Merging Three Spaces:

Exploring User Interface Framework for Spatial Design in Virtual Reality

by

Joshua Choi
Master of Architecture at Massachusetts Institute of Technology, 2014
B.A. at Washington University in St. Louis, 2010

Submitted to the Department of Architecture
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Architecture Studies
at the
Massachusetts Institute of Technology
June 2016

Signature of Author: ....
Department of Architecture
May 18, 2016

Certified by..
Takehiko Nagakura
Associate Professor of Design and Computation
Thesis Supervisor

Accepted by...
Takehiko Nagakura
Chair of the Department Committee on Graduate Students

Merging Three Spaces: *Exploring User Interface Framework for Spatial Design in Virtual Reality*

Takehiko Nagakura
Associate Professor of Design and Computation
Thesis Supervisor

Scot Osterweil
Creative Director of the Education Arcade
Research Director in the MIT Comparative Media Studies/Writing Program

Merging Three Spaces: *Exploring User Interface Framework for Spatial Design in Virtual Reality*

by
Joshua Choi

Submitted to the Department of Architecture on
May 18, 2016 in Partial fulfillment of the
Requirements for the Degree of Master of Science in Architecture Studies

Abstract

This thesis proposes a framework for deploying a tool that provides designers with an alternative spatial environment in Virtual Reality (VR). The physical, projected, and immersive spaces are examined as three kinds of available spaces for them to operate. To compare these spaces, a series of subject experiments is conducted in architectural space. Then a framework for a new tool is prepared with consideration to the experiment results, and a prototype is created to demonstrate its unique user interface for virtual reality environment.

Three experiments are designed to probe the differences and similarities in human perception amongst the three spaces and to prove the following hypotheses.

- *Hypothesis 1:* VR technology can simulate perception of scale and proportion of physical space with minimal error.
- *Hypothesis 2A and 2B*
  - 3D model with realistic textures do not enhance the degree of perception for scale and proportion of the physical space;
  - 3D model with realistic textures enhances spatial perception with greater confidence and shorter recognition time.
- *Hypothesis 3:* Compared to a first person view in VR, a bird's-eye view mode in 2-D screen offers better perception of orientation and location of different objects.
- *Hypothesis 4:* Compared to bird's-eye view in 2D screen, the first person view mode in VR offers better perception of scale of objects.

The results from these experiments lead to a framework for creating a user interface for VR. The experiment on hypothesis 1 supports that virtual space can replace physical space for spatial design purposes. The experiments on hypotheses 3 and 4 suggest that virtual UI should simultaneously include dual perspectives: bird-eye view and first person view. And the experiments on hypotheses 2 and 3 support providing two different modes of renderings. For dynamic interactions, such as between and among moving objects, the rendered mode should be without texture for computational efficiency. For visual interactions, such as navigation, the space can be rendered with photo-realistic textures without losing efficiency. A prototype UI that implements this framework in VR environment is built, and demonstrate how design process can be enhanced.

In summary, a framework for unique Virtual Reality User Interface (VRUI) is explored for spatial design. It is derived from the way people perceive physical, projected, and immersive virtual environments. Designers can use this novel multidisciplinary design tool, whether they design for physical architecture or 3D environments for digital video games.

Thesis Supervisor: Takehiko Nagakura
Associate Professor of Design and Computation

Table of Contents

CHAPTER 1

INTRODUCTION

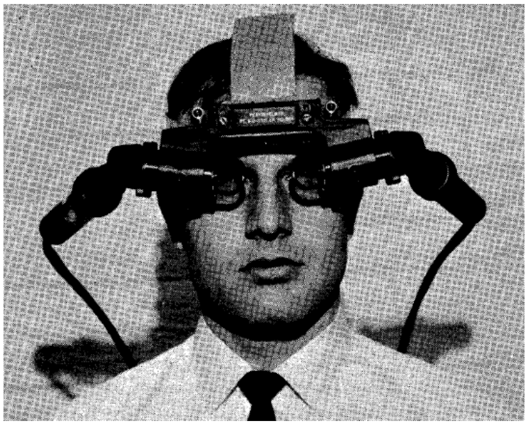


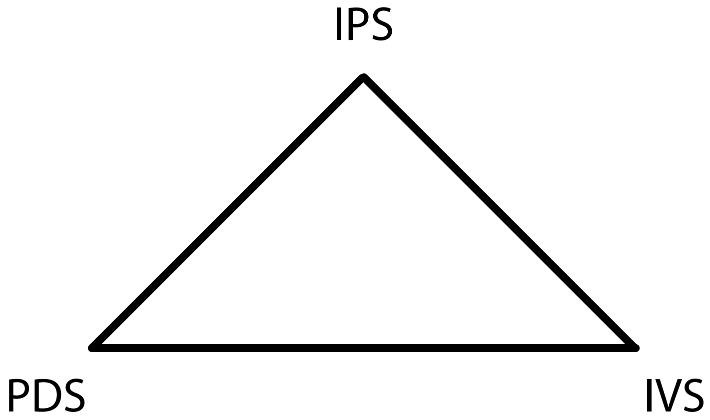
Figure 1: Ivan Sutherland with his VR headset (1968)

Three Spaces

In this thesis, Three Spaces refer to the following: Intuitive Physical Space (IPS), Projected Digital Space (PDS), and Immersive Virtual Space (IVS).

- IPS refers to the actual real 3-dimensional physical space that a person occupies. In IPS, architects can use their physical body to understand the world by touching and navigating through objects and spaces. Architects also make physical models in IPS, and this action of hands-on production enhances the understanding of a design.
- PDS refers to the space mapped out and projected on flat 2-dimensional screen. In PDS, architects create 2D plan and section drawings to organize spaces in patterns to express design intents. Architects also translate 3-dimensional models into PDS, which allows viewing design models from multiple perspectives, including on a flat screen.
- IVS refers to virtual 3-dimensional immersive space that architects can experience by wearing a virtual reality headset. In IVS, architects can place themselves in a designed 3-dimensional space that resembles the physical space.

IVS is a recently developed space that architects tend to use for only visualizing designs. This thesis aims to expand the use of IVS so that it can be used not only for spatial design visualization but also for spatial design process itself.



A diagram of three spaces as a triangle

Ivan Sutherland, our MIT alumni and a creator of Sketchpad and of the first virtual reality headset, said that IVS can “look real, act real, sound real, and feel real.” (Figure 0). According to Sutherland, IVS is about realistic simulation of IPS which provides immersive experience beyond the limits of PDS. Due to its realistic and immersive nature, IVS can become the ideal space for spatial designing. However, I believe that a unique Virtual Reality User Interface (VRUI) that also incorporates the strengths of IPS and PDS can further enhance the process of spatial designing in IVS. To create a framework for such VRUI, this thesis conducts a comparative study of the three spaces in order to identify the strengths of each space in three experiments.

Background Research

This section describes the recent experiments by other academics that provided support for designing the thesis's three experiments.

1. Physical space vs. virtual space

For virtual space to be an effective platform for spatial design process, virtual space should be able to simulate physical space for spatial perception. Heydarian A. has shown that virtual space can simulate physical space for task performance. For example, people are able to perform tasks, such as object identification, in virtual space just as they do in physical space (2015). When the user was asked to identify an object in an office and in the virtual space with photo-realistic 3D model of an office, the user performed just as well in the virtual office as in the real office (figure 2).


Figure 2a: a real office room

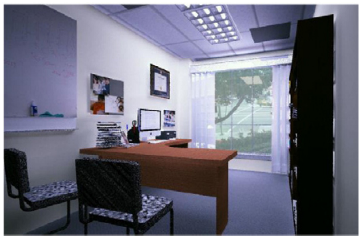


Figure 2b: a detailed 3D model of the office room.

However, for spatial designing, the ability to perceive space is as important as the ability to perform task, if not more. Therefore, it must be tested whether virtual space can simulate physical space for spatial perception to establish whether people are able to perceive scale and proportion in virtual space just as they do in physical space. In addition to exploring whether spatial perception in virtual space can resemble spatial perception in physical space, this paper also tests how much the virtual space has to resemble the physical space in order to be used as an effective platform for spatial design process. Heydarian tested task performance in virtual space with realistic texture (2015). It would be interesting to test how much spatial perception--sensing scale and proportion--in virtual space relies on realistic texture, if at all.

2. PDS vs. IVS

PDS has long been used as the main platform for spatial design. Comparing spatial perception in PDS and IVS can provide useful insight on the unique advantages of each space for spatial design process. Kozhevnikov has shown that people perceive space differently in PDS and IVS by conducting an experiment on how people perform mental rotation differently in PDS and IVS (2015). In PDS, people tend to use allocentric spatial processing, relating an object to another object (figure 3). In an increasingly immersive environment, including IVS, people tend to rely more on egocentric spatial processing, relating an object to their own body. This thesis seeks to not only confirm that people perceive space differently in PDS and IVS but also take a step further in exploring the unique advantages of allocentric and egocentric spatial processing.

Figure 3: PDS condition with a desktop setup was used

3. Flexible cognition

Since people tend to rely on egocentric spatial processing--relating body to object--in IVS, it is important to consider how people represent self in virtual space to enhance spatial design process. As demonstrated by the “Rubber Hand Illusion” study, human recognition is flexible (Ehrsson 2014). When a person’s actual hand is hidden from view, the person starts to take ownership of the rubber hand in front of them, with the rubber hand being exposed to the same stimulus as the actual hand. Likewise, Kilteni has shown that although a user’s actual physical hand is hidden from view in the virtual space, the user may start to take ownership of the fake representation of “hand” in virtual space, as the user interacts with the virtual space using the “hand” (2012).

Even when the “hand” in virtual space was longer than the real body proportion, the users gradually took ownership of the virtual hand and used it to interact with the surrounding space (figure 4). With current VR technology, floating controllers can become representations of self in virtual space (figure 5).

This thesis seeks to test if users sense controllers as representations of self to engage in egocentric spatial processing in virtual space. This thesis also seeks to explore further into how self can be represented differently in virtual space--other than just two floating controllers--to enhance the design process.

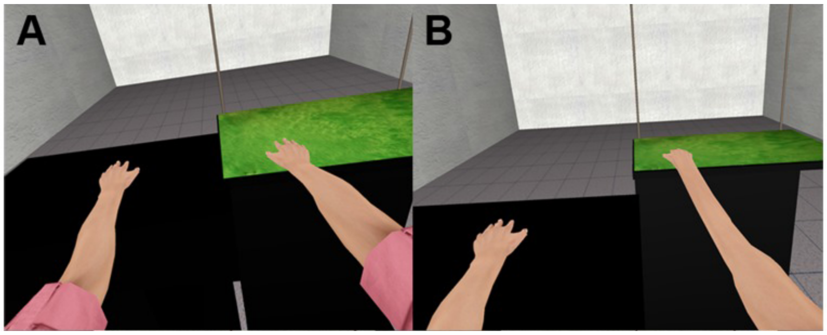


Figure 4: The elongation of the virtual arm

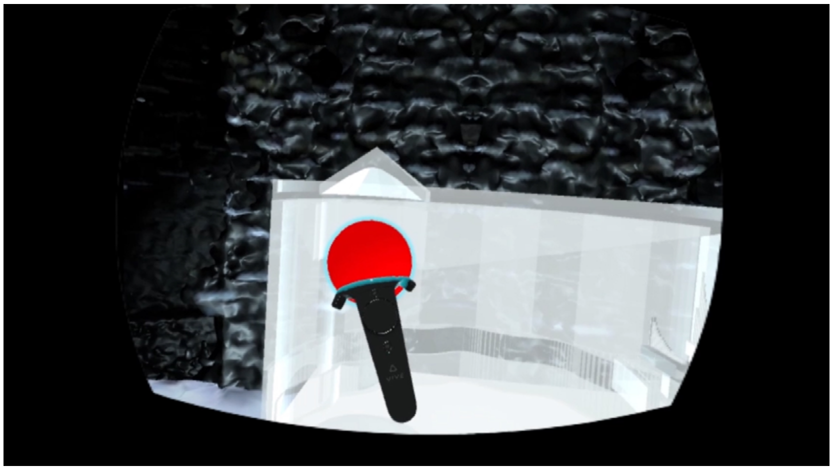


Figure 5: Visualization of a physical controller in IVS

CHAPTER 2

METHOD OF RESEARCH

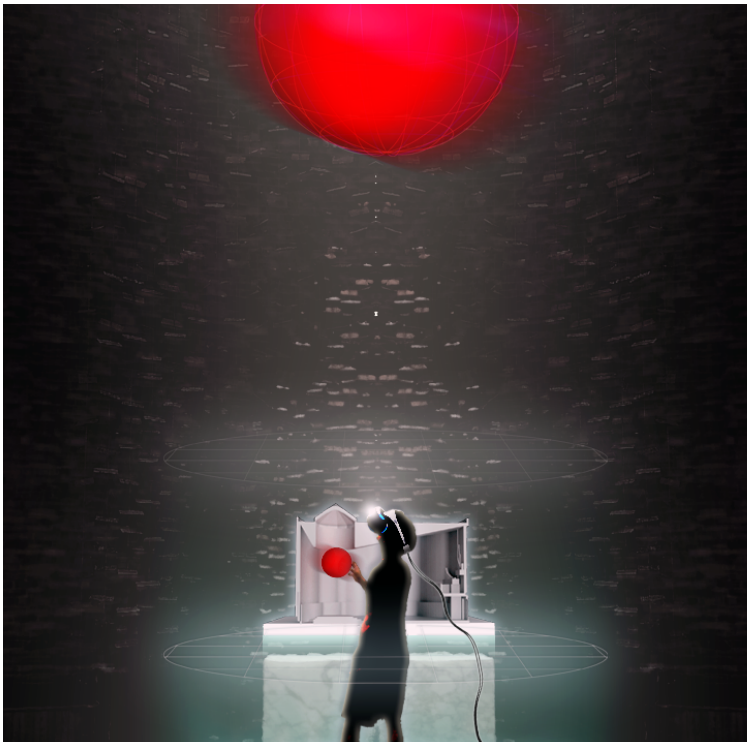


Figure 6: Concept Image for "Merging Three Space", Image collage by Joshua Choi 2016

For the method of this thesis, I conduct three subject experiments that led to building a framework, which tested with a prototype for a unique user interface for virtual reality environment.

Step 1: Testing different VR headsets

In 1960s, Ivan Sutherland created the one of the first head mounted stereo display system. However, it is only recently that a head mounted display system became available for an everyday consumer. In order to determine the optimal experimentation tool, I experimented with 5 different consumer headsets: Google Cardboard, Samsung GearVR, HTC SteamVR, OSVR, and Oculus DK 2. Out of these five, I chose to use two devices, GearVR and SteamVR.

GearVR is wireless and easy to carry around requiring minimal time to set up to start virtual reality experiments (figure 7). However, this device has a limitation in motion tracking only allowing head rotation movement. I used GearVR for first two experiments which did not require users to use their body to interact with virtual environment.

Figure 7: Samsung GearVR

Figure 8: HTC SteamVR with a headset and two controllers

Steam VR enables the motion tracking. I used Steam VR for the third experiment because I wanted to observe user behaviors interacting in IVS. It also provides two controllers that participants can visualize and interact with virtual environments (figure 8). Steam VR requires a significant time to set up, but in return, it provides the highest quality of VR experience for its motion tracking ability and a high resolution display screen.

Step 2: Constructing Hypotheses

For this portion of the thesis, the main effort was on conducting comparative study on human perception in the following three spaces: intuitive physical space, project digital space, and immersive virtual space. The thesis conducted total three experiments comparing and contrasting between those spaces in order to prove following hypotheses.

- *Hypothesis 1:*
  VR technology can simulate perception of scale and proportion of physical space with minimal error.
- *Hypothesis 2:*
  2A: 3D model with realistic textures do not enhance the degree of perception for scale and proportion of the physical space;
  2B: 3D model with realistic textures enhances spatial perception with greater confidence and shorter recognition time.
- *Hypothesis 3:*
  Compared to a first person view in VR, a bird's-eye view mode in 2-D screen offers better perception of ***orientation and location of different objects.***
- *Hypothesis 4:*
  Compared to bird's-eye view in 2D screen, the first person view mode in VR offers better perception of scale of objects.

Step 3: Conducting Three Experiments

The goal of experiments is to find key strengths of each space, and then to merge these strengths to create a framework for designing user interface for IVS to enhance design process. During the course of three experiments, about fifty people participated from MIT and Harvard. Half of the sample have an architecture background while the other half consisted of different backgrounds, mainly computer science. These three experiments will be described in details in Chapter 3.

Step 4: Creating Framework for Designing UI

Using the results from above, this thesis sets up a framework for creating the back-end of user interface. Hypothesis 1 supports that immersive virtual space can simulate physical space for spatial perception. Hypotheses 3 and 4 suggest that virtual UI should enable multi-perspectives of viewing a design such as bird-eye view, 2D plan view and first person view. Hypotheses 2 and 3 suggest to have two different level of abstraction of 3D models, one is 3D model without textures and much detail and the other one is a photogrammetric model with realistic textures.

CHAPTER 3

EXPERIMENTS & RESULTS

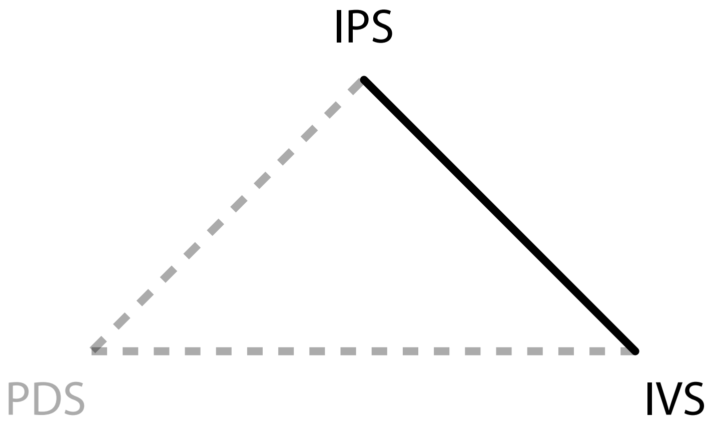


Diagram of three spaces as a triangle

Experiment 1

The first experiment aims to compare and contrast between IPS and IVS in order to prove following hypotheses.

- Hypothesis 1:
  IVS can simulate perception of scale and proportion of IPS with minimal error.
- Hypothesis 2:
  2A: 3D model with realistic textures do not increase the level of perception for perceiving scale and proportion of IPS.
  2B: 3D model with realistic textures enhances spatial perception with greater confidence and shorter recognition time.

This experiment takes a place in a tea room of Japanese house in Boston Children's Museum. This room is selected for its unfamiliar scale and proportion, for example, the height of the door in the Japanese house is 1730mm (5'8"), while the standard residential door in the State is typically 2030mm (6'8"). With this unfamiliarity, I intend that participants cannot guess the room scale and proportion during the virtual reality experiment unless they physically experience and study the room.

Figure 9. A photogrammetric model of a tea room in Japanese House from Boston Children's Museum

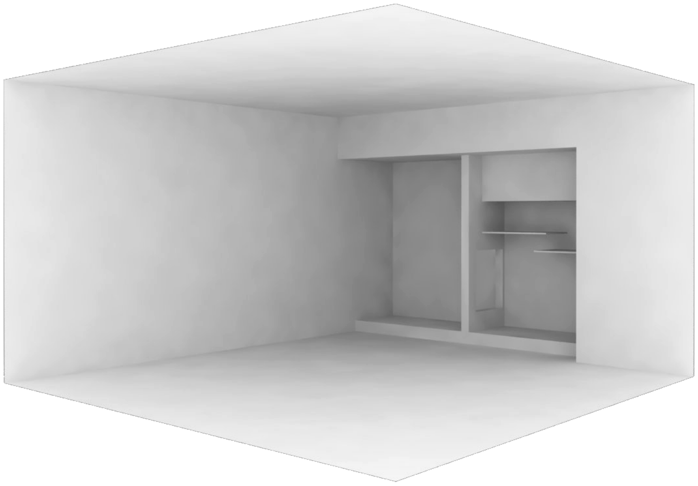


Figure 10. 3D massing model built from Rhinoceros 5 without detailed textures

I prepared two 3D models. The first model is a photogrammetric model of the Japanese tea room with photo-realistic textures (figure 9). The second model is an abstract massing model without any textures (figure 10). The 3D abstract model not only lacks textures, but also major details such as doors. These models are placed inside IVS in which users will be able to interact through VR App. I created. These two 3D models are visualized in IVS with correct scales and proportions as the physical real room. There are mainly two input functions that users can use in IVS- one is to select buttons by pressing the touch-pad on the side of GearVR, and the other is a swipe function of the touch-pad which increases or decreases scale or proportion of the two 3D models (figure 11).

Part 1: Seeing the room

1. A participant enters the room blind.
2. He/she wears the VR headset at the center of the room.
3. He/she sees the room in IVS.
4. He/she takes off the VR headset and sees the physical room.
5. I ask a question,

    "Is the VR room smaller or bigger than the physical room?"

Part 2: Interacting with VR App.

1. He/she studies the physical room.
2. He/she wears the VR headset by sitting at the center of the room.
3. He/she starts the VR App..
4. Task #1: Correct the proportion of abstract model
    - The abstract model appears out of proportion.
    - He/She corrects the proportion by swiping the touch-pad.
    - He/she selects a button to save the data.
5. Task #2: Correct the proportion of realistic model
    - The realistic model appears out of proportion
    - Repeat 4b and 4c

Preparation

Figure 11: Swiping interaction with a touch-pad

Steps

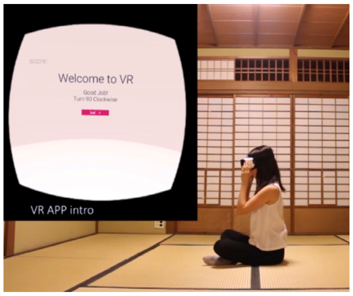
Step 1 from Part 1

Step 2 from Part 1

Step 3 from Part 1

Step 1 from Part 2

Step 2 from Part 2

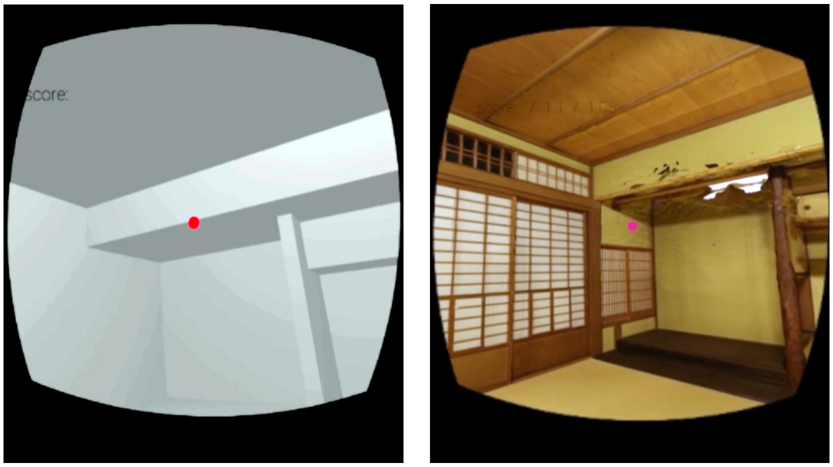


Step 3 from Part 2

6. Task #3: Correct the scale of abstract model
    - The abstract model appears out of scale.
    - Repeat 4b and 4c
7. Task #4: Correct the scale of realistic model
    - The realistic model appears out of scale.
    - Repeat 4b and 4c

8. An interview question at the end,

    "Which was easier to scale, abstract texture-less or realistic model and why?"



Step 4 from Part 2 (left)
Step 5 from Part 2 (right)

Five people participated in the first experiment.
From the top left, Sarah Lee (Chemistry major), Bumjin Kim (Architect), Eunji Kim (Piano major), Sharon Kim (Biology major), and Michelle Suh (Computer Science major)

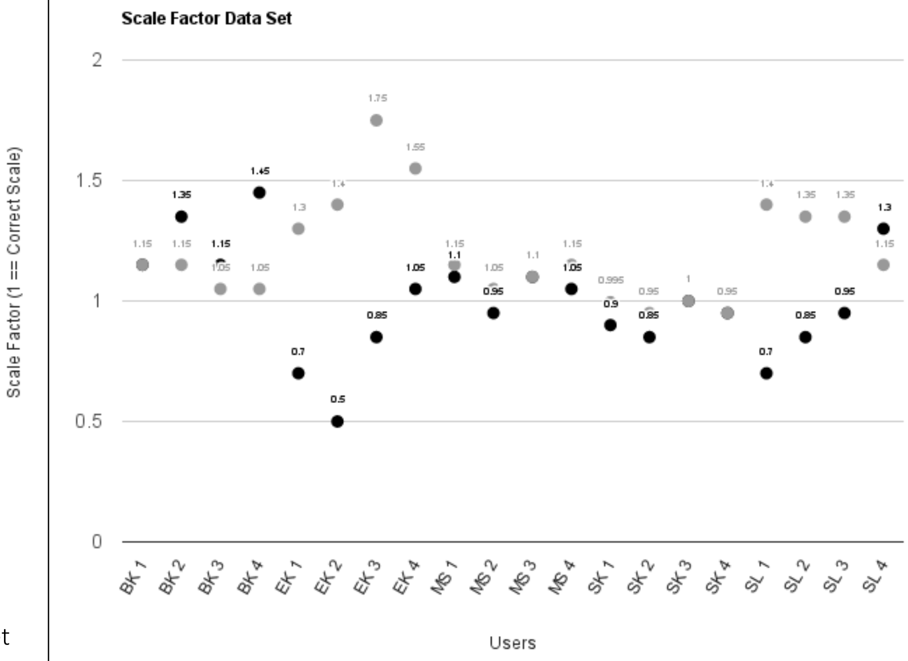
Results

Qualitative Data

At the end of ‘part 1: Seeing the room’, five participants were asked if they perceived the VR room smaller or bigger than the physical room. **4 out of 5 participants answered that the VR room felt smaller or felt closer.** This answer was not expected since the dimension of the room is the same for both spaces. With curiosity, I conducted a personal experiment of ‘part 1: Seeing the room’ with two different devices in order to check if every VR device makes IVS feel smaller than IPS. It was about GearVR vs. SteamVR. My personal experiment concluded that SteamVR performed much better for representing the correct scale - through SteamVR, the room felt very similar to the real room. This personal experiment needs more data with more subjects. However, it seems that different devices produce different depth perception and experiences.

At the end of ‘part 2: Interacting with VR App.’, I interviewed each participant whether having textures helped when correcting the proportion and scale of the room. 4 out of 5 participants answered that **having textures was much easier because they had more information or more clues to work with.** The quantitative data relating to this answer will be described in next section.

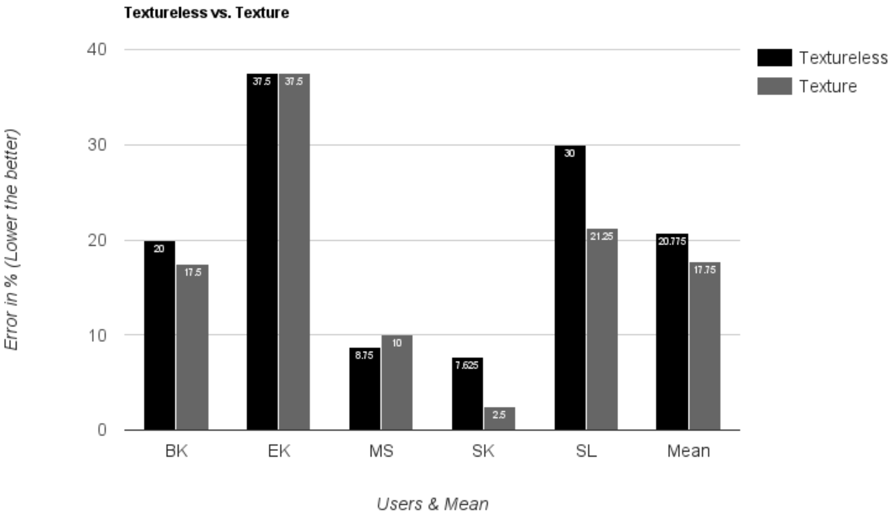
Quantitative Data



Graph 1: Scale factor data set collected from 5 participants

For graph 1, there are two colors, black and gray. The color black represents when the room appeared smaller, while gray represents when the room appeared bigger. Each participant performed both scenarios which means that they actually participated in ‘part 2: Interacting with VR App.’ twice in order to neutralize the data set. The x-axis represents the resulting data from each task from 5 participants. The y-axis represents the scale factor; a value, 1, represents the correct scale of the room, while a value, 1.5, represents that the room was scaled 50% bigger than the real by a participant.

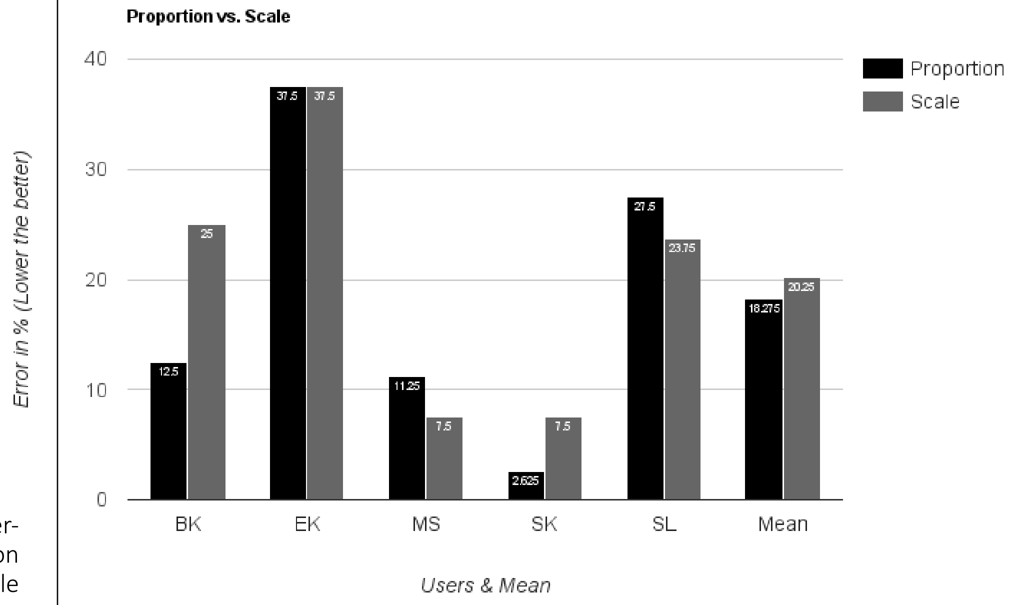
The average scale factor of all data set came out to be +9.57%, showing that in overall, participants scaled the room bigger by 9.57% than the real room. This result of 9.57% error corresponds to how participants perceived the room in IVS from ‘part 1: Seeing the room’. According to them, VR room felt smaller, thus they ended up scaling the VR room slightly bigger in order for them to perceive the virtual room similar to how they perceived the real room. Thus, this result supports that IVS can simulate IPS for perceiving scale and proportion of a space.



Graph 2: Comparing a user performance between texture-less abstract model and textured realistic model

Graph 2 compares the performance of having the abstract model and the realistic model. The x-axis represents five individual performances and the calculated mean at the end. The difference of average errors between the texture-less model and textured model are 3%. This is not a significant difference, thus this result supports that textures do not increase the level of perceiving the proportion and scale in IVS.

Graph 3 compares between two different tasks, correcting the proportion and correcting the scale. The difference is 2% which is even less noticeable than the difference from graph 2. Thus, this result supports that there is no significant difference for perceiving a proportion or scale of a space in IVS



Graph 3: Comparing a user performance between proportion and scale

Discussion

Technical challenge

As briefly discussed above, it would be a relevant experiment to compare and contrast different VR devices, and study their performance of depth perception.

Different site

This experiment took in a place in a small scale room which is about 4m by 4m. Future experiments can take in different places. One could be situated at the center of a city perceiving big buildings and public spaces. Another site could be a small desk with different objects. These experiments together can analyze how well IVS performs in different scale settings.

Conclusion

As conclusion, this first experiment proves two hypotheses.

- Hypothesis 1:
  IVS can simulate perception of scale and proportion of IPS with minimal error.
- Hypothesis 2
  2A: 3D model with realistic textures do not increase the level of perception for perceiving scale and proportion of IPS.
  2B: 3D model with realistic textures enhances spatial perception with greater confidence and shorter recognition time.

By analyzing the result about how participants scaled the room slightly bigger in order to compensate how VR felt smaller, it can be concluded that IVS can simulate perception of scale and proportion of IPS with minimal error. Also, participants produced similar outputs between having the abstract texture-less model or realistic model, thus this concludes that model with realistic textures do not increase the level of perception for perceiving scale and proportion of the physical space. However, with the qualitative data and by observing participants' performance, this experiment concludes that the realistic model enhances spatial perception with greater confidence and shorter recognition time.

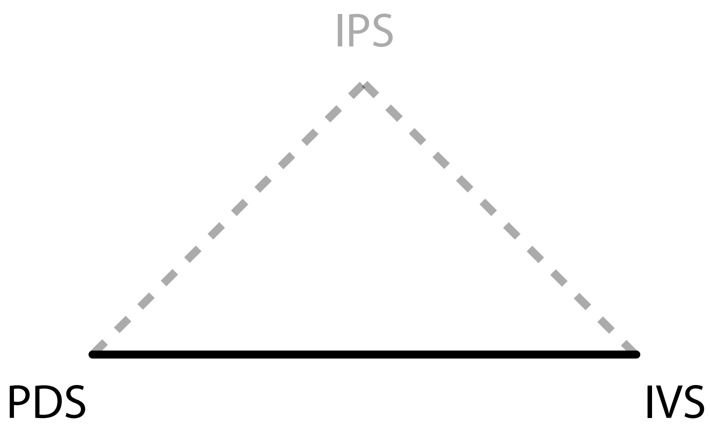


Diagram of three space

Experiment 2

The second experiment aims to compare and contrast between PDS and IVS to prove following hypothesis.

- Hypothesis 3: Compared to a first person view in IVS, a plan view mode in PDS offers better perception of orientation and location of different objects.

This takes a form of a puzzle game similar to a game about spotting the differences from two very similar images. During the game-play of this experiment, participants have a short amount of time to study the objects. After few seconds, objects may change their colors or locations, and the goal for participants is to find the difference and select the correct answer.

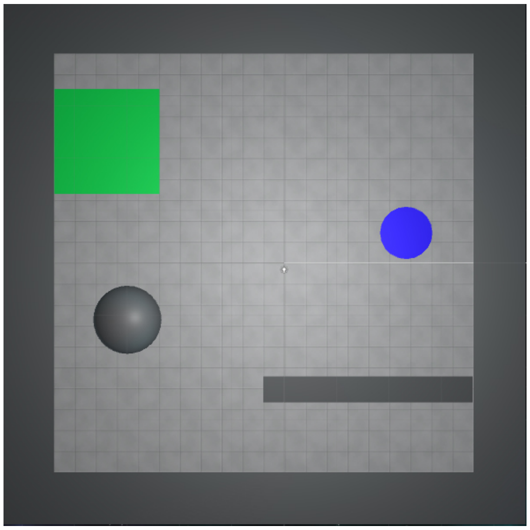


Figure 12: Plan view mode for PDS

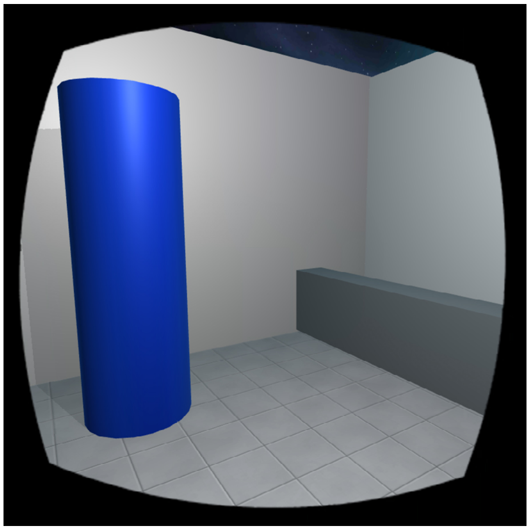


Figure 13: First person view mode for IVS

Preparation

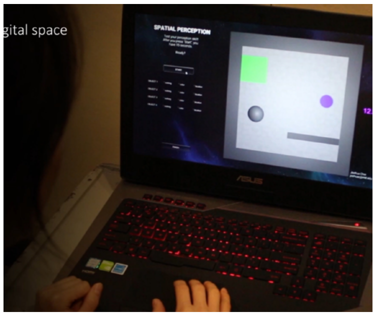
For this puzzle type game, I prepared two levels, easy mode with four objects and hard mode with seven objects. Each object has a simple geometry such as a box or sphere, and has a color of red, blue, green, or yellow. For the hard mode, there exists more complex geometry such as tree in order to increase complexity of a game-play. Participants play this game on two spaces, PDS and IVS, back and forth. In PDS, participants have a plan view of objects (figure 12), while in IVS, they have a first person view of objects situated at the center of the space (figure 13). In IVS, participants can rotate 360 degree, but they cannot move closer or further away from objects.

1. Puzzle in PDS: Easy mode
    - a. A participant presses ‘start’ button to begin.
    - b. He/she studies 4 objects on a plan view for 15 seconds.
    - c. The 4 objects either change in color, change in location, or do not change at all.
    - d. He/she identifies whether each object changed in color, changed in location, or did not change at all.
2. Puzzle in IVS: Easy Mode
    - a. He/she wears VR headset to begin.
    - b. He/she studies 4 objects on a first person view for 15 s.
    - c. The four objects either change in color, change in location, or do not change at all.
    - c. He/she selects identifies whether each object changed in color, changed in location, or did not change at all.
3. Puzzle in PDS: Hard mode

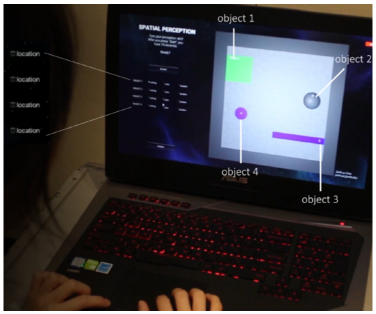
    Repeats step 1 but with 20 seconds given to study 7 objects.
4. Puzzle in IVS: Hard Mode

    Repeats step 2 but with 20 seconds given to study 7 objects. IVS offers better perception of scale of objects than bird’s-eye view in PDS.

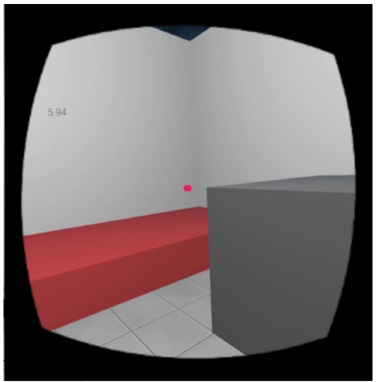
Steps



Step 1-b



Step 1-c



Step 2-b

Step 2-c

C# Code: Each participant’s data set is saved into dictionary format for analysis

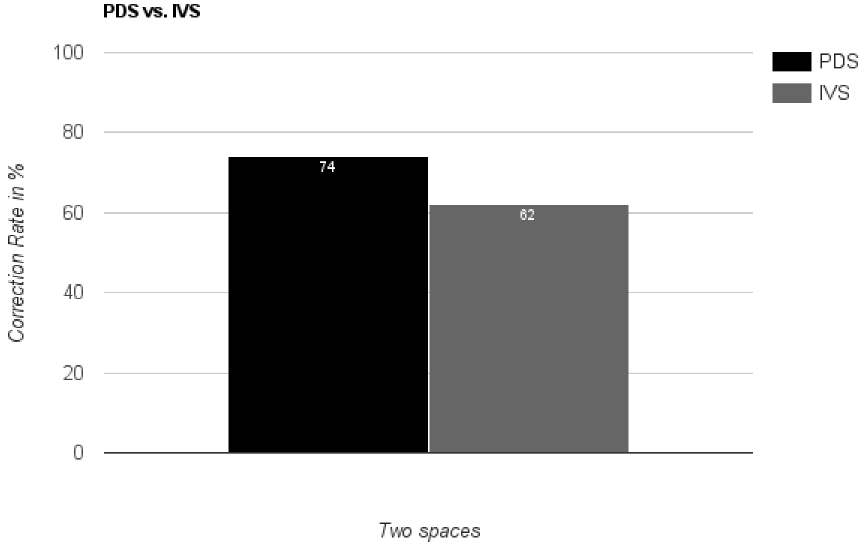
```
Dictionary<string, Dictionary<string, string>> data_9 = new Dictio-
nary<string, Dictionary<string, string>>
    {
      {
        “info”,
        new Dictionary<string, string>
        {
          {“name”,”Danny” }
        }
      },
      {
        “data”,
        new Dictionary<string, string>
        {
          {“2D_E_A”,”1111”},
          {“2D_E_B”,””},
          {“2D_H_A”,”1101110”},
          {“2D_H_B”,””},
          {“VR_E_A”,””},
          {“VR_E_B”,”1111”},
          {“VR_H_A”,”1111111”},
          {“VR_H_B”,””}
        }
      }

    };
```

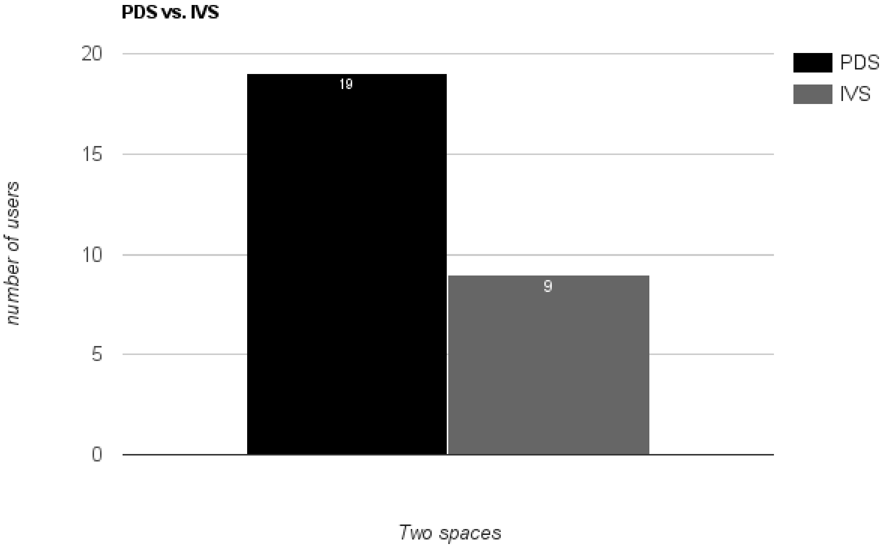
Results

All the answers are recorded, and they are saved into a dictionary format in C#. Total 36 people participated; 24 from MIT and 12 from Harvard (figure 14). Half of them are architects while other half is consisted of different disciplines, but mainly computer science students.

Graph 4 shows that participants performed 12% better in PDS than in IVS, supporting that PDS with the plan view mode offers better perception of objects’ location and orientation than the first person view mode of IVS. Also, a brief interview conducted at the end of the experiment supports that the most of participants had much easier time in PDS. Graph 5 shows that out of 36 participants, there are 9 people who performed better in IVS. Interestingly, most of them from those 9 people said that PDS was easier even though they performed better in IVS. There was no significant difference in performance between ‘easy mode’ and ‘hard mode’.



Graph 4: In average, participants got 74% correct in PDS, while they got 62% correct in IVS- this combines both ‘easy’ and ‘hard’ mode.



Graph 5: There are 19 participants who performed better in PDS, 9 in IVS, and 8 participants who performed the same - these 8 participants are not shown on this graph.

Danniely A Staback Rodriguez is March student from MIT, who ranked number one for this experiment, and I got to interview her again few days later the experiment (figure 13). She got everything right in IVS, but got two wrong for PDS, but during the interview, she still claimed that playing in PDS was easier. She said that PDS was easier because she could view the objects as a whole, which gave her an opportunity to find a pattern for memorizing - allocentric encoding. I asked what strategies she used for memorizing the objects in IVS. She said, she used her hands, even though the VR app did not provide visualization of her hands, in order to relate virtual objects to her body. She used her body as a reference point to memorize objects around her- egocentric encoding.

Through studying results found from this experiment, I have found strategies used for each space. For PDS, it is about pattern recognition. People use a computer screen as a frame to study relationship between objects to find patterns. As discussed from Background Research section of this thesis, people tend to rely more on allocentric encoding in less immersive environment. For IVS, there are two main strategies used for perceiving the space. Similar to PDS, participants rely on allocentric encoding by trying to relate object to object or object to the virtual environment. However, relying only on this strategy performed poorly. In IVS, participants cannot perceive all the objects at once. So that they have to create more than one patterns in order to connect all the objects in the scene, which made them confusing when answering the questions. The second strategy for IVS relies on egocentric encoding by relating objects to one's body, which was main strategy used by Danniely.

Figure 13: Danniely acting with hands to set up relationship between her body and virtual objects in IVS. She is relying on egocentric encoding in order to perceive objects.

Discussion

Different backgrounds

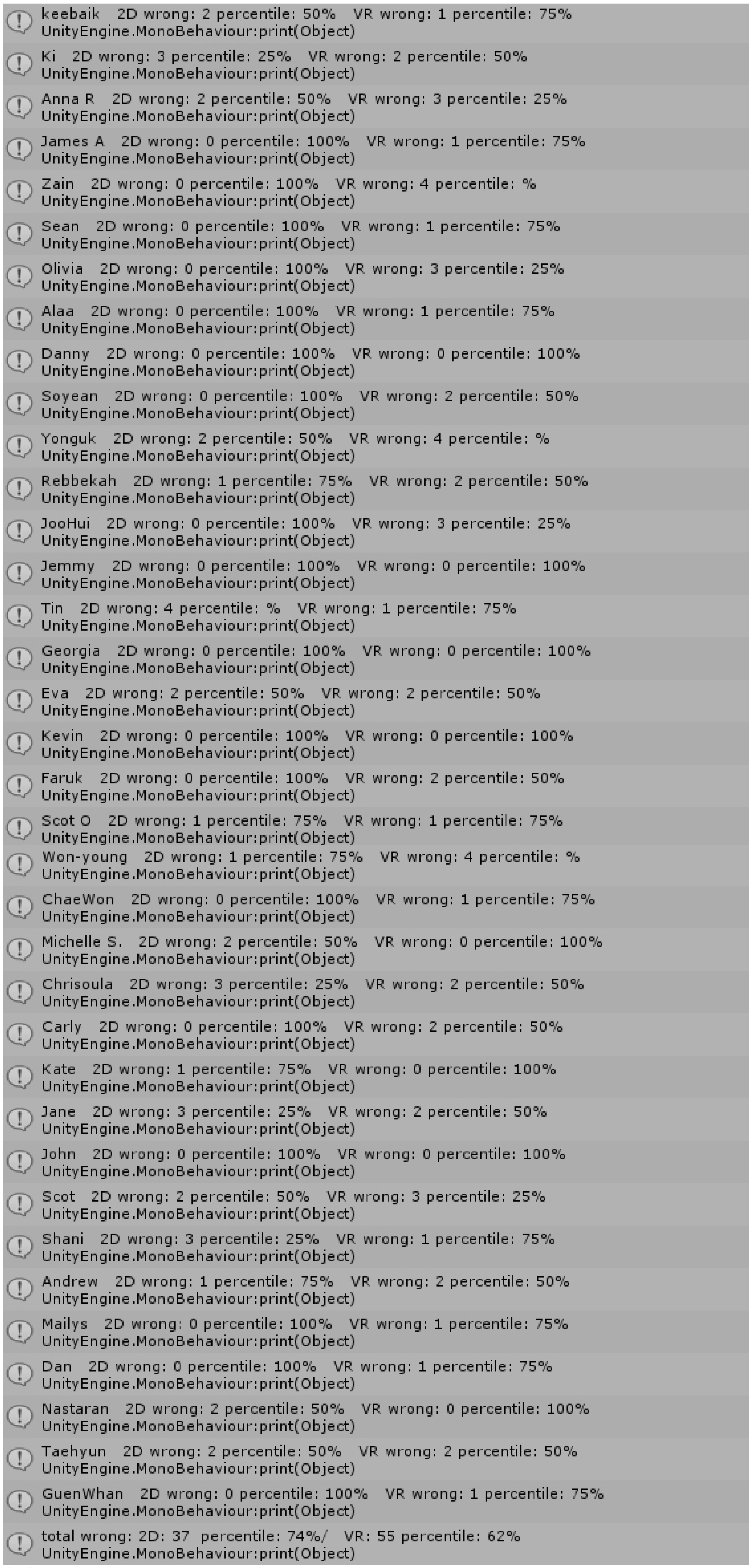
During this experiment, MIT students produced better results than Harvard students. However, within MIT, computer science students performed better than architecture students. In future, it would be interesting to test different backgrounds of students. I wonder if spatial perception skill relates to one's creativity during spatial design process, or if it is possible to calculate one's spatial creativity at all.

Visualization of body

Even though Kozhevnikov's research (2015) shows that immersive environment motivates egocentric encoding, not all participants behaved in egocentric way during this experiment. I believe that is because participants could not see their body in IVS. My hypothesis is that if participants could see their body and hands in IVS, then they would rely on egocentric encoding helping them perceive better in IVS, thus perform better in IVS. In future, I will experiment on how to increase egocentric encoding for participants behaving in IVS by providing them visualization of their body parts.

Conclusion

By looking at the average error produced from PDS and IVS, this experiment concludes that compared to a first person view in IVS, a plan view in PDS offers better perception of orientation and location of objects. Out of 36 participants, 9 participants performed better in IVS and 8 participants performed the same in two spaces. However, most of them still believe that PDS was easier than IVS. I believe this is because, for perceiving objects' orientation and location, allocentric encoding works more intuitively.



```
keebaik   2D wrong: 2 percentile: 50%   VR wrong: 1 percentile: 75%
UnityEngine.MonoBehaviour:print(Object)
Ki   2D wrong: 3 percentile: 25%   VR wrong: 2 percentile: 50%
UnityEngine.MonoBehaviour:print(Object)
Anna R   2D wrong: 2 percentile: 50%   VR wrong: 3 percentile: 25%
UnityEngine.MonoBehaviour:print(Object)
James A   2D wrong: 0 percentile: 100%   VR wrong: 1 percentile: 75%
UnityEngine.MonoBehaviour:print(Object)
Zain   2D wrong: 0 percentile: 100%   VR wrong: 4 percentile: %
UnityEngine.MonoBehaviour:print(Object)
Sean   2D wrong: 0 percentile: 100%   VR wrong: 1 percentile: 75%
UnityEngine.MonoBehaviour:print(Object)
Olivia   2D wrong: 0 percentile: 100%   VR wrong: 3 percentile: 25%
UnityEngine.MonoBehaviour:print(Object)
Alaa   2D wrong: 0 percentile: 100%   VR wrong: 1 percentile: 75%
UnityEngine.MonoBehaviour:print(Object)
Danny   2D wrong: 0 percentile: 100%   VR wrong: 0 percentile: 100%
UnityEngine.MonoBehaviour:print(Object)
Soyean   2D wrong: 0 percentile: 100%   VR wrong: 2 percentile: 50%
UnityEngine.MonoBehaviour:print(Object)
Yonguk   2D wrong: 2 percentile: 50%   VR wrong: 4 percentile: %
UnityEngine.MonoBehaviour:print(Object)
Rebbekah   2D wrong: 1 percentile: 75%   VR wrong: 2 percentile: 50%
UnityEngine.MonoBehaviour:print(Object)
JooHui   2D wrong: 0 percentile: 100%   VR wrong: 3 percentile: 25%
UnityEngine.MonoBehaviour:print(Object)
Jemmy   2D wrong: 0 percentile: 100%   VR wrong: 0 percentile: 100%
UnityEngine.MonoBehaviour:print(Object)
Tin   2D wrong: 4 percentile: %   VR wrong: 1 percentile: 75%
UnityEngine.MonoBehaviour:print(Object)
Georgia   2D wrong: 0 percentile: 100%   VR wrong: 0 percentile: 100%
UnityEngine.MonoBehaviour:print(Object)
Eva   2D wrong: 2 percentile: 50%   VR wrong: 2 percentile: 50%
UnityEngine.MonoBehaviour:print(Object)
Kevin   2D wrong: 0 percentile: 100%   VR wrong: 0 percentile: 100%
UnityEngine.MonoBehaviour:print(Object)
Faruk   2D wrong: 0 percentile: 100%   VR wrong: 2 percentile: 50%
UnityEngine.MonoBehaviour:print(Object)
Scot O   2D wrong: 1 percentile: 75%   VR wrong: 1 percentile: 75%
UnityEngine.MonoBehaviour:print(Object)
Won-young   2D wrong: 1 percentile: 75%   VR wrong: 4 percentile: %
UnityEngine.MonoBehaviour:print(Object)
ChaeWon   2D wrong: 0 percentile: 100%   VR wrong: 1 percentile: 75%
UnityEngine.MonoBehaviour:print(Object)
Michelle S.   2D wrong: 2 percentile: 50%   VR wrong: 0 percentile: 100%
UnityEngine.MonoBehaviour:print(Object)
Chrisoula   2D wrong: 3 percentile: 25%   VR wrong: 2 percentile: 50%
UnityEngine.MonoBehaviour:print(Object)
Carly   2D wrong: 0 percentile: 100%   VR wrong: 2 percentile: 50%
UnityEngine.MonoBehaviour:print(Object)
Kate   2D wrong: 1 percentile: 75%   VR wrong: 0 percentile: 100%
UnityEngine.MonoBehaviour:print(Object)
Jane   2D wrong: 3 percentile: 25%   VR wrong: 2 percentile: 50%
UnityEngine.MonoBehaviour:print(Object)
John   2D wrong: 0 percentile: 100%   VR wrong: 0 percentile: 100%
UnityEngine.MonoBehaviour:print(Object)
Scot   2D wrong: 2 percentile: 50%   VR wrong: 3 percentile: 25%
UnityEngine.MonoBehaviour:print(Object)
Shani   2D wrong: 3 percentile: 25%   VR wrong: 1 percentile: 75%
UnityEngine.MonoBehaviour:print(Object)
Andrew   2D wrong: 1 percentile: 75%   VR wrong: 2 percentile: 50%
UnityEngine.MonoBehaviour:print(Object)
Mailys   2D wrong: 0 percentile: 100%   VR wrong: 1 percentile: 75%
UnityEngine.MonoBehaviour:print(Object)
Dan   2D wrong: 0 percentile: 100%   VR wrong: 1 percentile: 75%
UnityEngine.MonoBehaviour:print(Object)
Nastaran   2D wrong: 2 percentile: 50%   VR wrong: 0 percentile: 100%
UnityEngine.MonoBehaviour:print(Object)
Taehyun   2D wrong: 2 percentile: 50%   VR wrong: 2 percentile: 50%
UnityEngine.MonoBehaviour:print(Object)
GuenWhan   2D wrong: 0 percentile: 100%   VR wrong: 1 percentile: 75%
UnityEngine.MonoBehaviour:print(Object)
total wrong: 2D: 37  percentile: 74%/   VR: 55 percentile: 62%
UnityEngine.MonoBehaviour:print(Object)
```

Figure 14: Output from C# Code calculating 36 individual data set in order to rank them and to calculate means to compare PDS and IVS.

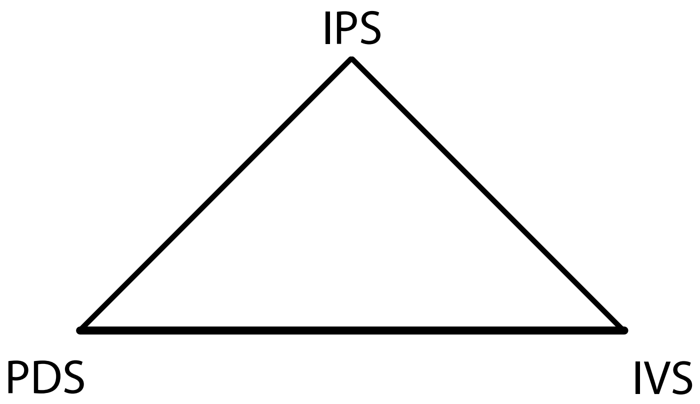


Diagram of three space

Experiment 3

The third experiment compares and contrasts between all three spaces, IPS, PDS and IVS. This experiment aims to prove the fourth hypothesis and to observe people's behaviors in IVS.

- Hypothesis 4: Compared to bird's-eye view in 2D screen, the first person view mode in VR offers better perception of scale of objects.

This experiment is about scaling a chair to the correct size in both PDS and IVS after having a chance to study the chair in IPS for a short time.

Preparation

For this experiment, I prepared an abstract 3D model of a room with desks and a column, and also a realistic model of a chair. Participants use SteamVR which allow them to sit or walk around in IVS while being able to increase or decrease the size of the chair using two physical controllers- these two controllers are visualized in IVS. In PDS, participants are in a bird-eye view mode, and it allows them to rotate the scene around to provide a view of the chair in different angles.

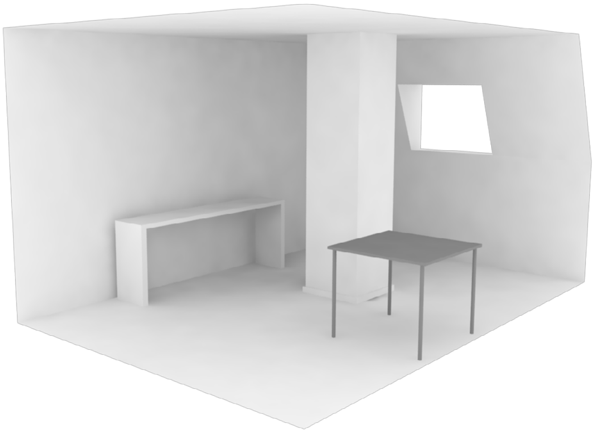


Figure 15: Abstract 3D model of a room with a column at the center and two desks

Figure 16: Realistic chair captured through photogrammetry

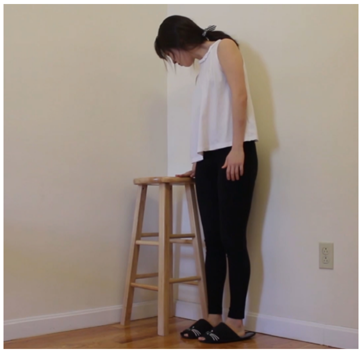
1. A participant enters a physical room and study the room.
2. He/she observes a physical chair outside the room.
3. Task 1: Scaling the Chair in PDS *without context**
    - a. A realistic chair appears out of scale.
    - b. He/she increases/decrease the scale of the chair.
    - c. He/she can rotate the screen.
    - d. When finished, the data is saved.
4. Task 2: Scaling the Chair in IVS *without context*
    - a. He/she wears a VR headset and grab two controllers.
    - b. He/she increases/decrease the scale of the chair.
    - c. He/she can move around the space.
    - d. When finished, the data is saved.
5. Task 3: Scaling the Chair in PDS *with context**
    - Repeats step 3
6. Task 4: Scaling the Chair in IVS *with context*
    - Repeats step 4

**Without context:* for PDS, only the floor plane of the room is provided while for IVS, the floor plane and walls are provided. The walls are not provided for PDS for participants to have the vision of the room's interior space.

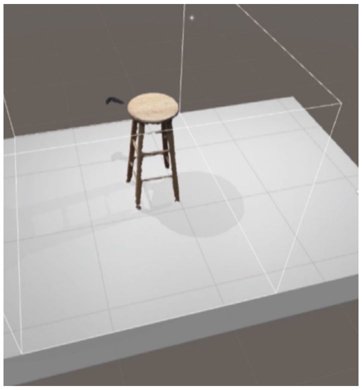
**With context:* The central column and two desks are added from above.

Steps

Step 1



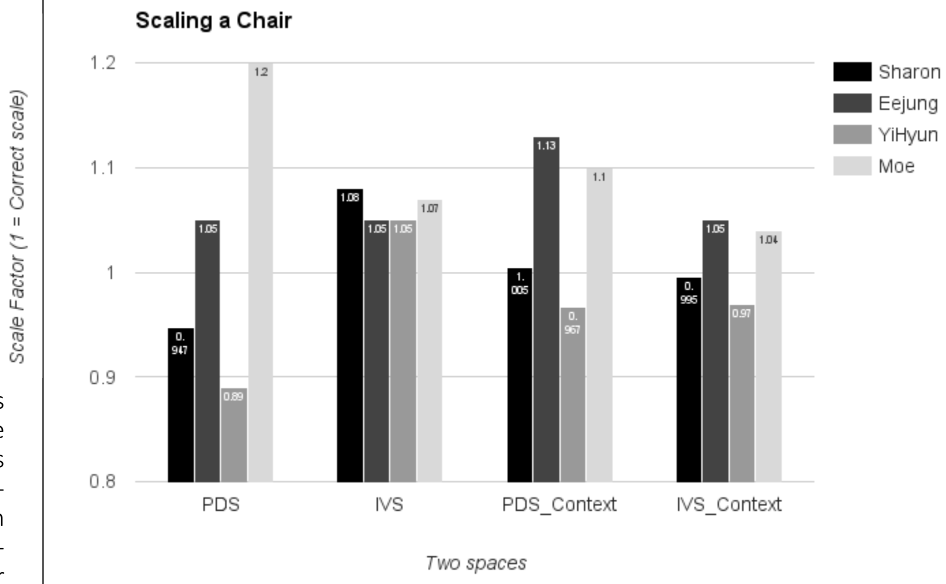
Step 2



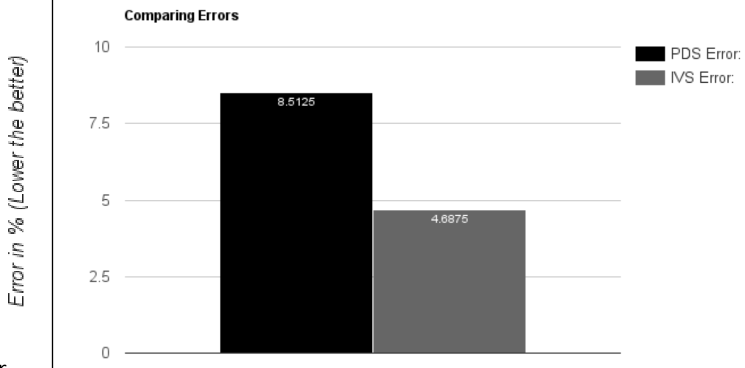
Step 3-a

Step 4-a

Results



Graph 6: This shows individual's performance throughout the four tasks. Closer to 1 on Y-axis corresponds to better performance. It shows that 'with context' produced better performance. IVS produced better performance with more stability compare to PDS.



Graph 7: This shows the average errors from PDS and IVS.

Four people participated for this experiment. Graph 6 shows scale factors recorded for all the four tasks: PDS without context, IVS without context, PDS with context, and IVS with context. This graph shows individual performance and also shows the average scale factor which is 1.03. The recorded error for IVS is less than 4%, which supports the first hypothesis, IVS can simulate IPS.

Seen in graph 7, The average error in PDS was 8.5%, and 4.7% for IVS. This is noticeable difference supporting that IVS works better for perceiving the scale of an object.

Figure 17: Set of photos taken during Step 2. Each participant is observing the physical chair in his/her own way.

Figure 18: Set of photos taken during Step 4. Each participant is acting very similar to the way he/she was acting to study the physical chair.

During step 2 in IPS, I took photos of participants in order to study how each participant observes the chair (figure 17). Two participants reached close to the chair and measured the height by referencing to their body height. One participant observed the chair in distance standing at one fixed point. Last participant used her hands to measure the height and the width of the chair. During step 4 in IVS, they interacted with the virtual chair very similar to the way they observed the chair from step 2 (figure 18). One participant who measured the chair using hands tried to measure the virtual chair using her hands, even though she could not see physical body in IVS. This observation hints that there is close relationship of how people act in both IPS and IVS.

Discussion

More participants

It was not easy to invite many participants as SteamVR needs a significant effort for setting up the experiment. However, in future, the experiment needs more data for more close analysis, especially for observing their behaviors in IPS and IVS.

Conclusion

As seen from quantitative data above, the third experiment proves that the first person view mode in IVS offers better perception of scale of objects than bird's-eye view in PDS. The experiment shows the clear relationship between the way participants interact with an object between IPS and IVS. For example, one participant who measured the chair in IPS with her hands acted the same in IVS even though she knew she could not see her hands.

CHAPTER 4

PROPOSED FRAMEWORK

Strengths of Three Spaces

Three experiments presented in this thesis have compared and contrasted between three spaces, intuitive physical space (IPS), projected digital space (PDS), and immersive virtual space (IVS). Through these experiments, important features of each space that assist architects in spatial design process have been identified and selected. These selected features form a framework for creating a virtual reality UI for spatial design in IVS.

Strength of IPS

The strength of IPS is the ability to use “body” as a tool. In IPS, we understand objects and environments by moving our muscles and receiving haptic feedback from the physical world. During the design process, we are eager to make a scale model that we can physically touch and feel, so that we can better understand the structure and materiality of a design, which otherwise cannot be understood by the limitation of pure imagination. We use our body as a tool for measuring objects. Our hands are not perfect but suitable replacement of rulers when we like to quickly design and evaluate. Our footsteps become a distance measurement. Being able to move slightly to view an object in a different angle is crucial for us to understand the depth that we cannot perceive through projected digital screen where everything is perfectly flattened. Thus, from IPS, the physical body and its ability to navigate, measure, and touch becomes the strength when merging to create the framework for UI – physical ‘body’ as a tool.

Strength of PDS

PDS has its strength in simplifying a space with objects on the flat 2D screen which enables human to perceive the space as a whole. This gives an opportunity for pattern recognition which is suitable when studying spatial organization and orientation of different objects. Having more information with details and textures may increase the overall experience, thus enable more in depth evaluation of the space. However, when studying relationship between spaces and objects or calculating distances that are hard to perceive in a first person view, such abstraction from projected digital space is necessary. Thus, from PDS, the framework will take its ability to abstract the spatial information – abstraction for spatial information.

Strength of IVS

In IVS, it provides an immersive experience where we believe what we see is true. This means that IVS simulates visual perception of physical space with high accuracy. Also found from first experiment, we found that IVS not only mimic the realism of the physical world, it enables us to perceive scale and proportion of the physical world with minimal error. In IVS, we can interact with virtual objects similar to the way we interact in physical space. By having physical controllers as extended body parts from our physical arms, we studied that human can interact with virtual objects significantly naturally. Thus, from IVS, the framework will take its ability to simulate physical space in which IVS itself will be the master platform that all the strengths from IPS and PDS are merged into – IVS as complex platform merging all the strengths from three spaces.

Features for Framework

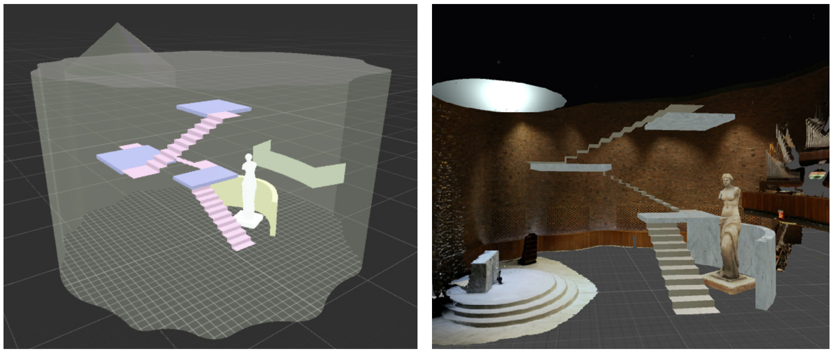


Figure 19: Left is an abstraction model of MIT Saarinen chapel. right is an realistic model of the chapel. Throughout this chapter, I will describe the features using a prototype I created for the thesis presentation, which used the chapel as a site.

1. Abstraction

When designing a space, a massing model, either physical or digital without realistic textures can benefit designers, because abstraction takes off unnecessary information and help designers focus on identifying patterns. The result of the second experiment shows that abstraction, such as being able to view the space with a plan view as a whole, helps people find patterns which enhances a spatial memory. Abstraction is a way to help design decision makings, and it is a crucial feature for UI to incorporate. Thus, the proposed UI will have abstraction models along with realistic models to acquire both advantages of being able to find patterns, and to experience the space during the design process (figure 19).

2. Multiple Models in Different Scales

Feature 1 proposes that UI needs to have two models, one is abstraction model without textures, and the other one is a realistic model that provides realistic experience for evaluating the design, thus assists design process in multiple levels. I propose that UI should have at least two models with different scales (Stoakley 1995). One should be small scale massing model without textures, and the other one should be the a realistic model in full scale (figure 20). It can be described as a model inside a model inside a model - you can input even more abstracted model into small abstraction scale model.

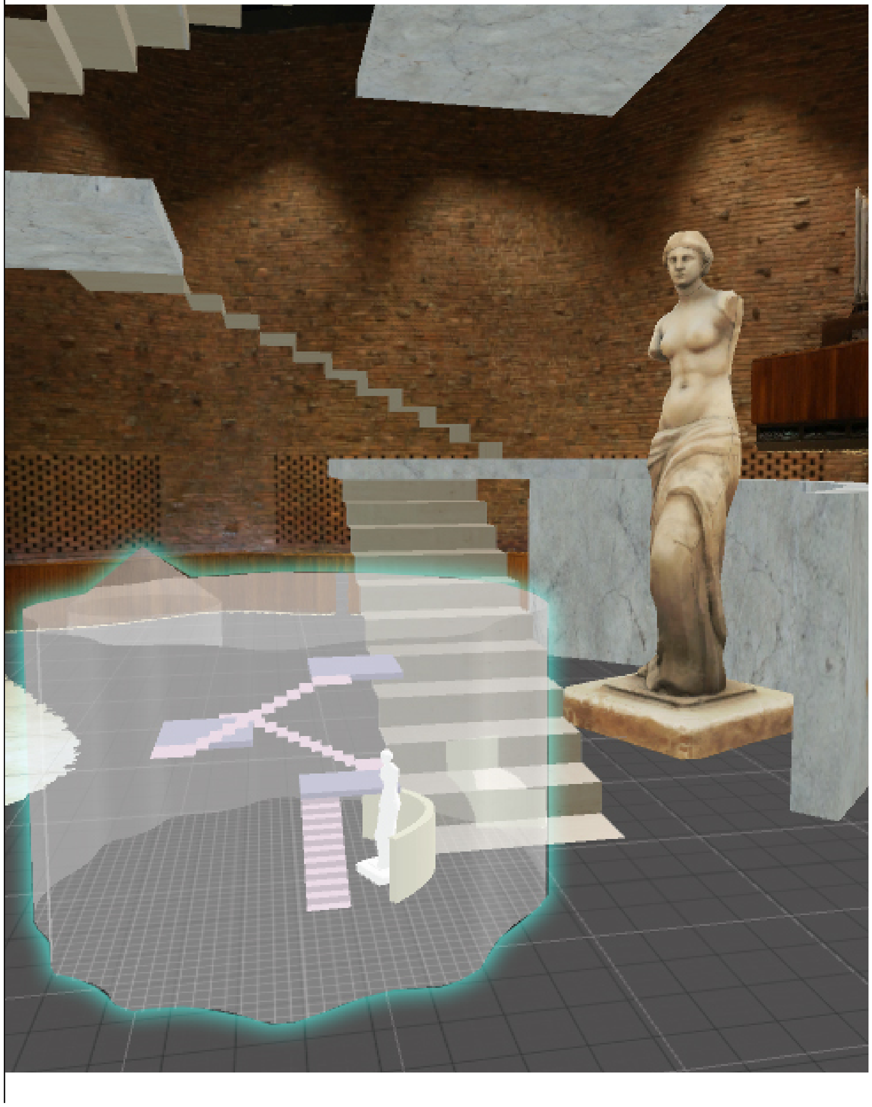


Figure 20: The background is the realstic model of the chapel in full scale. There is also an abstraction model in front of the camera without textures. With this proposed UI, designers will be able to interact with this abstraction model in order to move and scale objects, and also teleport to different locations without physically moving.

There are few ways to view a scale model in IVS. When a user first enter IVS, a user is fully immersed in a full scale model with realistic textures where a user spends some time experiencing the realistic space. When a user is ready for more actions, he/she can use a left-hand controller (for a right handed user) to summon a small abstraction model at a location of her left hand. She can bring the abstraction model closer into her face to study closely or she can place the model on the air floating, and then walk around the model to view it in many different angles. Also, in this abstraction model, it has built in feature to show dimensions of objects. This is important because the third experiment shows that in bird's eye view mode, perceiving scale is not as easy as in IVS.

3. Navigation

Navigation is a challenging feature in immersive virtual space. Often times, the physical space that a user is situated in is not as big as the virtual space represented in IVS, so a user has a limited area to walk around to explore the virtual environments. Thus, there has to be alternative ways to travel a distance in IVS other than physically moving.

The proposed UI does not require movements that make users travel more than a meter distance in IPS. The major movements that UI allow is walking around the small abstraction model for viewing. For navigating vertically or traveling a significant distances in IVS, I propose a teleporting system which is often used in video game design. A user can select objects in the small abstraction model with left-hand (for right handed person) to teleport to the selected object in the full scale model- in this case, the abstraction model is being treated as a video game's mini-map system.

4. Interaction with Virtual Objects

Up until now, all the interactions happened through a left-hand. A user can use the left hand controller to summon the small abstraction model, and then to select objects in that model to teleport to the full scale model objects. The left hand is a navigational tool.

For moving the objects, a user uses a right hand controller. She can only interact with objects inside the abstraction model - she cannot select and move objects of a full scale model. When a user brings her right hand controller onto the object she wants to move, an object is highlighted to show that it is ready for the further actions - a visual feedback is very important because IVS lacks haptic feedback. She can grab the highlight object in order to move. When the object starts move, the same object from the full scale model also moves in real-time to provide instant feedback of how the design in the full scale is being changed.

5. Body as a measuring Tool

As learned from 'rubber hand illusion', human cognition is flexible, so that users can easily learn to use controllers as if they are extended virtual body parts from IPS. Observing from the third experiment, users quickly adopt to use controllers as their hands, and used controllers as a measuring tool. In IVS with proposed UI, a user can use these controllers as a measuring tool to understand the scale of the full scale objects, and then to re-scale if necessary.

A user studies object's scale in the small scale model and teleport to one object to study it more closely to check if its height works with the design. She can measure the object's height using two controller (figure showing the distance between two controllers). She can also use her body, which is a representation of a ruler, to measure the object (figure of the body as a ruler). She can use the right controller to re-scale the object until she is satisfied with the design.

6. Superpower Features

Being in immersive virtual space opens unlimited opportunities for exploration of special effects, such as your body becoming small, Alice in Wonderland, or your eye becoming a fish, fish-eye lens effect. These types of special effects can benefit for discovering unknown. Instead of having the small scale model on your hand as proposed above, you can become small and enter into the small scale model without any details or textures. Or you can become small and explore the realistic model as if you are an ant or a mouse, and travel into small spaces, or even between walls.

You can play with virtual camera lens. Human vision covers 120 degree, and what if you can see the world in 180 degree? You have eyes of different animals, insects, or even become a rain and perceive the space dropping from the sky. These types of unrealistic, playful simulation can be simulated in IVS, and this possibility can increase our imagination and creative during the design process.

CHAPTER 5
CONCLUSION

This thesis proposes a framework for designing a unique user interface that provides architects with an alternative spatial environment in Virtual Reality. Such framework is created by examining the three spaces: intuitive physical space (IPS), projected digital space (PDS), and immersive virtual space (IVS). IPS is defined as the real physical space we live in, in which designers use their physical body as a tool to understand the world by touching and navigating through different objects and spaces. PDS is defined as the space projected on the flat 2D screen, in which designers produce 2D plan drawings or bird-eye view renderings. IVS is defined as virtual 3D immersive space, in which designers can experience their designs, and this space is the main focus of the thesis.

The thesis conducts three comparative studies of IPS, PDS, and IVS, which elucidate the nature of spatial perception and interaction in the three spaces. First, IVS is an ideal space for visualization of spatial design. As shown in Experiment 1, people can perceive proportion and scale in IVS just as they do in IPS. Therefore, there is an opportunity that IVS can become a main alternative environment for architects to design and share their designed spaces with others. Second, IPS and PDS have their own unique strengths for spatial design. PDS is better than IVS in observing the overall pattern of objects in space (Experiment 2), although IVS offers better perception of scale of individual objects (Experiment 3). The strength of IPS is the ability to use physical body as a tool for measuring objects. Interestingly, people also use their “body” as a tool for measuring objects in IVS (Experiment 3).

The results of the three experiments can be used as a framework for designing a virtual reality user interface that allows architects to use IVS not only as a space for spatial visualization but also as a space for spatial design process. The unique strengths of IPS, PDS, and IVS can be used to design features of such a virtual reality user interface. For example, the real-time dual scale modeling feature, which combines the strengths of physical scale model from IPS and projected plan view from PDS, enables the architect to simultaneously design and experience the space in multi scale levels. By incorporating superpower features, which is only possible through virtual reality technology, the user interface can also amplify entertaining and creative aspects of the spatial design process, allowing unexpected discoveries and maximizing the imaginative nature of design process.

The thesis proposes a framework for designing user interface by reflecting on the results from the experiments that highlight the unique strengths of IPS, PDS, and IVS. Then, it describes a prototype of such a user interface with features that enhance spatial designing process for architects situated in virtual space through ***merging three spaces***. This thesis shows strong support for active incorporation of virtual reality technology into architectural spatial design process and visualization, which allows an architect to experience his or her imagination and to share that experience with others. If a powerful virtual reality user interface that combines the strengths of traditional spatial design methods with the unique characteristics of virtual reality is created, the potential of spatial designing in virtual space is unlimited.

Figure: *Corbuiser Yesterday.* He is imagining the design by looking at the physical model (Le Corbusier 1954).

Figure: *Corbuiser Today.* He is wearing a VR headset to experience his design, Image collage by Joshua Choi 2016.

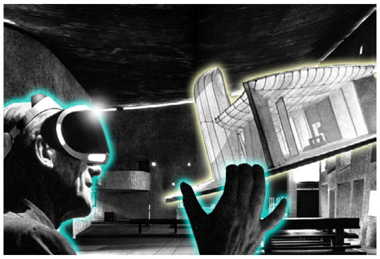


Figure: *Corbuiser Tomorrow.* He is not only experiencing, but designing in IVS, image collage by Joshua Choi 2016.

CHAPTER 6

ACKNOWLEDGMENT

I would like to thank the following people.

Takehiko Nagakura, my thesis advisor for guiding and motivating me since my previous thesis for the Master of Architecture degree at MIT;
Scot Osterweil, my thesis reader, for trying out my experiment and providing insightful feedback on video game theory and playful system;
Federico Casalegno, for giving me an opportunity to serve as a research assistant and funding my tuition;
2015 Harold Horowitz (1951) Student Research Fund, for allowing me to purchase all the VR devices for this thesis;
Akemi Chayama, for allowing me to conduct experiments at Boston Children's Museum;
All the participants from MIT and Harvard who helped me collect meaningful data for the thesis;
Sotirios D Kotsopoulos and Daniel Tsai, who are great life-advisors and sources of inspiration;
All my friends from Design and Computation Group, WashU, and Korea, for always being there for me to lean on and to have fun;
Lea Yoon, for helping me with English;
My family--parents, brother, aunts, cousins, and nephews--for being the best family;
And finally, **Sharon Kim** for being the best model for all the experiment videos and being there for a discussion about architecture even though you are a bio major.

CHAPTER 7

REFERENCES

- “Allocentric vs. Egocentric Spatial Processing.” Imagery Lab RSS. N.p., n.d. Web. 19 May 2016.
- “History Of Virtual Reality - Virtual Reality.” Virtual Reality Society. N.p., 25 Dec. 2015. Web. 19 May 2016.
- “Bibliography & Resources.” Japanese House Exhibit. N.p., n.d. Web. 19 May 2016.
- Kilteni, Konstantina, Jean-Marie Normand, Maria V. Sanchez-Vives, and Mel Slater. “Extending Body Space in Immersive Virtual Reality: A Very Long Arm Illusion.” PLoS ONE 7.7 (2012)
- A CIDADE BRANCA, Le Corbusier. 1950–1954. Chapelle Notre Dame du Haut, Ronchamp, France, Availble from: tumblr, http://acidadebranca.tumblr.com/post/103853451839/19501954-le-corbusier-chapelle-notre-dame-du
- Kozhevnikov, Maria, Lee Rong Cheng, and Michael Kozhevnikov. “Effect of Environment Immersivity on Encoding Strategies of Spatial Tasks.”Procedia Manufacturing 3 (2015): 5059-066.
- Heydarian, Arsalan, Joao P. Carneiro, David Gerber, Burcin Becerik-Gerber, Timothy Hayes, and Wendy Wood. “Immersive Virtual Environments versus Physical Built Environments: A Benchmarking Study for Building Design and User-built Environment Explorations.” Automation in Construction 54 (2015): 116-26.
- “VR Interface Design and the Future of Hybrid Reality.” Motion Blog. N.p., 08 Oct. 2015. Web. 19 May 2016.
- Sutherland, Ivan E. “A Head-mounted Three Dimensional Display.”Proceedings of the December 9-11, 1968, Fall Joint Computer Conference, Part I on - AFIPS ‘68 (Fall, Part I) (1968)
- Stoakley, Richard, Matthew J. Conway, and Randy Pausch. “Virtual Reality on a WIM.” Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI ‘95 (1995)
- Ehrsson, H. H. “That’s My Hand! Activity in Premotor Cortex Reflects Feeling of Ownership of a Limb.” Science 305.5685 (2004)