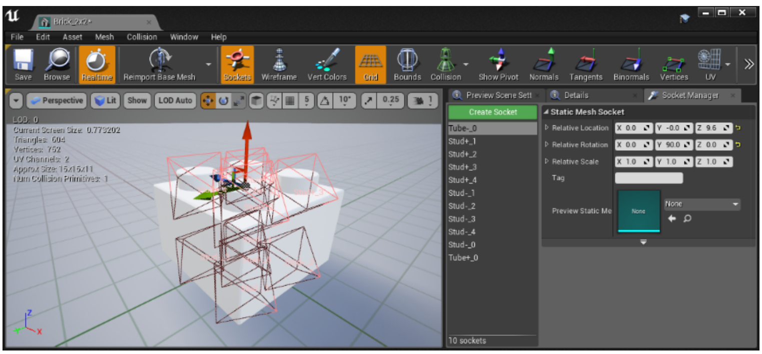

Fig. 5. Connection sockets of a 2x2 brick created and positioned in UE4's Socket Manager.

This socket polarity-based system allowed the application to simulate the same connection rules as physical LEGO pieces.

3.2 Object Interactions

VR interaction fidelity is a measure of the objective degree of realism of user interactions with virtual objects [35, 36]. Higher interaction fidelity, within the limitations of the hardware, helps users adapt intuitively to the immersive virtual environment with little learning required for interactions [2]. Prior research shows that higher interaction fidelity also improves user experience in virtual object manipulation tasks [37].

The interaction approach of the "Dreamscape Bricks VR" tool is based on the concept of direct manipulation. Therefore, we designed object interactions to enable users to manipulate the virtual objects in 3D space using intuitive hand gestures and touch-based interactions that emulate the physical LEGO bricks building process.

McMahan's updated Framework for Interaction Fidelity Analysis (FIFA) [35] defines three primary factors for interaction fidelity: (1) *biomechanical symmetry*– the similarity degree of body movements required to perform a task in the virtual environment to the body movements for that action in the real world, (2) *input veracity*– the similarity degree in which the input devices measure and capture the user actions, and (3) *control symmetry*– the similarity degree of control that user has over a task's interactions in the virtual environment to the control over the task in real-world [35].

We reviewed the object interaction options and their performance according to McMahan's framework, also considering the available hardware technology. Table 4 shows three input devices compared. As previous studies suggested [38], the VR system controllers (Oculus Touch or HTC Vive Controllers) provide a convincingly higher interaction fidelity with optimal biomechanical symmetry (hand movements, index finger, and middle finger actions), optimal input veracity (accurate and reliable tracking in wide range with low latency), and optimal control symmetry (6DoF *-six degrees of freedom-* hand tracking, index, and middle finger triggers, thumbsticks and thumb buttons) between these options.

Table 4. Reviewing the interaction fidelity of input devices available for object interactions.

Input devices	Hand tracking	Finger inputs	Tracking Accuracy	Object manipulation	Haptic feedback
Gamepad (Xbox Wireless Controller)	None	Index finger triggers	n/a	Thumbsticks (2D-axis)	Yes
VR controllers (Oculus Touch or HTC Vive controllers)	6DoF	Index and middle finger triggers	High	Hand movements	Yes
Hand tracking (Leap Motion Controller)	6DoF	All fingers tracked	Medium	Hand gestures	No

Therefore, we decided to design Dreamscape Bricks VR's control scheme based on the VR controllers. Figure 6 shows inputs available on Oculus Touch left controller, mapped with a left hand's primary fingers for object interactions. Right hand and left hand inputs and interactions are exactly mirrored, which provides a more intuitive user experience. We used the OpenVR controller input table [39] to map these inputs for other OpenVR-supported controllers, such as HTC Vive controllers.

We also identified the real-life object interactions that would also apply to physical LEGO building as (1) touching an object, (2) grabbing and holding an object, (3) moving or rotating the held object, (4) dropping an object, and two more brick building-specific interactions, (5) connecting bricks, and (6) separating connected bricks. To provide a high biomechanical symmetry for these interactions in VR, biomechanical mechanisms of human hand and tool use must be investigated. Napier defined two primary grip styles as precision grip and power grip [40]. This scheme is further elaborated with subdivisions in other studies [41–43].

In precision grip actions, the thumb is used to support, while one or more of other fingers apply pressure on the object [41–43], which is often used when handling LEGO bricks (grab, hold, move, and rotate actions). According to our observations, when connecting and separating LEGO pieces, objects are often supported by the thumb and held steady with the middle finger (and maybe other fingers), while force is applied with index fingers. Therefore, we implemented a control scheme that enables users to perform the same finger gestures on the Oculus Touch controller in Dreamscape Bricks VR. The middle fingers are used to grab and hold objects, and the index fingers are used to apply force on the virtual LEGO objects, which enables the objects being held to attach or detach. Meanwhile, the thumbs are held or rest on the top buttons, which are used for non-realistic interactions such as teleport locomotion, or changing user scale (see Fig. 6).

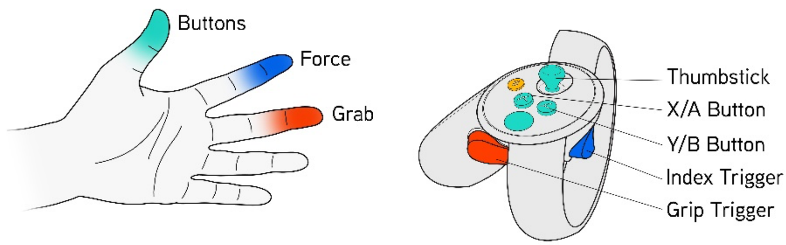

Fig. 6. Controller input mapping and primary fingers for virtual object interactions in Dreamscape Bricks VR.

Table 5. Object interactions mapped with inputs and feedbacks in Dreamscape Bricks VR.

Interaction	Instructions	Inputs	Feedback
Touch	Move your hand very close to an object	(movement)	Visual highlight, haptic
Grab and hold	Touch the object, hold the **Grip** to grab, and hold it	Grip Trigger (middle finger)	Haptic
Move and rotate	Move and rotate your hand while holding the object	(movement)	-
Drop	Release the **Grip**	Grip Trigger (middle finger)	Haptic
Connect bricks	Hold the brick, bring it closer to the brick you want to connect it with, apply force (squeeze the **Trigger**), release the **Grip**	Grip Trigger (middle finger) Index Trigger (index finger)	Haptic, audio (click)
Separate bricks	Apply force (squeeze the **Trigger**), hold the **Grip**, the held brick will detach, stop applying force (release the **Trigger)**	Index Trigger (index finger) Grip Trigger (middle finger)	Haptic, audio

Table 5 shows the main object interactions, user actions, inputs, and feedbacks in Dreamscape Bricks VR.

Figure 7.a shows connecting a group of LEGO pieces onto the main body of the building. When force is applied, a blue ghost version of the pieces held appears in the possible connection points, based on the socket polarity rules defined earlier. Fig. 7.b shows the top plate being separated from the rest of the building.

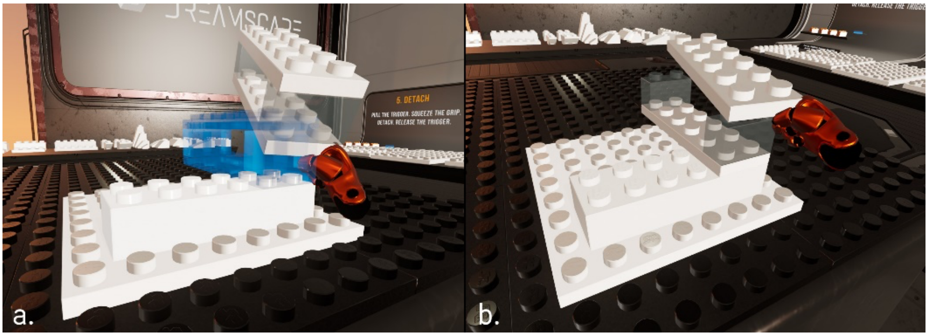

Fig. 7. Object interaction in Dreamscape Bricks VR: connecting and separating pieces.

All types of virtual LEGO pieces that are available in the inventory are placed on the shelves around the virtual building platform of Dreamscape Bricks VR. Each type of LEGO piece is placed on an invisible bricks dispenser which spawns another instance of the same piece once the user grabs one from the shelves. This system allows rapid and intuitive visual and spatial access to all virtual LEGO pieces.

3.3 Locomotion in VR

The sense of navigation is one of the key requirements to achieve a higher presence and immersion within the virtual world [44, 45]. Although it gained wide research interest through the years [44–48], the design of human locomotion remains a challenge for VR. Recent works have focused on newly released VR headsets and their capabilities [49–52]. Various locomotion techniques have been developed to address this challenge, yet there is currently no locomotion technique that is suitable for all applications.

Boletsis's systematic review lists 11 VR locomotion techniques under four main categories: (1) *motion based*– the user's limited real-world motion enables locomotion in VR environment, such as swinging arms to move forward, (2) *room-scale-based*– the user's natural physical movement is tracked and applied in VR space, (3) *controller based*– user navigates in VR space using controller inputs, and *(4) teleportation based*– user is teleported[1] within the VR space [49]. Controller-based locomotion techniques reportedly cause more motion sickness and nausea [49, 52] while requiring the thumbsticks to be allocated for navigation. Motion-based navigation techniques require

[1] Teleportation is moving to a new location in 3D space instantaneously without physical locomotion. It can be triggered by a controller input, or an interaction in the virtual space.

more physical effort [51, 52] and have less biomechanical symmetry in navigation actions. Therefore, we used real-walking (room-scale-based) and point-and-teleport (teleportation-based) as the core locomotion techniques.

In Dreamscape Bricks VR, users can navigate through the virtual space by walking in and looking around in the real world (real-walking). However, their reach would be limited to the available free space of the real world, which has 3 meters by 3 meters floor area. To overcome this, users can use point-and-teleport to move anywhere in the virtual space at any time. The user pushes the thumbstick button to start casting the teleport marker, points it to the desired location, rotates the teleport marker with thumbsticks to the direction to be faced, and releases the thumbstick button to teleport to the defined location.

Teleportation is not a natural locomotion and often causes a sense of disorientation when not implemented properly. To minimize disorientation after teleporting, a marker shows the previous position and direction of the user. We also implemented a feature that we call "blink" to maintain visual comfort, where the vision fades to black as the teleport is initiated, and the new vision fades in at the new location after half a second.

Dreamscape Bricks VR's total operational area corresponds to 6 meters by 6 meters on the default scale, twice the length of one side of the floor area. Thus, the user can ideally reach across the corners of the VR area by walking in room-scale and teleporting once. Users can perform all building actions using real-walking around the virtual construction platform without teleporting. They can either change scale or use point-and-teleport if they need to reach farther.

3.4 Rewind

In many computer programs, including the legacy CAD approach, correcting user errors relies on the "Undo" interaction [53, 54]. In addition to undoing mistakes, keeping a history of actions can also support designers to progressively refine their designs by going back to a previous state and trying a different approach [55–57]. Since there is no undo interaction for error recovery in the real world, as we were thinking about ways to roll moves back in reality without using current computer interaction terminology, the concept of time travel and temporal rewind emerged. Rewinding time is being used as a gameplay mechanic and a narrative device in an increasing number of video games [58], such as *Prince of Persia: The Sands of Time (2004)* where the player can rewind time to avoid death and fix mistakes, *Braid (2008)* where the player needs to rewind time to solve puzzles by reversing the effects of their previous actions, and *Life is Strange (2015)* where the player makes choices that have a significant impact on the story, which can be quickly undone to experiment with different options. Rewinding time is consistent with how humans often think about mistakes; we often think, "if only I had done X instead of Y," after we realize that Y was a mistake or that Z could be a better alternative. When used for a design application in the virtual environment, rewinding time can be a way to give the user control over their actions and allow them to explore different design options without having to start from scratch.

Rewinding allows the users to undo their actions in Dreamscape Bricks VR. When the user presses and holds the X and A buttons on both controllers, simultaneously to avoid accidental inputs, time is rewound backward frame by frame, giving the user an ethereal experience of having control over the direction of time. Rewinding time undoes the last actions in a reversed temporal continuum, with the speed of their occurrences, as opposed to "Undo" functions where the last step is undone instantly.

3.5 Scaling the User

The user's ability to scale is a key design feature of Dreamscape Bricks VR. The users can scale themselves in the virtual environment relative to the LEGO bricks, to a comfortable smaller size to place bricks with higher precision, or the size of a LEGO Minifigure to experience the entire structure at any stage of the design process. There are three pre-defined scales the users can switch between: (1) *Lifesize bricks scale (1:1)*, (2) *Precision building scale (1:10)*, and (3) *Figure-sized user scale (1:42.5)*. Figure 8 shows the boundaries of the 3 meters by 3 meters physical VR play space and Dreamscape Bricks VR's design area at different scales.

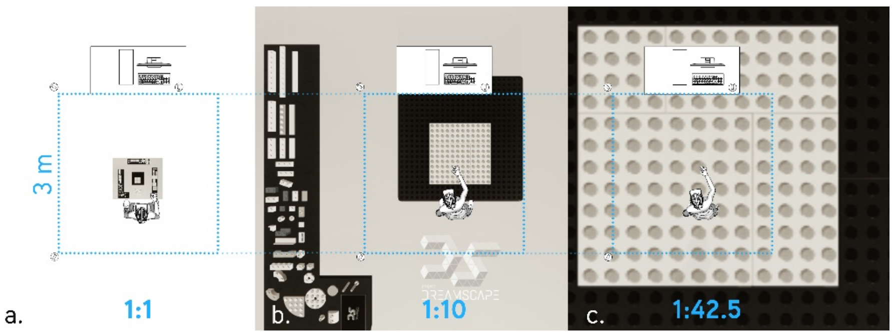

Fig. 8. Dreamscape Bricks VR's building platform compared with physical play area at different user scales.

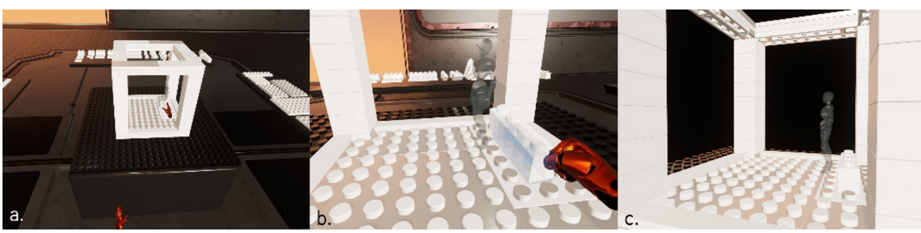

Fig. 9. User's point of view at *(a)* life-size bricks scale (1:1), *(b)* precision building scale (1:10), and *(c)* figure-sized user scale (1:42.5).

Life-size bricks scale (1:1) makes the virtual LEGO bricks the same size in real life, and it is helpful for seeing all the pieces at once (Fig. 8.a, Fig. 9.a).

Precision building scale (1:10) makes the virtual LEGO blocks ten times bigger than in real life, which is useful for building with precision (Fig. 8.b, Fig. 9.b). After the development playtests and trying other scale values, 1:10 is set as the default scale.

Figure-sized user scale (1:42.5) shrinks the user by 42.5 times, making a 170 cm tall user the same size as a 4 cm LEGO Minifigure, and the virtual LEGO blocks are 42.5

times bigger than in real life (Fig. 8.c, Fig. 9.c). This scale puts designers on the same scale as the Minifigure users of the spaces they create in a hypothetical scenario where Minifigures are human-sized, and LEGO pieces are building materials proportionally.

The user's ability to scale has a significant impact on the locomotion as well. At the life-size scale, the user can easily see and reach the whole design area without teleporting or walk around the virtual construction platform by moving within the physical play area.

3.6 Save/Load System

Save/Load system stores the positions, configurations, and structural hierarchy of the pieces that are placed on the virtual black desk. It is useful for reloading previous models between sessions. It can also be used as a design history tool that enables designers to iterate between different stages of their designs.

3.7 Tutorial

Dreamscape Bricks VR also features a tutorial for onboarding new users with step-by-step instructions. Tutorials are represented as seven exhibition units located around the building platform, each exhibition unit instructing a key feature of Dreamscape Bricks VR: (1) teleport, (2) grab, (3) rewind time, (4) attach (connect bricks), (5) detach (separate bricks), (6) colorize elements, and (7) change user scale.

3.8 Audio

The audio design in the virtual environment is the most important element to create a realistic VR experience [2]. Auditory cues such as sound effects, are essential as it can provide feedback about the actions, as well as about the status of the system.

The sound effects in Dreamscape Bricks VR are designed based on the real physical LEGO pieces, with additional sound effects for non-realistic virtual interactions such as teleporting or changing scale. An array of real physical LEGO foley effects are used to emulate the sounds of virtual LEGO pieces. The sound cues of the pieces are designed to be realistic, and simulated according to the weight, friction, and size of the piece, and environmental parameters. Audio cues of physics collisions are also randomly modulated within a small pitch and volume range to produce more realistic sounds from the recorded foley sounds.

3.9 Haptics

Haptic feedback plays an essential role in creating realistic and immersive VR experiences [59, 60]. Early studies indicate that one of the most problematic aspects of object manipulation with VR technology is the absence of haptic feedback [61]. Although complex and natural haptic feedback as in the real world is not possible with current consumer VR technologies, it is possible to provide haptic effects with VR controllers [62] as shown in Table 4.

Dreamscape Bricks VR has different haptic feedback effects that fit different interactions, such as touching an object, grabbing an object, connecting and separating bricks, teleport initiation, teleport marker casting, and teleporting to the point (Table 5). The effects are designed to actual haptics or intensity of each interaction in Unreal Engine 4's Haptic Feedback Effect editor, in which the frequency, amplitude, and duration of the effect can be edited on a curve graph.

Other Features. Dreamscape Bricks VR also features a *photo mode* (Fig. 9.c) for documenting the current design as a screenshot image, *design statistics* that show how many pieces are used and how many of them are currently on the design platform, backend *event logging* for recording the key events in sessions.

4 User Experience Evaluation

After finishing the initial development of Dreamscape Bricks VR, we conducted a test study to evaluate the user experience of the experimental tool. The users of the tool were asked to create a specific design with given instructions using the "Dreamscape Bricks VR" tool (Figure 10). After completing the modeling task, we conducted four questionnaires to evaluate the usability, presence, and comfort performance of the experimental tool. The test users were asked to describe their experience, report problems they encountered, and leave comments. The results of the evaluation are presented in this section.

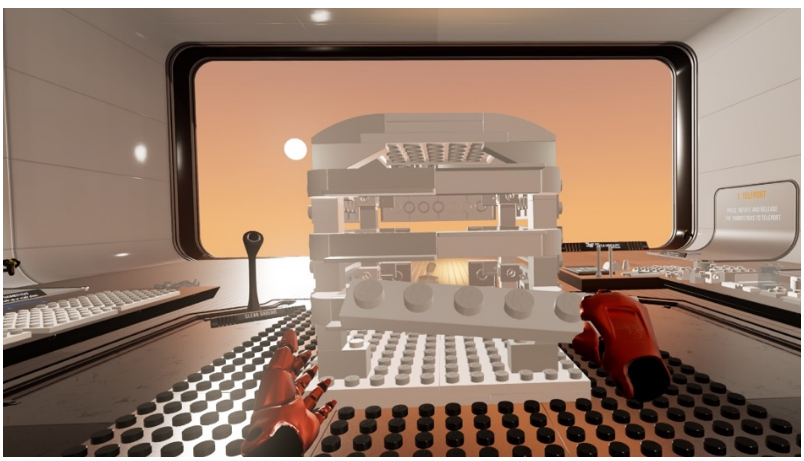

Fig. 10. A screenshot of Dreamscape Bricks VR from a user test session.

Minor iterations, improvements, and optimizations to the design tool were made based on the results of these user studies as necessary in order to make the process of design with Dreamscape Bricks VR more intuitive and natural.

4.1 Participants

The user experience tests were conducted with 12 participants (6 females and 6 males). The participants consist of 9 architects, 2 interior architects, and 1 urban designer. The participants were sorted based on their professional expertise level, their familiarity with virtual reality, and their VR application development status.

Two participants were initiates (17%), six participants were proficient (50%), and four participants were experts (33%) in their respective design professions. Five participants (42%) have some VR application development experience (developers), and seven participants (58%) have no development experience (non-devs). Seven participants (58%) stated to have used design tools in VR before, whereas five participants (42%) have no previous design experience with a VR tool.

4.2 Apparatus

The user tests were conducted using with Oculus Rift CV1 VR headset, a pair of Oculus Touch controllers, and three sensors for a room-scale VR setup (Fig. 8). The VR system was tethered to a PC with an NVIDIA GeForce GTX 1080Ti graphics card, Intel Core i7 8700K processor, and 16 GB memory. Initial performance tests of the Dreamscape Bricks VR application showed it to run with stable framerates of 80-90 FPS on the same setup.

4.3 Testing Procedure and Questionnaires

After having completed the basic features tutorial, the participants were given one of four LEGO building instructions to build in Dreamscape Bricks VR. The participants were instructed to take their time and try out all features while building with the given instructions. There was no time limit for the task so that the users could freely experiment with the tool and experience the design tool with minimum pressure.

User experience evaluation was done at the end of the test to assess the experimental Dreamscape Bricks VR tool following the completion of the task. The participants were asked to complete four questionnaires: Nielsen's usability heuristics and Sutcliffe and Gault's heuristic evaluation for usability testing, the Spatial Presence Experience Scale (SPES) for evaluating presence, and the Simulator Sickness Questionnaire for evaluating comfort.

Usability testing. Usability testing is a set of methods that have evaluators examine or inspect usability-related aspects of a user interface [63, 64]. Nielsen and Molich define heuristic evaluation for investigating the usability of user interface design [63, 64], which would allow diagnosing and attending problems with an iterative design approach [65]. Nielsen slightly modifies the original work, defining ten usability heuristics [64, 66]. We used Nielsen's usability heuristics with a five-point Likert scale as the first step of our usability questionnaire. The results can be seen in Table 6.

Sutcliffe and Gault propose another heuristic evaluation for virtual reality applications, which consists of twelve heuristics considering virtual environment-specific principles [67]. We used Sutcliffe and Gault's heuristic evaluation with a five-point Likert scale as the second step of our usability questionnaire (Table 7).

Presence testing. There are several questionnaires measuring spatial presence in virtual environments. However, the *Spatial Presence Experience Scale (SPES)* of Hartmann et al. is stated to measure presence more reliably since it was published in 2015 and is more suitable for the recent VR technologies compared to earlier questionnaires such as *Presence Questionnaire (PQ)* [68]. The SPES consists of twenty items, ten items under the self-location (SL) subdomain, and another ten items under the possible actions (PA) subdomain [69]. We used the SPES as a questionnaire with a five-point Likert scale to measure the user presence in Dreamscape Bricks VR (Table 8).

Comfort testing. The *Simulator Sickness Questionnaire (SSQ)* was originally published in 1993 [70] and still is one of the most popular simulator sickness assessments to date [71]. The questionnaire consists of sixteen questions about simulator sickness-like symptoms to be scored on a four-point scale ranging from 0 (none) to 3 (severe) [70]. We used the SSQ to measure the general comfort level of users after completing the given tasks in Dreamscape Bricks VR (Table 9).

4.4 Questionnaire Results and Findings

The usability test results show that the basic features of the Dreamscape Bricks VR can be used intuitively by the majority of users. The participants reported that they could easily use the features and controls in the application. The ease of use of the application is stated to be "Good" and "Very Good" by the majority of users.

Table 6 shows that the tool met the heuristics proposed by Nielsen between "Good" and "Very Good" scores, with an average of 4.55 out of 5. "Error prevention" has the lowest score of 4.08, which is still "Good." It is important to note that some users find the tool cannot always prevent errors, and there is room for slight improvement.

Table 6. Nielsen's Interaction Principles evaluation of Dreamscape Bricks VR.

#	Questions	Mean Response Value	Standard Deviation	Response Variables
1	Visibility of system status	4.58	0.67	5: Very Good 4: Good 3: Acceptable 2: Poor 1: Very Poor
2	Match between system and the real world	4.58	0.52	
3	User control and freedom	4.42	0.67	
4	Consistency and standards	4.92	0.29	
5	Error prevention	4.08	0.79	
6	Recognition rather than recall	4.50	0.52	
7	Flexibility and efficiency of use	4.50	0.67	
8	Aesthetic and minimalist design	4.75	0.62	
9	Help users recognize, diagnose, and recover from errors	4.42	0.79	
10	Help and documentation	4.75	0.45	

Table 7 shows the tool also met the VR-specific heuristics proposed by Sutcliffe and Gault, with an average score of 4.70 out of 5. The participants skipped the "clear turn-taking" item since their VR session had a single-person task. "Faithful viewpoints" was rated 5.00, indicating that the perspectives provided by the tool are very realistic. The score of 4.75 on "navigation and orientation support" validates our locomotion design decisions and implementations.

Table 7. Sutcliffe and Gault's Heuristic Method evaluation of Dreamscape Bricks VR.

#	Questions	Mean Response Value	Standard Deviation	Response Variables
1	Natural engagement	4.50	0.67	
2	Compatibility with the user's task and domain	4.58	0.67	
3	Natural expression of action	4.67	0.49	
4	Close coordination of action and representation	4.83	0.39	5: Very Good
5	Realistic feedback	4.83	0.39	4: Good
6	Faithful viewpoints	5.00	0.00	3: Acceptable
7	Navigation and orientation support	4.75	0.45	2: Poor 1: Very Poor
8	Clear entry and exit points	4.25	0.75	
9	Consistent departures	4.83	0.39	
10	Support for learning	4.83	0.39	
11	Clear turn-taking	n/a	n/a	
12	Sense of presence	4.67	0.65	

The presence test results in Table 8 show that Dreamscape Bricks VR provides a strong sense of presence in the virtual environment. The average presence score is 4.65 out of 5. The score of SL-10 is 5.00 out of 5, which shows that all participants felt immersed in the virtual environment. "PA-8 / It seemed to me that I could do whatever I wanted in the virtual environment" got the lowest score of 3.58. This result was anticipated because the environment of the tool was designed in a way that is not distractive for the users as they focus on their design on the building platform. Conversely, "PA-1 / The objects in the virtual environment gave me the feeling that I could do things with them" got a score of 4.92, which shows that the virtual objects that were intended to be interactable, i.e., bricks, provided very realistic interactions.

The results of SSQ show that the participants experienced minimal discomfort while using the tool, with an average score of 0.28 out of 3. The tool achieved a score of 0 on 5 out of 16 items of the questionnaire. "General discomfort" and "fatigue" have a score of 0.58, which means the participants experienced mild discomfort, probably because of the use of the Oculus Rift VR headset that weights approximately 470 grams. "Eyestrain" is the most reported discomfort by the participants, with a score of 1.08 out of 3, which is still marginally above "slight" discomfort. "Fullness of head" is a discomfort due to the filling of the sinuses, which is mostly seen in physical simulators manipulating the acceleration of gravity. It was unexpected to see participants report that with a score of 0.67. However, they may have reported a discomfort caused by the weight and physical restriction of the VR headset as the fullness of head.

Table 8. Spatial Presence Experience Scale evaluation of Dreamscape Bricks VR.

#	Questions	Mean Respons e Value	Standard Deviation	Response Variables
SL-1	I felt like I was actually there in the virtual environment	4.83	0.39	
SL-2	It seemed as though I actually took part in the action	4.83	0.39	
SL-3	It was as though my true location had shifted into the virtual environment	4.33	0.65	
SL-4	I felt as though I was physically present in the virtual environment	4.25	1.06	
SL-5	I experienced the virtual environment as though I had stepped into a different place	4.25	0.87	
SL-6	I was convinced that things were actually happening around me	4.67	0.65	
SL-7	I had the feeling that I was in the middle of the action rather than merely observing	4.83	0.39	
SL-8	I felt like the objects in the virtual environment surrounded me	4.75	0.62	
SL-9	I experienced both the confined and open spaces in the virtual environment as though I was really there	4.33	0.65	5: Strongly agree 4: Agree 3: Neutral 2: Disagree 1: Strongly Disagree
SL-10	I was convinced that the objects in the virtual environment were located on the various sides of my body	5.00	0.00	
PA-1	The objects in the virtual environment gave me the feeling that I could do things with them	4.92	0.29	
PA-2	I had the impression that I could be active in the virtual environment	4.67	0.89	
PA-3	I had the impression that I could act in the virtual environment	4.67	0.49	
PA-4	I had the impression that I could reach for the objects in the virtual environment	4.75	0.45	
PA-5	I felt like I could move around among the objects in the virtual environment	4.83	0.39	
PA-6	I felt like I could jump into the action	4.58	0.90	
PA-7	The objects in the virtual environment gave me the feeling that I could actually touch them	4.50	0.91	
PA-8	It seemed to me that I could do whatever I wanted in the virtual environment	3.58	1.17	
PA-9	It seemed to me that I could have some effect on things in the virtual environment, as I do in real life	4.33	0.89	
PA-10	I felt that I could move freely in the virtual environment	4.33	0.65	

Table 9. Simulator Sickness Questionnaire evaluation of Dreamscape Bricks VR.

#	Questions	Mean Response Value	Standard Deviation	Response Variables
1	General discomfort	0.58	0.52	
2	Fatigue	0.58	0.67	
3	Headache	0.17	0.39	
4	Eyestrain	1.08	0.79	
5	Difficulty focusing	0.25	0.45	
6	Increased salivation	0.00	0.00	
7	Sweating	0.42	0.67	0: None
8	Nausea	0.00	0.00	1: Slight
9	Difficulty concentrating	0.25	0.62	2: Moderate
10	Fullness of head	0.67	0.78	3: Severe
11	Blurred vision	0.25	0.45	
12	Dizziness (eyes open)	0.17	0.39	
13	Dizziness (eyes closed)	0.17	0.39	
14	Vertigo	0.00	0.00	
15	Stomach awareness	0.00	0.00	
16	Burping	0.00	0.00	

The fact that no motion sickness symptoms were reported (such as increased salivation, nausea, vertigo stomach awareness, and burping) can be attributed to the tool's high running performance with low latency and high frame rate, as well as successful design and implementation of VR locomotion and virtual interactions.

The questionnaire results show that the Dreamscape Bricks VR tool has high usability, good user presence, and low discomfort level for the users. This indicates that the user experience of the tool is positive. The tool can be used to evaluate LEGO brick-based architectural design activities in VR without major reservations about the user experience and competence of the tool.

5 Conclusion

In this study, we introduced the DREAMSCAPE framework for architectural design tools in VR, which adopts an intuitive direct manipulation approach. The proposed framework focuses on three main design activities: embodying conceptualized ideas, experiencing the initial design results spatially at any stage, and manipulating the design output to conceive new ideas. The framework enables the designer to translate ideas into virtually embodied products without being limited by the preconceptions of legacy 3D design and CAD tools. The freedom to spatially experience and manipulate the design at any stage is also a crucial feature that can improve the designer's perception of the design, collection and compilation of ideas and concepts while generating new ideas and concepts.

The DREAMSCAPE framework was demonstrated through the development of a VR design tool called Dreamscape Bricks VR, which simulates the elements and connection rules of physical LEGO bricks in VR. The tool was intended for architects and architecture students with varying levels of professional experience; therefore, it has been designed with intuitive interactions that are accessible for novice users who have no prior CAD or VR experience. The development of this experimental tool as the first implementation of the framework also helped us establish, test, and further elaborate the framework as it was evaluated with user tests.

The results of user tests showed that the Dreamscape Bricks VR tool offers high usability, good user presence, and low discomfort level where the users stated to have a positive and exciting experience in general. The slight discomfort levels caused by the use of the current relatively bulky VR headset technology suggest that there is room for ergonomic and sensory improvements for future VR hardware. Based on user tests, we also received a lot of valuable feedback regarding user experience and suggestions for improvement. The suggestions and comments we received from the users were used to improve the VR design tool, usability, and user experience in VR in general.

The DREAMSCAPE framework aims to investigate the potential of virtual reality as a design environment for architecture. As we continue to improve the framework, we intend to use the Dreamscape Bricks VR tool in design protocols that compare the process of architectural design in the physical environment and in VR for close to real-world design tasks and scenarios, such as designing an interior or a public space that is responsive to a list of design requirements.

The framework is intended to support collaborative design in the metaverse, in which designers can work together in real-time on a shared design in a virtual space. The collaborative design tests were out of the scope of this paper. Yet, the DREAMSCAPE framework's tools are expected to facilitate design collaboration in future work, where users can design and discuss together in real-time and co-locate in the same virtual design space, the ultimate dreamscape, regardless of their geographic location.

Dreamscape Bricks VR uses LEGO bricks as the base component. The following implementations of the framework can focus on more complex modular components, such as basic construction elements, generic parametric objects, furniture modules, etc., allowing the user to create varied designs by changing the component parameters. Therefore, the DREAMSCAPE framework is expected to contribute to a new understanding of design tools for future CAD and BIM applications through a more intuitive, embodied, and responsive design process in the virtual environment instead of directly copying the discussed legacy CAD approaches to VR.

Virtual reality is a technology with the potential to radically transform the way we design, build and experience architecture. Soon, with the increased use of the metaverse environments, and the introduction of more lightweight VR headsets, it is reasonable to expect an increase in the number of professionals adopting the technology along with a natural integration of VR into the architectural design process. The authors of this work remain confident that similar to the essential use of flight simulators in aviation training, VR also has the potential to become an integral part of architectural education.

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gave voluntary written informed consent for study participation as well as for scientific use of process outputs and research data collected.

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