ITU A|Z • Vol 19 No 3 • November 2022 • 631-649

An investigation of architectural design process in physical medium and VR

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Received: December 2021 • Final Acceptance: June 2022

Abstract
Virtual Reality (VR) is a powerful medium to design and experience architecture which researchers and practitioners are currently exploring with increasing interest. This paper investigates the impact of the use of VR in architectural design. We developed an interactive VR design tool by using the Unreal Engine 4 game engine, Dreamscape Bricks VR, in which the participants can design and build architectural models using virtual LEGO pieces via direct manipulation. We conducted design experiments comparing the physical medium and VR design processes with 14 subjects, including architects, graduate, and undergraduate design students. Each participant was asked to design a shelter and a pavilion, one with physical LEGO bricks (in situ) and another in Dreamscape Bricks VR (in virtuo). The design processes in both the physical medium and VR were analyzed by video recording of participants with retrospective think-aloud reporting and a post-experiment survey. The Function-Behavior-Structure (FBS) framework was used to analyze the participants' cognitive design process, while the Embody-Experience-Manipulate (EEM) framework was developed and used to analyze the recorded design activities. The results showed similarly rich cognitive design processes in both media. Embodying and experiencing activities were significantly higher in VR. The analysis results and participant comments indicated that the ability to change the user scale in VR provides novel opportunities for the design process that are not available in the physical medium. This study offers insight into the impact of using VR in architectural design processes and the potential and limitations of VR design tools.

Keywords
Virtual reality, Architectural design, Design cognition, FBS ontology, Dreamscape.

doi: 10.5505/itujfa.2022.77019

1. Introduction

Design is more than just a process of making; it is a process of thinking (Cross, 2011). Visual representation of ideas where designers can externalize and explore their initial design thoughts by perceptually interacting with them is a crucial part of the design process (Suwa & Tversky, 1997). External representations, such as sketches, diagrams, and physical models, play a pivotal role as cognitive tools for memory and information processing (Tversky, 2005). These representations also allow designers to externalize an idea, better explore its features and relationships, and further assist, inform, and inspire design (Schon & Wiggins, 1992). Immersive virtual reality (VR) is a technology that allows users to create, interact with, and explore immersive virtual worlds. As a powerful and effective tool for visualization and interaction, VR provides a new immersive design environment that eliminates physical restrictions. Thus, VR enables designers to create, experiment, and iterate their ideas as they transcend the physical world's limitations while being bodily present in the environment. How we design is deeply rooted in our physical bodies (Pallasmaa, 2017). Our bodies are the medium through which we interact with the world and express ourselves. Hence, we lose a fundamental link to our design process with digital tools that induce disassociation from our physical process. However, VR offers us a unique opportunity to explore new design possibilities by simulating bodily presence and directly manipulating the design space. Therefore, VR is a tool that facilitates novel ways of thinking by allowing experimentation with ideas that could not be tested using traditional methods.

Many studies address the use of virtual environments in architectural design and education (Milovanovic et al., 2017; Ummihusna & Zairul, 2022), and other disciplines of architecture, engineering, and construction industries (Wang et al., 2018). The systematic reviews of studies on VR in architectural design have revealed that the main concepts that stand out are representation, design, cognition, visualization, cooperation, and education (Milovanovic et al., 2017). While some studies focus on the impacts of the VR environment on spatial cognition (Rahimian et al., 2011; Zhao et al., 2020), other studies focus on the collaborative potentials of virtual space (Dorta et al., 2016; Gül et al., 2017). This study focuses on individual designers' design process and cognition while using VR in architectural design.

In the literature, a distinction is often made between immersive virtual reality (IVR) and virtual reality (VR) (Tuker & Tong, 2021). VR is an umbrella term for all simulated environments that can provide a perceptual experience to the user, which includes 3D virtual environments viewed on 2D displays. IVR, on the other hand, provides the user with a perceptual experience via natural sensorimotor feedback and is often associated with immersive stereoscopic 3D displays using devices such as VR (Radianti et al., 2020; Slater & Sanchez-Vives, 2016), headsets, motion trackers, and controllers. Due to the rapid growth of IVR technologies in recent years, the industry has begun to use the term VR for IVR. Therefore, in this work, we use the term VR to refer to immersive virtual reality.

This study was designed to investigate fundamental differences in the design process and architects' design experiences in the physical environment (in situ) and in VR (in virtuo) by comparing the design process of similar tasks in both media. Therefore, we used LEGO bricks as an environment-independent modular design component. The LEGO system is a widely recognized modular design component with well-established and standardized connection rules, which can be used in various contexts and scales to create designs of varying complexity. As previous studies have shown, LEGO bricks simulated in VR and IVR behave physically similarly and in accordance with the same connection rules as the real-world bricks (Authors, in press, 2021). The high degree of analogy between physical and digital LEGO bricks enables direct manipulation-based interaction in VR and helps us isolate the effect of the design medium alone, which differs from

Figure 1. *The system architecture and design features of Dreamscape Bricks VR.*

most of the existing VR design applications that are either command-based or use selection-and-placement tools. Moreover, the use of LEGO bricks in design activities has been well established and applied in numerous studies (Doma & Şener, 2021; Ranscombe et al., 2020; Tseng & Resnick, 2012), including CAD analogies (Aish, 1979; Gross, 1996) and published use in professional architectural practice and education (Barris, 1972; MVRDV, 2012; Turner, 2014). Participants have likely been familiar with LEGO bricks and the rules for building with them since childhood, even before they held a pencil, which could allow for an increased germane cognitive load due to the already existing brick building schemas in their long-term memory. In addition, LEGO bricks are large enough to be easily handled by hand and require less precise motor skills than drawing or building models. This could reduce the skills required to work with the base design components in VR.

We developed an experimental immersive virtual design tool in Unreal Engine 4, *Dreamscape Bricks VR*, enabling users to create architectural models and designs with direct manipulation using virtual LEGO pieces as building components. Direct manipulation refers to the user's ability to interact with the virtual objects directly, manipulating them as one would in using real objects (Shneiderman, 1982). Dreamscape Bricks VR is the first application of our DREAMSCAPE (a backronym of Digital Reality Environment As a Medium for Studio Collaboration in Architectural Production & Education) framework, which adopts direct manipulation as one of its key features. The framework of DREAMSCAPE proposes a design process based on EEM (embody/experience/manipulate) design activity flow, performed iteratively in a spatial and temporal succession: (1) embodiment of conceptual design ideas, (2) experiencing preliminary design outputs, (3) manipulation of design outputs to generate new ideas (Doma & Şener, 2022). The pieces, the building process, and object interactions in *Dreamscape Bricks VR* are realistic simulations akin to designing and building a LEGO model in real life. Users can pick up, rotate, connect, separate, and stack up virtual bricks to create a model. Figure 1 shows the system architecture and design features of *Dreamscape Bricks VR*.

The experience and process of designing in *Dreamscape Bricks VR* are similar to that with physical LEGO bricks. While LEGO pieces enable in situ design, the tailor-made *Dreamscape Bricks VR* tool facilitates in virtuo design. The medium being the primary distinction between experiments presents a unique opportunity to compare design processes performed in the VR environment with that in the physical environment. The tool aims to create a user experience of intuitive and interactive design where users design freely by attaching, detaching, moving, removing, or modifying the design components in the familiar ways of the physical world. Compared to the legacy CAD workflow based on point-and-click interactions, some differences stand out in commands and interactions. While the legacy CAD workflow forces the user to think within the possibilities of available CAD commands, our direct manipulation approach is more intuitive and natural.

Cognitive Load Theory (CLT) suggests that the amount of information processing required by a task can be divided into three categories: (1) intrinsic cognitive load, the amount of information processing required by the inherent nature of the task, (2) extraneous cognitive load, the amount of information processing required by the instructional design of the task, and (3) germane cognitive load, the amount of information processing required for learning or acquiring new knowledge and skills related to the task (Sweller et al., 1998, 2019). The DREAMSCAPE framework aims to minimize extraneous cognitive load to compare task performances under the same intrinsic cognitive load conditions in situ and in virtuo. To achieve this, we implemented an interface that leverages users' existing knowledge of working with LEGO pieces and direct manipulation to minimize extraneous cognitive load.

2. Methods

We designed two protocols to investigate the design process in situ and in virtuo. Fourteen participants selected by convenience sampling (see Section 2.2) were given a different design task in each session and asked to design small habitations with similar requirements, scale, functions, and complexity levels. We recorded the sessions, documented the models designed, conducted retrospective think-aloud interviews, and asked the participants to fill out a post-experiment questionnaire. Analysis of the in situ / in virtuo activities and design behavior of the participants was conducted using protocol analysis, a qualitative method that has earned popularity in design research over the past two decades and is widely used in design research (Chai & Xiao, 2012). Protocol analysis offers a powerful way to understand design cognition by systematically analyzing the design process and avoiding researcher interpretation subjectivity. The method focuses on designers' cognitive processes and offers insights into the design thinking based on user descriptions (Gero et al., 2011; Kan & Gero, 2017). We used the FBS framework to analyze the participants' cognitive design process, and the EEM framework to analyze the recorded design activities.

We adopted the FBS ontology with the syntactic approach to analyze the design protocols to better reveal the architects' in situ and in virtuo cognitive design process. The retrospective think-aloud reports were segmented into phrases expressing design thoughts or actions, and these segments were coded with the FBS coding scheme. This ontological framework categorizes design issues and processes (Kan & Gero, 2017). The FBS framework defines six design issues, and their relationships: Requirement (R) represents the functional requirements of the design problem (Kan & Gero, 2017). The designers' functional intentions are represented by Function (F), and Structure (S) defines the designed structural components and their representations (Kan & Gero, 2017). Expected Behavior (Be) is the behavior that designers expect in the design solution, and Structural Behavior (Bs) represents the behavior that is achieved as a result of the structure (Kan & Gero, 2017). Description (D) represents the design depictions and descriptions (Kan & Gero, 2017). The FBS framework also describes eight design processes (Formulation, Synthesis,

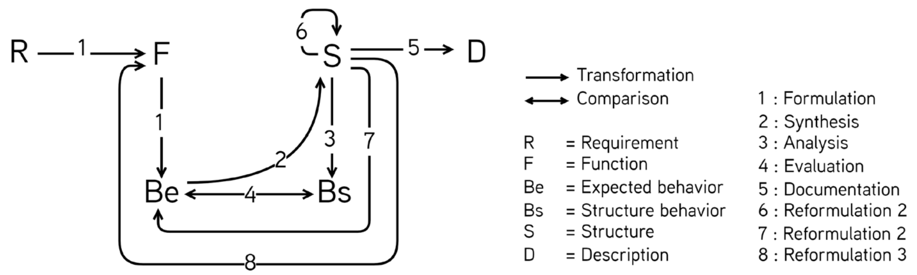


Figure 2. *FBS ontology explained, reproduced after Kan and Gero (2017).*

Analysis, Evaluation, Documentation, Reformulation I, Reformulation II, Reformulation III) resulting from the sequential relationships between design issues (Kan & Gero, 2017), suggesting that the design processes are cognitively linked to the syntactic and semantic transitions of the design actions taking place (Figure 2).

Dreamscape Bricks VR tool adopts the iterative design activity flow as Embody - Experience - Manipulate (EEM) (Table 1). In the study protocol, all identified design activities, performed in situ with LEGO pieces and in virtuo with the virtual design tool used, are categorized by EEM actions. The distribution, sequence, and transitions of the EEM actions also allow for in-depth analysis of design activities.

EEM framework is similar to the FBS ontology that classifies design steps. However, two key differences are: (1) It categorizes designers' cognitive processes, not through their verbal expressions but observed design actions (embodying, experiencing, and manipulation). The EEM coding focuses on the externalizations of design actions, complementing the think-aloud report coding based on the construction of the design narrative. (2) It is created specifically for the current design protocol's tools, media, and processes. While the FBS ontology classifies design issues in their self-reported verbalizations and interprets design processes based on transitions between the issues, the EEM framework is based on observed design actions without any interpretation. It allows us to focus on design actions (such as LEGO brick manipulation actions) that might be missed in more universal analysis methodologies such as FBS taxonomy. Therefore, using both the FBS taxonomy and the EEM framework complementarily provides an in-depth look into the design process of designers.

2.1. Study design

We conducted a within-subjects experimental design to investigate the impact of virtual reality on the archi-

Table 1. *Design activities defined in the EEM framework.*

Category	Action	Event Type	Description
Embody	Hold	Point	Hold a brick.
	Drop	Point	Drop a brick on the ground.
	Try	Point	Try a placement without connecting.
	Attach	Point	Connect one LEGO brick to another.
	Pick	Point	Choose LEGO bricks from the dispensers.
Experience	Think	State	Thinking state, evaluating the design.
	Figure placing	Point	Use human figure/Minifigure for scale.
	Scale 1:1	State	Design in 1:1. (In situ default)
	Scale 10:1	State	Design in 10:1 (In virtuo default, VR only)
	Scale 42.5:1	State	Design in 42.5:1 (VR only)
	Teleport	Point	Teleport to another location (VR only)
Manipulate	Detach	Point	Detach one LEGO brick.
	Replace	Point	Detach and reconnect one LEGO brick.
	Break	Point	A part of structure unintentionally breaks.
	Fix	Point	Fix the broken bricks or components.
	Rewind	State	Rewind time to undo the last moves.
	Restart	Point	Decide to start over.

tectural design process and experience by comparing two sessions of design experiments with 14 participants using physical LEGO pieces and virtual bricks in VR. The design protocols, one investigating the design process in situ, the other in virtuo, were set up to be as similar as possible except for the medium.

Each participant started with a 15-minute warm-up session with the physical LEGO pieces. They then completed the tutorial on the virtual design tool so they could focus on their designs during the experiments rather than learning new interfaces or processes. During the warm-up session, the participants were asked to build models using step-by-step LEGO building instructions without any design prerogative, aiming to minimize the extraneous cognitive load associated with the task. All participants received the same set of two different building instructions with similar complexity, one for the in situ, and one for the in virtuo warm-up. The design protocols were initiated following the warm-up sessions.

The case-crossover study design was specifically chosen to equally distribute the positive and negative effects of the first session's experience in the second session between in situ and in virtuo, i.e., warming up, familiarity with the design tasks, or fatigue. Seven participants were randomly assigned to start with in situ sessions, and the remaining seven with in virtuo sessions. Although no time restriction was given for completing the design protocols, the participants were informed that they were expected to finish the task at hand in approximately 40 to 80 minutes. The study protocol was approved by the ethics committee of Istanbul Technical University.

2.2. Participants

Study participants were recruited through a printed 'call for participants' posted at various locations at ITU Faculty of Architecture and an announcement on the institution's social media. All architects, faculty members, and students of the ITU Faculty of Architecture were eligible to participate. Student participation was not restricted to architecture majors as all undergraduate students of the institution had completed the multidisciplinary Foundation Studio and were equipped with the necessary design skills required in the experiment.

We recruited 14 participants on a first-come, first-served basis, nine female (64%) and five male (36%) designers, aged between 22 and 36 (mean: 25.57, SD: 4.62). The sample consisted of seven architects (50%), five architecture students (36%), one interior architecture student (7%), and one urban design student (7%). Eight participants (57%) had no prior experience using VR design tools, six participants (43%) had used a VR tool at least once for design or sketching. All participants had previous experience building physical models using LEGO bricks in their childhood, if not in the recent past. Study participants were informed about the purpose of this study and how their anonymized data would be used. All participants signed an informed consent form before starting the experiment.

2.3. Apparatus and procedures

This study uses the parts available in the LEGO Architecture Studio (#21050) set, which has a rich inventory of pieces intended for architectural design. In line with the characteristic freedom from physical constraints of VR, *Dreamscape Bricks VR* provided an infinite number of pieces from the inventory of the same physical LEGO set, which had a limited number of pieces in situ.

The VR setup includes an Oculus Rift CV1 headset, two Oculus Touch hand controllers, three sensors for room-scale tracking, and a VR-ready PC (Figure 3). The *Dreamscape Bricks VR* application has been on this setup and is assured to run with stable performance (i.e., 80-90 FPS frame rate).

The in situ session was a seated experience where the physical LEGO set was available on a 120 cm by 60 cm desk, pieces sorted by types in labeled organizer boxes. Two Minifigures were also provided for the human scale (Figure 3).

During the in virtuo sessions, participants put on a VR headset to experience the virtual environment of the Dreamscape Bricks VR application on

Figure 3. *The overview of in situ setup (left) and in virtuo setup (right).*

a physical area of 3 meters by 3 meters. Participants can stand, walk, sit or even crouch around a virtual building platform to interact with their models. Scales range from 1:1 (life-size bricks, where the bricks have the same dimensions as in real life) to 1:10 (precision building, where the bricks are ten times the size of real life) to 1:42.5 (figure-sized user, where the bricks are 42.5 times the size and the participant is approximately the size of a LEGO Minifigure). The pieces from the LEGO Architecture Studio set inventory are sorted on the shelves around the building platform, and when the user takes a brick, another instance of the same type is spawned. Two animated human figures, one standing and sitting, the other lying down, have been provided as human scales. The height of the building platform and shelves is set at one meter above the physical floor for all scales, around the user's waist level. The dimensions of the virtual environment are given in LEGO units, the width of a standard LEGO brick, and are indicated with the "λ" symbol as users can change scales. The building platform has an area of 24 λ by 24 λ, and the overall dimensions of the operating area are 75 λ by 75 λ, which corresponds to 60 cm by 60 cm on 1:1 scale, has the same width as the table in the physical setup. Therefore, the 1:1 scale in virtuo and the physical environment have the same dimensions, and all LEGO bricks are in the field of view of the users in both the physical and virtual environments.

The physical environment was recorded in situ using a smartphone on a tripod and via a webcam in virtuo. In virtuo sessions were also recorded by screen capturing *Dreamscape Bricks VR* with NVIDIA ShadowPlay.

2.4. Design tasks

In Design Task 1, the participants were asked to design a single-person survival shelter with a covered area for weather protection. The shelter was required to accommodate sitting and sleeping functions with LEGO bricks within a volume of 12 LEGO units (λ) by 12 λ by 12 λ.

A pavilion was selected as Design Task 2 since it has similar needs and scale to the first task (shelter). The participants were asked to design a small pavilion for an open park area with a narrative spatial experience of their choice, accommodating sitting and standing functions for one user within a volume of the exact dimensions (12 λ^3).

The human scale was defined as a standard LEGO Minifigure (4 cm or 5 λ). Assuming the standard human height as 170 cm, Minifigure gives the models a scale of 1:42.5. A length of 3 λ corresponds to 102 cm, making the design tasks in a 4 m cube on a human scale.

2.5. Data collection

Qualitative and quantitative data were collected in four steps (Figure 4).

2.5.1. Design session recordings

In situ sessions were recorded on video using a mobile phone on a tripod placed laterally to capture the participants' hands, models in progress, and the LEGO pieces. The duration of recordings was 15-20 minutes. In virtuo sessions were recorded via screen capturing *Dreamscape Bricks VR* with NVIDIA ShadowPlay overlayed on the corner with a simultaneous webcam video recording the participants' actions in the physical environment. These session recordings provided the primary video source for retrospective think-aloud reports. After all sessions were completed, the recordings were meticulously coded for each design action using the EEM framework (Figure 6.a) using BORIS, a software for logging events and behaviors in videos (Friard & Gamba, 2016). Design activity durations and action distributions were then compared between in situ and in virtuo, based on the EEM framework.

Observation of the participants' design session recordings by the researchers provided another dataset. We wrote memos based on the participants' design behaviors, which helped us answer several research questions about in situ versus in virtuo design activities.

2.5.2. Model documentation

After each session, participant creations were documented by taking photos of the completed model from primary and secondary views. All virtual models were documented using the Photo Mode feature of *Dreamscape Bricks VR*. Final models for all sessions were re-created as a digital model in BrickLink Studio 2.0, a CAD tool for building digital LEGO models using these photos and session recordings. Figure 5 shows the final products from the experiments.

2.5.3. Retrospective think-aloud reports

Following each session, the participants were asked to think aloud while watching the videos or screen captures of their design process. Since concurrent talking can distract participants, interfere with their thinking process, and increase the extraneous cognitive load, retrospective think-aloud interviews were conducted to recall design thoughts or actions. The participants were first asked to complete the task in silence, then reflect on their thoughts and processes from their long-term memory (Gero & Tang, 2001; Russo et al., 1989). Multimedia memory cues such as video recordings, screen

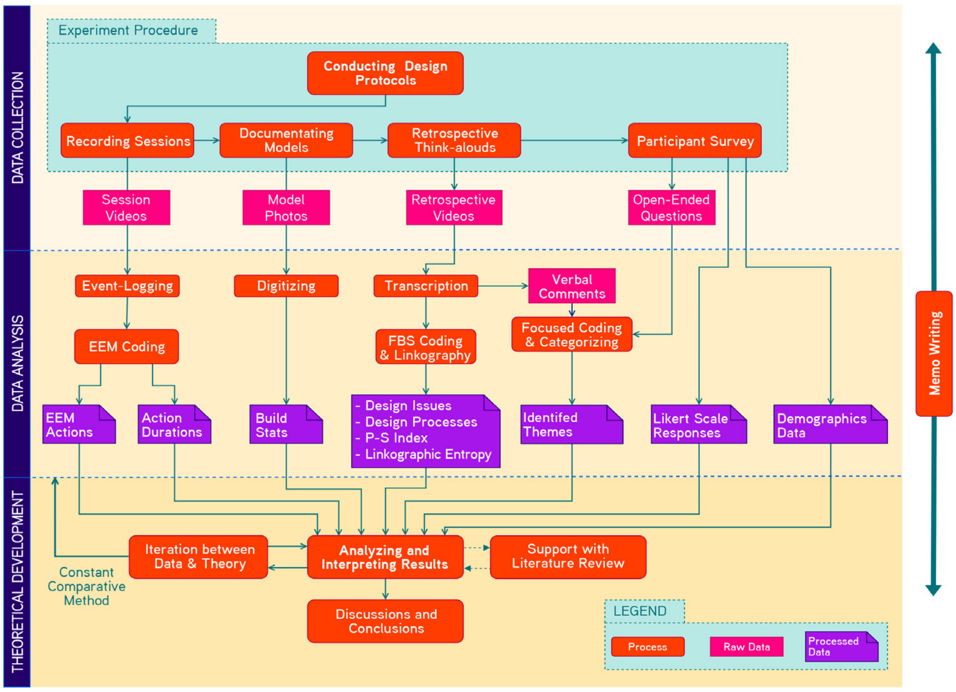


Figure 4. *Flowchart of data collection process in this study.*

captures, and other metrics were provided by the VR tool to control for errors and selective recall bias (Gero & Tang, 2001; Suwa & Tversky, 1997).

In these retrospective think-aloud reporting sessions, participants were encouraged to recall the entirety of the session, describe what went through their minds, what they were going to do next, and comment on their actions while videos of the design session were played back. The participant comments were captured on video, along with the session recordings playing in the background and transcribed for further analysis. The transcripts were divided into "design moves" categorized and analyzed based on the "design issues" identified in the FBS taxonomy (Figure 6.b). The researcher and a trained coder, a professional architect experienced in research and design, reviewed and independently coded 100% of the transcripts and reconciled them in consensus. Initial inter-coder reliability was 0.92. The differences between the two coders were resolved in consensus until a final agreement was reached.

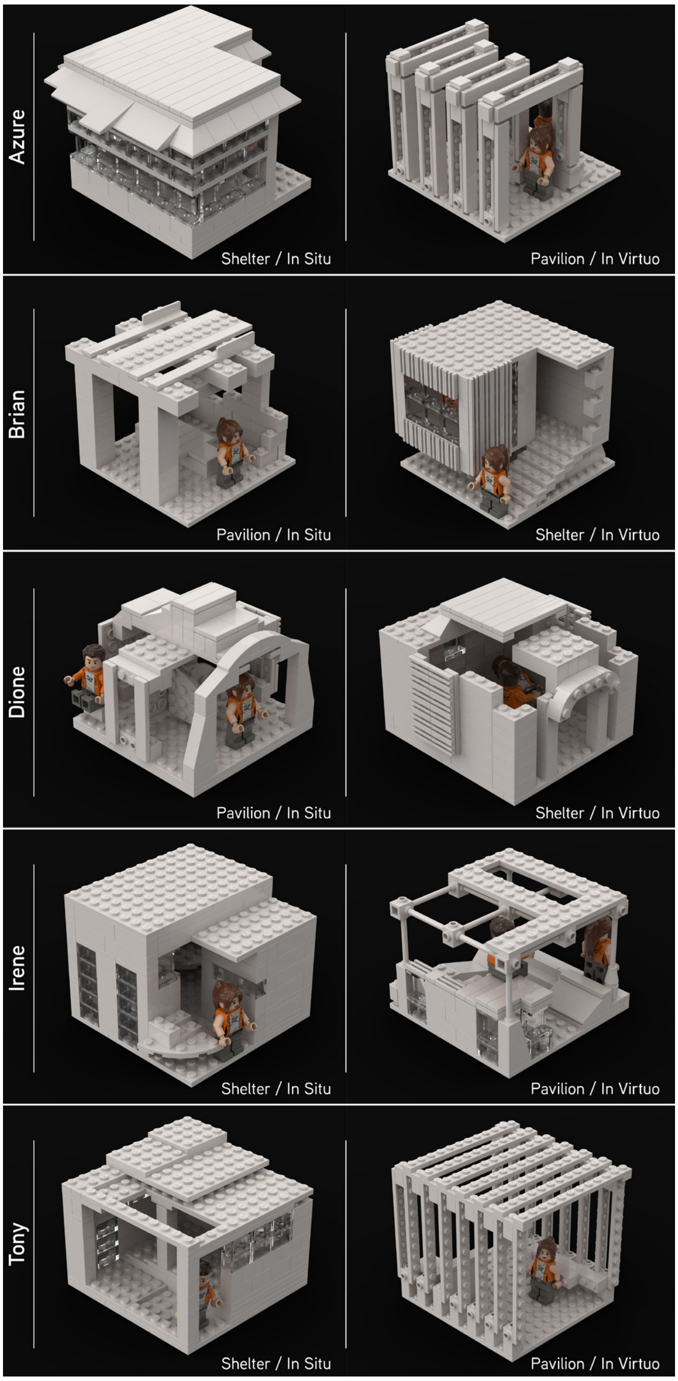


Figure 5. *The final products from in situ and in virtuo design protocols.*

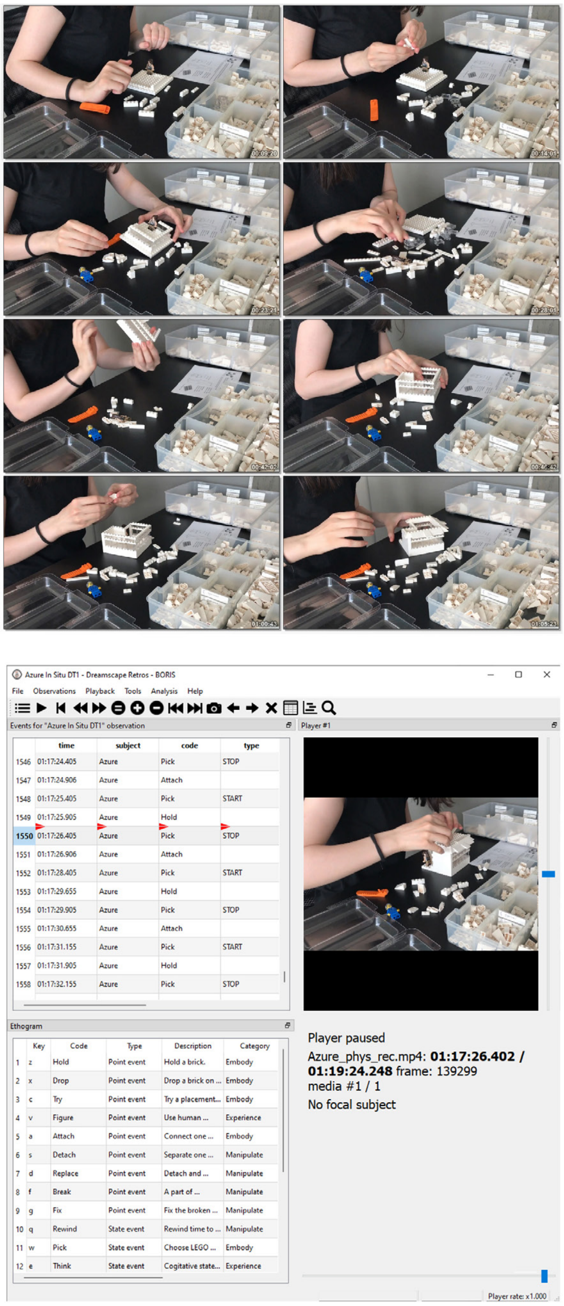
2.5.4. Participant surveys

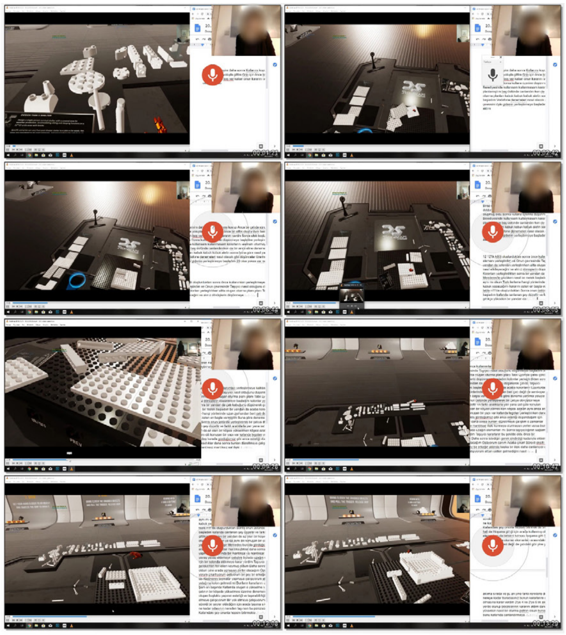
After completing the design protocols, participants were asked to fill out a survey containing demographic, post-experiment, and user feedback questionnaires. Survey questions focused on the perceived benefits of the design experience in situ and in virtuo. The post-experiment questionnaire included Likert-type assessment questions comparing design potentials of the two media. It also included open-ended questions to evaluate the participants' general experience during the design sessions, their views and opinions on the advantages and disadvantages of LEGO bricks, comments on the use of *Dreamscape Bricks VR*, and if they would use *Dreamscape Bricks VR* in their future design activities. Descriptive analysis of the questionnaire data was done following the completion of all sessions. Responses to open-ended questions were categorized and labeled to explore the emergence of recurring themes.

3. Results

In this study, quantitative and qualitative data were analyzed to compare the design processes in the physical medium and VR to assess the influence of the tool and physical versus virtual medium on user experience.

Quantitative data obtained in this study consisted of four datasets: (1) build statistics of the models produced during the design sessions, (2) FBS design issues and design processes in retrospective think-aloud reports, (3) EEM design actions and durations





#	Utterance	Code
1	I started with the shelter task.	R
2	First, I am trying to create a 12-by-12 base.	F
3	I am trying to get a little familiar with the controls.	D
4	First, I tried the 8x6 plate.	S
5	No, I used 6x6's.	S
6	So I created a 12x12 base.	F
7	First of all, I had the idea of building a cabin that was elevated above the ground.	R
8	So I wanted to make the pillars first to support the structure.	F
9	I placed the human figure on the ground to determine the scale of the pillars.	Be
10	I am looking from different scales here.	Be
11	I try to understand the size of the figure by comparing it to the human figure.	Be
12	At this point, I am thinking about where I should position the bearing pillars.	F
13	But later, their place will change as well.	D
14	Here I found that the pillars I chose first are very high.	Bs
15	They would greatly increase the height of the structure.	Be
16	And the stairs would take up too much space on the plan.	Be
17	So I decided not to raise the structure so far off the ground.	D
18	And I chose a pillar with less height.	S
19	Right now, I am trying to create the stairs.	F
20	I am looking at how wide the stairs will be and what parts I can use to build the stairs.	S

a. b.

***Figure 6**. Examples of data coding with EEM (a) and FBS (b) frameworks in physical and VR sessions.*

observed in session recordings, and (4) post-experiment questionnaire responses. IBM SPSS Statistics 27 and Microsoft Excel 2019 were used to assess and analyze the quantitative data.

Qualitative data collection consisted of: (1) open-ended questions in the post-experiment questionnaire and (2) selected comments from the retrospective think-aloud reports.

3.1. FBS design issues and design processes

The percentage of occurrences of *FBS design issues* and *design processes* found in the retrospective think-aloud analyzes of the sessions were compared using the Wilcoxon rank-sum test, the non-parametric counterpart of the paired t-test (Norman & Streiner, 2003), as shown in Figure 7. Design issues analysis shows that the significantly different issues between in situ and in virtuo sessions are Function and Description ($p<0.05$). Description issues recurring approximately 43% more in the VR sessions is an expected result since the participants used more descriptive expressions about the environment and the process while describing their work in VR. The fact that Function issues took place 33% less in VR sessions indicates that users make less verbal externalization about the functionality of their design. The correlated decrease in Function issues and increase in Description issues can be interpreted as a result of the immersive experience in VR, allowing the users to reflect more on their interactions and bodily experiences with their design, rather than on functional issues. Other design issues either occurred at similar percentages or did not show a statistically significant difference.

The analysis of design processes showed that the only significant difference between in situ and in virtuo sessions is the documentation process. This is also an expected result since Description issues showed a difference above, as the Documentation process occurs by the syntax of Structure issues to Description issues (Figure 7).

FBS ontology can also show whether the cognitive activity is mostly problem-oriented or result-oriented in the design protocols (Jiang et al., 2014).

In this analysis, Problem-Solution (P-S) indexes of issues and processes were calculated. According to the P-S issue index formula, Requirement, Function, and Expected Behavior issues indicate the cognitive efforts towards the problem definition, where Structure and Structure Behavior issues indicate the cognitive efforts for the solution (Jiang et al., 2014).

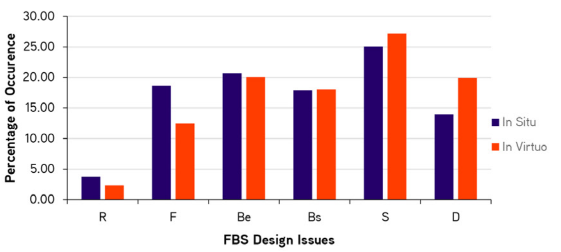
$$P\text{-}S\ issue\ index = \frac{Requirement + Function + Expected\ Behavior}{Structure + Structure\ Behavior}$$

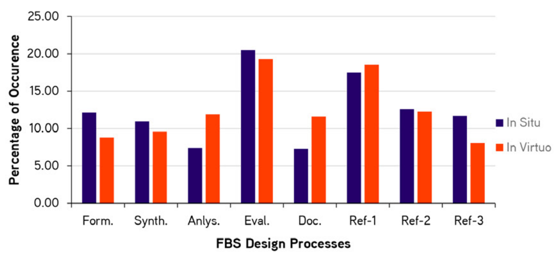
The P-S process index identifies the Formulation, Reformulation 2, and Reformulation 3 processes as problem definition, whereas the Analysis, Evaluation, Synthesis, and Reformulation 1 processes belong to the problem-solving phase.

$$P\text{-}S\ process\ index = \frac{Formulation + Reformulation\ 2 + Reformulation\ 3}{Analysis + Evaluation + Synthesis + Reformulation\ 1}$$

In this analysis, P-S indexes were calculated by dividing the design protocols into quintiles to better express the design processes' temporal flow (Figure 8).

When the cognitive effort reflected in the FBS-coded reports related to the problem and the solution are equal, the P-S index gets closer to 1, indicating balanced design protocols. A P-S index above 1 indicates that the participants' attention was focused on the problem, whereas a P-S index below 1 indicates the participants' attention was focused on the solution. When the graphs are examined, we have seen that in situ sessions create more problem-oriented expressions, while in virtuo sessions create more solution-oriented expressions. This can be explained in a similar way to the previous analysis of design problems. The increase in solution-oriented expressions is expected because participants better understood





Design issues	In situ mean	In situ σ	In virtuo mean	In virtuo σ	VR / Phys.	Z-score	p-value
Requirement	**3.77**	3.23	2.33	1.07	62%	-1.005	0.315
Function	**18.64**	8.60	12.44	4.34	67%	-2.621	**0.009**
Exp. Behavior	**20.69**	7.86	20.06	6.50	97%	-0.105	0.917
Str. Behavior	17.90	9.39	**18.06**	6.99	101%	-0.282	0.778
Structure	25.08	9.26	**27.21**	8.10	108%	-0.659	0.510
Description	13.95	4.29	**19.94**	6.77	143%	-2.229	**0.026**

Design processes	In situ mean	In situ σ	In virtuo mean	In virtuo σ	VR / Phys.	Z-score	p-value
Formulation	**12.15**	6.22	8.77	5.52	72%	-1.412	0.158
Syntesis	**10.96**	4.67	9.59	5.10	88%	-0.659	0.510
Analysis	7.41	4.72	**11.89**	5.02	161%	-1.948	0.051
Evaluation	**20.49**	13.32	19.27	12.59	94%	-0.157	0.875
Documentation	7.28	4.13	**11.59**	5.35	159%	-1.978	**0.048**
Reformulation-1	17.47	9.14	**18.53**	9.69	106%	-0.534	0.594
Reformulation-2	**12.58**	4.73	12.29	5.06	98%	-0.377	0.706
Reformulation-3	**11.67**	6.94	8.05	6.59	69%	-1.412	0.158

Figure 7. *FBS design issue (left) and design process (right) distribution of design protocols, with Wilcoxon rank-sum test results.*

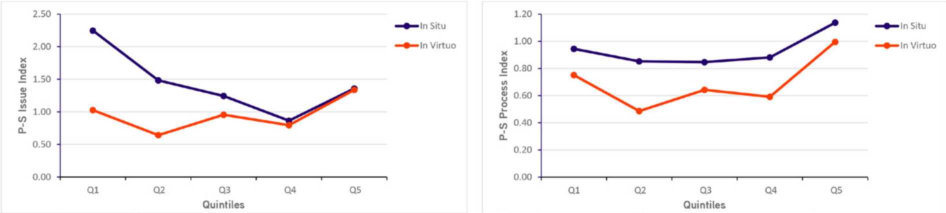


Figure 8. *P-S issue index (left) and process index (right) comparison of design protocols.*

their environment and had a more comprehensive experience while walking around and manipulating objects as a spatial experience on a human scale, compared to being confined to work with a hand-held object. In other words, it was easier for participants to find solutions with full interaction capabilities, which was also reflected in the verbal comments.

3.2. EEM design actions and durations

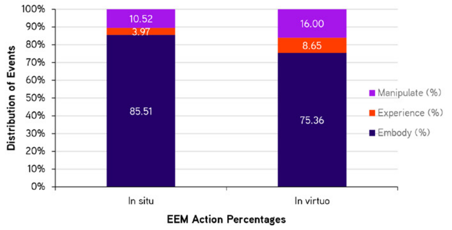
The analysis of EEM design actions shows the percentage distributions of embody, experience, and manipulate actions. Significant differences were found in the distribution of EEM action categories between in situ and in virtuo sessions. In the in virtuo sessions, the participants spent 22.26% of the session in life-size bricks scale (1:1), 71.36% in precision building scale (1:10), and 6.37% in figure-sized user scale (1:42.5) on average. In the in virtuo sessions, the actions to experience the design were 118% more, and the actions to manipulation were 52% more, whereas embody actions were 12% less (Figure 9). Based on this, it can be argued that the VR environment is more suitable for experiencing the design on a human scale and making design changes over this experience. When the ongoing actions of selecting parts (Pick) and thinking actions (Think) were compared, no difference was found between thinking actions. However, it was observed that the selection of the parts took a significantly (p=0.002) shorter time in virtuo compared to in situ (Figure 9). This is also reflected in the verbal statements of the participants, who explicitly pointed out that it was much easier to find parts in the VR environment.

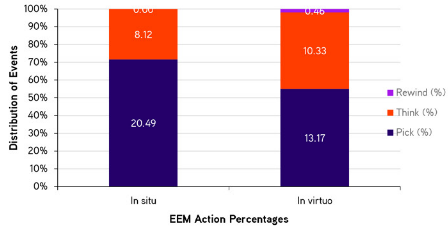
Design duration results indicate that participants built faster in situ (mean 41.7 min, SD=21.6) than in virtuo (mean 60.38 min, SD=26.52), which may be attributed to the accessibility or familiarity of the real world and the ease of physical interaction using hands. It must be noted that, regardless of how intuitive the virtual interactions designed in the currently available VR systems are, virtual reality is new to the users, and it takes time to learn and master this environment. We also observed that participants with visibly increased stress levels spent more time and prolonged their design processes. This situation may have negatively affected the design process in VR. Previous studies have shown that the weight and bulk of VR headsets can cause some level of discomfort among participants (Aksoy et al., 2021; Rupp et al., 2019), which is also consistent with questionnaire comments from two participants. Some level of frustration caused by the stress and the weight of the VR headsets may have prevented the participants from focusing on the design, resulting in longer design duration and slower design speed in virtuo.

3.3. Post-experiment survey

Participants were asked to provide their opinions on designing in both environments using Likert-type questions to get quantitative metrics based on their experience in this study. The post-experiment questionnaire was analyzed using descriptive statistics (Table 2). Results showed that the participants who found benefits of designing in VR compared to the physical environment relate more to the unique immersive spatial experience opportunities of VR concurrent with the design process than the manipulation capabilities.

According to the questionnaire results, there are no statistically significant differences between participant evaluation of design ideation (shown with * in Table 2) and design iteration





Design actions	In situ mean	In situ σ	In virtuo mean	In virtuo σ	VR / Phys.	Z-score	p-value
Total actions	**699.93**	322.72	683.50	292.47	98%	-0.345	0.730
Embody (%)	**85.51**	4.89	75.36	6.98	88%	-3.233	**0.001**
Experience (%)	3.97	2.33	**8.65**	3.93	218%	-3.233	**0.001**
Manipulate (%)	10.52	4.71	**16.00**	5.85	152%	-2.731	**0.006**

Action durations	In situ mean	In situ σ	In virtuo mean	In virtuo σ	VR / Phys.	Z-score	p-value
Pick (%)	**20.49**	6.18	13.17	5.18	64%	-3.045	**0.002**
Think (%)	8.12	7.85	**10.33**	10.03	127%	-1.036	0.300
Rewind (%)	n/a	-	0.46	0.69	n/a	-2.201	0.028

Figure 9. *EEM design actions (left) and action durations (right) comparison of design protocols, with Wilcoxon rank-sum test results.*

(shown with †) potentials of physical LEGO bricks and virtual LEGO bricks ($p>0.05$). The participants stated that designing with physical LEGO bricks had a slightly better advantage (3.43/5) than designing with virtual bricks. The abilities that the participants find to be the most advantageous in VR compared to the physical environment are: changing the scale (4.86/5), unlimited number of parts (4.79/5), and rewinding time (4.14/5), respectively. Thirteen of fourteen participants (93%) stated that they would prefer to use *Dreamscape Bricks VR* as a design tool, while one remaining participant (7%) stated that they would not prefer physical LEGO bricks for architectural design.

3.4. Participant comments

Participant responses to the questionnaire and selected comments from think-aloud reports were compiled into a 4000-word document. To highlight emerging themes, we filtered stop words (such as "a", "is", "the", "I", "this", "that", "and") and analyzed this compilation for the most frequently mentioned words. The ten most frequent words are in order as follows: (1) design, (2) scale, (3) parts, (4) environment, (5) LEGO, (6) physical, (7) VR, (8) time, (9) process, (10) human.

Through an inductive analysis of this qualitative dataset of 4000 words, we also identified positive and negative themes on *Dreamscape Bricks VR* and the use of LEGO for design. Table 3 shows these themes and their recurrence number in all participant comments.

The positive themes on *Dreamscape Bricks VR* mostly revolved around the idea of being able to change the scale of objects and iterate through designs quickly, without physical limitations. The downside is the difficulty of con-

Table 2. *Post-experiment questionnaire results.*

Questions	Mean Response Value (SD)	Response Variables
Design ideation potential with physical LEGO bricks*	4.36 (0.63)	1: Very poor 2: Poor 3: Acceptable 4: Good 5: Very Good
Design iteration potential with physical LEGO bricks†	4.29 (1.20)	
Design ideation potential with LEGO bricks in VR*	4.21 (0.58)	
Design iteration potential with LEGO bricks in VR†	4.29 (0.91)	
Advantage of designing with physical LEGO bricks over LEGO bricks in VR	3.43 (0.94)	1: Much worse 2: Somewhat worse 3: Stayed the same 4: Somewhat better 5: Much better
Advantage of the ability to change scale in VR over the physical world	4.86 (0.54)	
Advantage of the ability to rewind time in VR over the physical world	4.14 (1.10)	
Advantage of having an unlimited number of parts in VR over the physical world	4.79 (0.58)	
Would you use Dreamscape Bricks VR as a design tool?	0.93 (0.27)	No: 0, Yes: 1

* $p>0.05$, † $p>0.05$

Table 3. *Recurring themes in the participants' comments.*

Comments	Positive Themes	Negative Themes
On Dreamscape Bricks VR	(12) Changing scale, experiencing the space iteratively and instantaneously (9) Ease of connections in VR, less physical limitations (9) Unlimited parts to use in VR	(8) Difficulty of controls in the virtual environment
Use of LEGO for design	(10) Modular components help design faster (6) Fast feedback with LEGO pieces' inherent trial and error (5) Modular components increase creativity (4) Familiar and easily comprehensible (3) Ability to design three-dimensionally (2) Similarity of physical and virtual LEGO interactions	(9) Modular components decrease creativity

trols in VR. The positive themes on using LEGO for design mostly related to the idea that modular components help designing faster, with less need for planning and more opportunity for trial and error. Nine participants claimed LEGO pieces to be creatively restrictive, which contradicts the other five participants arguing that bricks increase creativity. These results suggest that people see the potential for using LEGO in VR for design, but some drawbacks need to be addressed.

3.5. Experimental design validation

We conducted a series of statistical tests (Mann-Whitney U test and Wilcoxon rank-sum test) on our results to check for any bias in the convenience sample, order of design tasks, or experimental procedure. We compared each variable with the cumulative linkographic entropy of design sessions (ΣH) as a metric of design complexity. The analyses showed no bias in (1) gender of participants, (2) previous VR experience, (3) selection of design tasks, and (4) interaction of in situ and in virtuo sessions. The effect of age and professional proficiency of participants can also be ignored when comparing in situ and in virtuo sessions because any effect it might have on the design process would be present in both physical and virtual environments, contributing equally to both sides of the comparison.

In addition, the features offered by *Dreamscape Bricks VR*, such as experiencing the space by changing the scale, providing unlimited LEGO bricks, and time rewinding are effectively used and benefited by the participants.

4. Discussion

Participants of all levels of education and expertise found LEGO bricks intuitive and practical for design. Using LEGO bricks in the design was a decision based on the participants' familiarity with the tool since childhood. However, our experiments show that the frequent CAD use in architectural education and practice made the participants familiar with the CAD tools, which affected the object manipulation tools and operations they preferred. In our study, the participants requested some common CAD tool features, such as grouping and copying. However, these features were deliberately avoided to prevent an advantage in repetitive building processes in virtuo versus in situ brick building in the study.

Among the perceived advantages of VR, the participants' impression of the ability to change user scale in the VR environment was the highest. User comments suggest that changing user scale can help the designer make more informed spatial design decisions since it is easier to get a feel for the size of the architectural design during VR design. For example, when the participants shrank themselves to the figure-sized user scale (1:42.5) to walk and navigate through their designs, they could better perceive the designed interior space and feel the size. They could also see the overall form of the building switching to a life-size bricks scale (1:1) and build in better precision in the 10:1 scale. The real-time feedback and ability to perceive the building from varying scales concurrently during the design process can be a new and powerful tool for designers to make more informed design decisions, contributing significantly to the experience of designing in VR.

The FBS design issue and design process analysis showed similar results in VR and in the physical environment. The analysis reveals that the cognitive activity is slightly more problem-oriented in situ and more solution-oriented in virtuo. This finding suggests that VR as a direct manipulation medium may promote a solution-oriented cognitive mode thanks to less physical constraints and more flexible interactions on different scales, congruent to the findings from the recurring themes in the participant comments (Table 3).

The analysis of EEM actions showed significant differences in the distribution, transition, and duration of design actions between in situ and in virtuo sessions. Our results indicate that the VR medium is more suitable for experiencing the design, making design changes over this experience, and evaluating design alternatives than the physical environment. This suggests that the experience and manipulation options in the VR medium complement the limited manipulation options in the physical medium. In our design sessions, the physical environment serves as a container for creating design representations with LEGO bricks at object scale. On the other hand, the VR environment provides a medium for designers to experience, embody, and manipulate the design spatially and as an object. The VR design tool allows users to navigate through the model and freely change the point of view to observe the whole model, rather than having to move and rotate the model in the physical space to try to observe the entire model within the restricted viewpoints.

The results of this study are in line with the other studies, which revealed that VR is useful for architectural education and 3D representation (Fonseca et al., 2017), and that VR has a positive impact on spatial experience and sense of scale (Pamungkas et al., 2018), and that VR enhances the creative performance by immersing designers in the designed artifact (Abu Alatta & Freewan, 2017).

As a result of the participants' comments on the cognitive design process and the analysis of the design activities, we observed a focus on spatial perception and object perception provided by the varying scales. Therefore, we believe the results can be explained from the perspective of the neuroanatomy of visuospatial perception. The studies of Mishkin et al. propose a subdivision of the human visual system between the ventral stream (temporal lobe) and the dorsal stream (parietal lobe) based on two key visual functions: object identification and spatial navigation (Mishkin et al., 1983; Tversky, 2005). The ventral stream is responsible for object recognition, whereas the dorsal stream supports the perception of spatial relationships between objects in the environment (McIntosh & Schenk, 2009; Mishkin et al., 1983). Another model postulates that the ventral stream is responsible for the vision for perception and the dorsal stream for the vision for action (Goodale & Milner, 1992). This division is now seen as heuristics to guide the theoretical and experimental research; both ventral and dorsal streams work in parallel aware of the other through functional network connections (McIntosh & Schenk, 2009; Schintu et al., 2014). This neuroanatomical perspective shows that designing in the physical environment only allows for the vision for object identification, whereas designing in the VR medium allows for the vision for both object identification and spatial perception and navigation. Designing through object vision only, without experiencing it spatially first-hand via the parts of the brain responsible for spatial experience can be compared to composing by writing notes without hearing the sounds. Since the artifacts of architectural design are intended to be experienced spatially by other people, the architect's ability to design with the vision of spatial perception should be a key to understanding the underlying effects of VR on the design process.

The conventional architectural practice uses physical models to evaluate and communicate design ideas during the design process. In *Libro Architettonico*, Filarete describes this process through an analogy of the scaled drawing or model being a baby building that is conceived through the partnership of the architect and the patron, which grows up to become a mature building after the construction (Kruft, 1994; Terim, 2019). However, in some cases, such as the Siege of Rhodes anecdote, the scale models that seem to respond to a need may prove otherwise on a bigger scale (Vitruvius, 1914). In this light, the use of virtual reality to physically simulate and experience artifacts at variable scales can be a valuable addition to the practice of architecture, combining designing by building and designing by representations.

5. Conclusion

This experimental study was conducted to investigate the architectural design process in VR and in the physical environment to better understand the impact of using virtual reality in the design process when using LEGO bricks as the base design components. Immersive VR is a tool for design representation, a medium for immersive experience and imagination that can shape designers' thinking and approach distinctively. Comparative design experience in-situ and in-virtuo revealed fundamental differences in the design process between the two media, primarily: allowing designing by building and providing a better experience through real-time exploration of the designed artifact. It is important to note that the currently available VR headsets are relatively heavy and bulky, causing slight levels of fatigue and eyestrain after a specific time of use and may not represent the full potential of VR. This limitation may have partially impeded the potential for a natural and comfortable design experience. However, as the availability of more portable and lightweight VR systems is pending, we anticipate that similar studies will be conducted on more advanced stand-alone VR systems in the near future. Also, the requirements of the design tasks given in this study were limited to a specific scope, namely the design of a shelter and a pavilion using LEGO bricks, which represents a small fraction of real-life architectural design scenarios. Therefore, future studies analyzing longer design sessions with a wider scope of architectural design tasks and with a different real-life design component other than LEGO bricks would be recommended. Also, this study was conducted with 14 participants, which was satisfactory for statistical and qualitative analysis methods but limited the generalizability of the results. Further studies with larger samples should be conducted for generalizable results.

In conclusion, the findings of this study suggest that the use of VR in architecture design opens up new possibilities starting from early conceptual stages by allowing the designers to spatially explore their designs with high immersion and simulated bodily presence. This feature encourages users to experiment and explore the design artifact differently, thus introducing new creative opportunities into the process, adding new perspectives, and perhaps ultimately leading to more creative designs that would otherwise not have been discovered.

We developed *Dreamscape Bricks VR* to support real-time multi-user collaboration, and we intend to conduct collaborative design protocols in the future, harnessing the findings and the experimental tool of this study. Finally, we believe it is safe to assume that VR will be an effective medium in concept development, conceptual design, and design development in the practice and education of architecture.

Acknowledgements

This study is conducted as a part of a research project supported by the Research Fund of Istanbul Technical University (ITU BAP Project ID: 41269). ITU Social and Human Sciences - Ethics Committee for Research with Human Subjects (SB-İNAREK) approved the study protocol on November 27th, 2017 (application number 64). All subjects gave voluntary informed written consent for study participation and scientific use of the anonymized research data.

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